Multiplierless 16-point DCT Approximation for Low-complexity Image and Video Coding

T. L. T. Silveira^{*} R. S. Oliveira[†] F. M. Bayer[‡] R. J. Cintra[§] A. Madanayake[¶]

Abstract

An orthogonal 16-point approximate discrete cosine transform (DCT) is introduced. The proposed transform requires neither multiplications nor bit-shifting operations. A fast algorithm based on matrix factorization is introduced, requiring only 44 additions—the lowest arithmetic cost in literature. To assess the introduced transform, computational complexity, similarity with the exact DCT, and coding performance measures are computed. Classical and state-of-the-art 16-point low-complexity transforms were used in a comparative analysis. In the context of image compression, the proposed approximation was evaluated via PSNR and SSIM measurements, attaining the best cost-benefit ratio among the competitors. For video encoding, the proposed approximation was embedded into a HEVC reference software for direct comparison with the original HEVC standard. Physically realized and tested using FPGA hardware, the proposed transform showed 35% and 37% improvements of area-time and area-time-squared VLSI metrics when compared to the best competing transform in the literature.

Keywords

DCT approximation, Fast algorithm, Low cost algorithms, Image compression, Video coding

1 INTRODUCTION

The discrete cosine transform (DCT) [1,2] is a fundamental building-block for several image and video processing applications. In fact, the DCT closely approximates the Karhunen-Loève transform (KLT) [1], which is capable of optimal data decorrelation and energy compaction of first-order stationary Markov signals [1]. This class of signals is particularly appropriate for the modeling of natural images [1,3]. Thus, the DCT finds applications in several contemporary image and video compression standards, such as the JPEG [4] and the H.26x family of codecs [5–7]. Indeed, several fast algorithms for computing the exact DCT were proposed [8–15]. However, these methods require the use of arithmetic multipliers [16,17], which are time, power, and hardware demanding arithmetic operations, when compared to additions or bit-shifting operations [18]. This fact may jeopardize the application of the DCT in very low power consumption contexts [19,20]. To

^{*}T. L. T. Silveira is with the Programa de Pós-Graduação em Computação, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, RS, Brazil

[†]R. S. Oliveira is with the Signal Processing Group, Departamento de Estatística, Universidade Federal de Pernambuco (UFPE); Programa de Graduação em Estatística (UFPE), Brazil, and the Department of Electrical and Computer Engineering, University of Akron, OH

[‡]F. M. Bayer is with the Departamento de Estatística, UFSM, and LACESM, Santa Maria, RS, Brazil, E-mail: bayer@ufsm.br [§]R. J. Cintra is with the Signal Processing Group, Departamento de Estatística, Universidade Federal de Pernambuco. E-mail: rjdsc@stat.ufpe.org

[¶]A. Madanayake is with the Department of Electrical and Computer Engineering, University of Akron, OH, Email: arjuna@uakron.edu

overcome this problem, in recent years, several approximate DCT methods have been proposed. Such approximations do not compute the exact DCT, but are capable of providing energy compaction [21, 22] at a very low computational cost. In particular, the 8-point DCT was given a number of approximations: the signed DCT [17], the level 1 approximation [16], the Bouguezel-Ahmad-Swamy (BAS) transforms [21, 23–26], the rounded DCT (RDCT) [27], the modified RDCT [28], the approximation in [29], and the improved DCT approximation introduced in [30]. These methods furnish meaningful DCT approximations using only addition and bit-shifting operations, whilst offering sufficient computational accuracy for image and video processing [31].

Recently, with the growing need for higher compression rates [30], the high efficiency video coding (HEVC) was proposed [32,33]. Unlike several image and video compression standards, the HEVC employs 4-, 16-, and 32-point integer DCT-based transformations [30,32]. In contrast to the 8-point DCT case—where dozens of approximations are available [21,25,27,28,30,34], —the 16-point DCT approximation methods are much less explored in literature. To the best of our knowledge, only the following orthogonal methods are available: the traditional Walsh–Hadamard transform (WHT) [35], the BAS-2010 [24] and BAS-2013 [26] approximations, and the transformations proposed in [31], [22], and [36].

In this work, we aim at proposing a low-complexity orthogonal 16-point DCT approximation capable of outperforming all competing methods in terms of arithmetic complexity while exhibiting very close coding performance when compared to state-of-the-art methods. For such, we advance a transformation matrix which combines instantiations of a low-complexity 8-point approximation according to a divide-and-conquer approach.

The remainder of this paper is organized as follows. Section 2 introduces the new DCT approximation, a fast algorithm based on matrix factorization, and a comprehensive assessment in terms of computational complexity and several performance metrics. In Section 3, the proposed approximation is submitted to computational simulations consisting of a JPEG-like scheme for still image compression and the embedding of the proposed approximation into a HEVC standard reference software. Section 4 assesses the proposed transform in a hardware realization based on field-programmable gate array (FPGA). Conclusions are drawn in Section 5.

2 16-POINT DCT APPROXIMATION

2.1 Definition

It is well-known that several fast algorithm structures compute the N-point DCT through recursive computations of the $\frac{N}{2}$ -point DCT [1,2,13,31,36]. Following a similar approach to that adopted in [31,36], we propose a new 16-point approximate DCT by combining two instantiations of the 8-point DCT approximation introduced in [28] with tailored signal changes and permutations. This procedure is induced by signal-flow graph in Fig. 1. This particular 8-point DCT approximation, presented as \mathbf{T}_8 in Fig. 1, was selected because (i) it presents the lowest computational cost among the approximations archived in literature (zero multiplications, 14 additions, and zero bit-shifting operations) [28] and (ii) it offers good energy compaction properties [37].



Figure 1: Signal-flow graph of the fast algorithm for **T**. The input data x_i , i = 0, 1, ..., 15 relates to the output data X_j , j = 0, 1, ..., 15 according to $\mathbf{X} = \mathbf{T} \cdot \mathbf{x}$. Dashed arrows represent multiplications by -1.

As a result, the proposed transformation matrix is given by:

The entries of the resulting transformation matrix are defined over $\{0, \pm 1\}$, therefore it is completely multiplierless. Above transformation can be orthogonalized according to the procedure described in [3, 27, 38]. Thus the associate orthogonal DCT approximation is furnished by $\hat{\mathbf{C}} = \mathbf{S} \cdot \mathbf{T}$, where $\mathbf{S} = \sqrt{(\mathbf{T} \cdot \mathbf{T}^{\top})^{-1}}$ and the superscript $^{\top}$ denotes matrix transposition. In particular, we have:

$$\mathbf{S} = \frac{1}{4} \cdot \operatorname{diag}\left(1, 1, 2, \sqrt{2}, \sqrt{2}, 1, 2, 2, 1, 2, 2, \sqrt{2}, \sqrt{2}, 2, 2, 2\right).$$

In the context of image and video coding, the diagonal matrix \mathbf{S} does not contribute to the computational cost of $\hat{\mathbf{C}}$. This is because it can be merged into the codec quantization steps [22, 25, 27, 31]. Therefore, the actual computation cost of the approximation is fully confined in the low-complexity matrix \mathbf{T} .

Transform	Mult	Add	Shifts	Total
Chen DCT	44	74	0	118
WHT	0	64	0	64
BAS-2010	0	64	8	72
BAS-2013	0	64	0	64
Transform in [22]	0	72	0	72
Transform in [31]	0	60	0	60
Transform in [36]	0	60	0	60
Proposed approx.	0	44	0	44

Table 1: Comparison of computational complexities

2.2 FAST ALGORITHM AND COMPUTATIONAL COMPLEXITY

The transformation \mathbf{T} requires 112 additions, if computed directly. However, it can be given the following sparse matrix factorization:

$$\mathbf{T} = \mathbf{P}_2 \cdot \mathbf{M}_4 \cdot \mathbf{M}_3 \cdot \mathbf{M}_2 \cdot \mathbf{P}_1 \cdot \mathbf{M}_1,$$

where

$$\begin{split} \mathbf{M}_{1} &= \begin{bmatrix} \mathbf{I}_{8} & \overline{\mathbf{I}}_{8} \\ \overline{\mathbf{I}}_{8} & -\mathbf{I}_{8} \end{bmatrix}, \\ \mathbf{M}_{2} &= \operatorname{diag}\left(\begin{bmatrix} \mathbf{I}_{4} & \overline{\mathbf{I}}_{4} \\ \overline{\mathbf{I}}_{4} & -\mathbf{I}_{4} \end{bmatrix}, \begin{bmatrix} \mathbf{I}_{4} & \overline{\mathbf{I}}_{4} \\ \overline{\mathbf{I}}_{4} & -\mathbf{I}_{4} \end{bmatrix} \right), \\ \mathbf{M}_{3} &= \operatorname{diag}\left(\begin{bmatrix} \mathbf{I}_{2} & \overline{\mathbf{I}}_{2} \\ \overline{\mathbf{I}}_{2} & -\mathbf{I}_{2} \end{bmatrix}, -\mathbf{I}_{4}, \begin{bmatrix} \mathbf{I}_{2} & \overline{\mathbf{I}}_{2} \\ \overline{\mathbf{I}}_{2} & -\mathbf{I}_{2} \end{bmatrix}, -\mathbf{I}_{4} \right), \\ \mathbf{M}_{4} &= \operatorname{diag}\left(\begin{bmatrix} 1 & 1 & 0 \\ 1 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}, \mathbf{I}_{4}, \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & -1 \end{bmatrix}, -\mathbf{I}_{4}, \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \right), \end{split}$$

matrices \mathbf{P}_1 and \mathbf{P}_2 correspond to the permutations $(1)(2)(3)(4)(5)(6)(7)(8)(9)(10\ 12\ 16\ 10)(11\ 13\ 15\ 11)(14)$ and $(1)(2\ 9)(3\ 8\ 16\ 15\ 5\ 4\ 12\ 11\ 7\ 6\ 10\ 14\ 13\ 3)$ in cyclic notation [39], respectively; and \mathbf{I}_N and $\mathbf{\overline{I}}_N$ denote the identity and counter-identity matrices of order N, respectively. The above factorization reduces the computational cost of \mathbf{T} to only 44 additions. Fig. 1 depicts the signal-flow graph of the fast algorithm for \mathbf{T} ; the blocks labeled as \mathbf{T}_8 denote the selected 8-point approximate DCT [28].

A computational complexity comparison of the considered orthogonal 16-point DCT approximations is summarized in Table 1. For contrast, we also included the computational cost of the Chen DCT fast algorithm [8]. The proposed approximation requires neither multiplication, nor bit-shifting operations. Furthermore, when compared to the methods in [31,36], the WHT or BAS-2013, and the transformation in [22], the proposed approximation requires 26.67%, 31.25%, and 38.89% less arithmetic operations, respectively.

2.3 Performance assessment

We separate similarity and coding performance measures to assess the proposed transformation. For similarity measures, we considered the DCT distortion (d_2) [40], the total error energy (ϵ) [27], and the mean square error (MSE) [1,2]. For coding performance evaluation, we selected the the transform coding gain (C_g) [1] and the transform efficiency (η) [1]. Table 2 compares the performance measure values for the discussed

Transform	d_2	ϵ	MSE	C_g	η
Chen DCT	0.000	0.000	0.000	9.455	88.452
WHT	0.878	92.563	0.428	8.194	70.646
BAS-2010	0.667	64.749	0.187	8.521	73.634
BAS-2013	0.511	54.621	0.132	8.194	70.646
Transform in [22]	0.152	8.081	0.046	7.840	65.279
Transform in $[31]$	0.340	30.323	0.064	8.295	70.831
Transform in [36]	0.256	14.740	0.051	8.428	72.230
Proposed approx.	0.493	3 41.00	0.095 0	7.851	7 67.608

Table 2: Coding and similarity performance assessment

transforms. The proposed approximation could furnish performance measure which are comparable to the average results of the state-of-the-art approximation. At the same time, its computational cost is roughly 30% smaller than the lowest complexity method in literature [31,36].

3 Image and video coding

In the following subsections, we describe two computational experiments in the context of image and video encoding. Our goal is to demonstrate in real-life scenarios that the introduced approximation is capable of performing very closely to state-of-the-art approximations at a much lower computational cost. For the still image experiment, we employ a fixed-rate encoding scheme which avoids quantization. This is done to isolate the role of the transform in order to emphasize the good properties of energy compaction of the approximate transforms. On the other hand, for the video experiment, we include the variable-rate encoding equipped with the quantization step as required by the actual HEVC standard. Thus, we aim at providing two comprehensive experiments to highlight the capabilities of the introduced approximation.

3.1 Image compression experiments

We adopted a JPEG-like procedure as detailed in the methodology presented in [17] and reproduced in [21, 24, 25, 31, 36]. A total of 45 512×512 8-bit grayscale images obtained from a standard public image bank [41] was considered. This set of image was selected to be representative of the imagery commonly found in real-life applications. Color images could be treated similarly by processing each channel separately. Each given input image **A** was split into 1024 16×16 disjoint blocks ($\mathbf{A}_k, k = 1, 2, \ldots, 1024$) which were submitted to the forward bidimensional (2-D) transformation given by: $\mathbf{B}_k = \mathbf{\tilde{C}} \cdot \mathbf{A}_k \cdot \mathbf{\tilde{C}}^{\top}$, where $\mathbf{\tilde{C}}$ is a selected 16-point transformation. Following the zig-zag sequence [42], only the first $1 \leq r \leq 150$ elements of \mathbf{B}_k were retained; being the remaining ones zeroed and resulting in $\mathbf{\tilde{B}}_k$. The inverse 2-D transformation is then applied according to: $\mathbf{\tilde{A}}_k = \mathbf{\tilde{C}}^{\top} \cdot \mathbf{\tilde{B}}_k \cdot \mathbf{\tilde{C}}$. The resulting matrix $\mathbf{\tilde{A}}_k$ is the lossy reconstruction of \mathbf{A}_k . The correct rearrangement of all blocks results in the reconstructed image $\mathbf{\tilde{A}}$. This procedure was performed for each of the 45 images in the selected data set. To assess the approximation in a fair manner, we consider the ratio between performance measures and arithmetic cost. Such ratio furnishes the performance gain per unit of arithmetic computation. Fig. 2 shows the average PSNR and structural similarity index (SSIM) [43] measurements per unit of additive cost. The proposed approximation outperforms all approximate DCT for any value of r in both metrics. The introduced 16-point transform presents the best cost-benefit ratio among



Figure 2: Average (a) PSNR and (b) SSIM measurements per additive cost at compression ratios.

all competing methods.

Fig. 3 displays a qualitative and quantitative comparison considering standard Lena image. The PSNR measurements for the Lena image were only 4.75% and 5.69% below the results furnished by the transformations in [31, 36], respectively. Similarly, considering the SSIM, the proposed transform performed only 0.62%, 6.42%, and 7.43% below the performance offered by the transformations in [22], [31], and [36]. On the other hand, the proposed approximate DCT requires 38.8% and 26.6% less arithmetic operations when compared to [22] and [31,36], respectively. The proposed approximation outperformed the WHT, BAS-2010, and BAS-2013 according to both figures of merit. Indeed, the small losses in PSNR and SSIM compared to the exact DCT are not sufficient to effect a significant image degradation as perceived by the human visual system, as shown in Fig. 3.



(a) Original image

(b) PSNR = 28.55 dB, SSIM = (c) PSNR = 21.20 dB, SSIM = 0.7915 0.2076







(d) PSNR = 25.27 dB, SSIM = (e) PSNR = 25.79 dB, SSIM = (f) PSNR = 25.75 dB, SSIM = 0.6735 0.6921 0.7067



(g) PSNR = 27.13 dB, SSIM = (h) PSNR = 27.40 dB, SSIM = (i) PSNR = 25.84 dB, SSIM = 0.7505 0.7587 0.7023

Figure 3: Original (a) Lena image and compressed versions with r = 16 according to (b) the DCT, (c) WHT, (d) BAS-2010, (e) BAS-2013, (f) transform in [22], (g) transform in [31], (h) transform in [36], and (i) proposed 16-point approximation.



Figure 4: Performance of the proposed DCT approximation in HEVC standard for several QP values.

3.2 VIDEO COMPRESSION EXPERIMENTS

The proposed approximation was embedded into the HM-16.3 HEVC reference software [44], i.e., the proposed approximation is considered as a replacement for the original integer transform in the HEVC standard. Because the HEVC standard employs 4-, 8-, 16-, and 32-point transformations, we performed simulations in two scenarios: (i) substitution of the 16-point transformation only and (ii) replacement of the 8- and 16-point transformations. We adopted the approximation described in [28] and the proposed approximation for the 8- and 16-point substitutions, respectively. The original 8- and 16-point transforms employed in the HEVC standard require 22 multiplications and 28 additions; and 86 multiplications and 100 additions, respectively [45]. In contrast, the selected DCT approximations are multiplierless and require 50% and 56% fewer additions, respectively. The diagonal matrices associated to the 8- and 16-point approximations are fully embedded into the quantization step according to judicious scaling operations of the standard HEVC quantization tables [45].

In both scenarios, we have considered 11 CIF videos of 300 frames obtained from a public video database [46]. The default HEVC coding configuration for Main profile was adopted, which includes both 8-bit depth intra and inter-frame coding modes. We varied the quantization parameter (QP) from 5 to 50 in steps of 5. We adopted the PSNR as figure of merit, because it is readily available in the reference software. Measurements were taken for each color channel and frame. The overall video PSNR value was computed according to [47]. Average PSNR measurements are shown in Fig. 4. The proposed approximation is multiplierless and effected 66% and 53.12% savings in the number of additions considering Scenarios (i) and (ii), respectively. At the same time, the resulting image quality measures showed average errors less than 0.28% and 0.71%, for Scenarios (i) and (ii), respectively. Fig. 5 displays the first frame of the Foreman encoded video according to the unmodified codec and the modified codec in Scenarios (i) and (ii). The approximate transform could effect images that are essentially identical to the ones produced by the actual codec at a much lower computational complexity.



Figure 5: First frame from 'Foreman' video in the HEVC experiment with QP = 35.

Table 3: Hardware resource and power consumption using Xilinx Virtex-6 XC6VLX240T 1FFG1156 device

Method	CLB	\mathbf{FF}	$T_{\rm cpd}$	F_{\max}	D_p	Q_p	AT	AT^2
Transform in [36] Proposed approx.	$\begin{array}{c} 499\\ 303 \end{array}$	$\begin{array}{c} 1588\\ 936 \end{array}$	$3.0 \\ 2.9$	333.33 344.83	$7.4 \\ 7.9$	$3.500 \\ 3.509$	$\begin{array}{c} 1497\\ 879 \end{array}$	4491 2548

4 HARDWARE IMPLEMENTATION

In order to evaluate the hardware resource consumption of the proposed approximation, it was modeled and tested in Matlab Simulink and then it was physically realized on FPGA. The employed FPGA was a Xilinx Virtex-6 XC6VLX240T installed on a Xilinx ML605 prototyping board. The FPGA realization was tested with 10,000 random 16-point input test vectors using hardware co-simulation. Test vectors were generated from within the Matlab environment and routed to the physical FPGA device using JTAG based hardware co-simulation. Then the data measured from the FPGA was routed back to Matlab memory space.

The associated FPGA implementation was evaluated for hardware complexity and real-time performance using metrics such as configurable logic blocks (CLB) and flip-flop (FF) count, critical path delay (T_{cpd}) in ns, and maximum operating frequency (F_{max}) in MHz. Values were obtained from the Xilinx FPGA synthesis and place-route tools by accessing the **xflow.results** report file. In addition, the dynamic power (D_p) in mW/GHz and static power consumption (Q_p) in mW were estimated using the Xilinx XPower Analyzer. Using the CLB count as a metric to estimate the circuit area (A) and deriving time (T) from T_{cpd} , we also report area-time complexity (AT) and area-time-squared complexity (AT^2) .

Because the transformation in [36] possesses a very low arithmetic complexity (cf. Table 1) and presents good performance (cf. Table 2), it was chosen for a direct comparison with the proposed approximation. The obtained results are displayed in Table 3. The proposed approximation presents an improvement of 41.28% and 43.26% in area-time and area-time-square measures, respectively, when compared to [36].

5 CONCLUSION

This paper introduced an orthogonal 16-point DCT approximation which requires only 44 additions for its computation. To the best of our knowledge, the proposed transformation has the *lowest* computational cost among the meaningful 16-point DCT approximations archived in literature. The introduced method requires from 26.67% to 38.89% fewer arithmetic operations than the best competitors. In the context of

image compression, the proposed tool attained the best performance vs computational cost ratio for both PSNR and SSIM metrics. When embedded into the H.265/HECV standard, resulting video frames exhibited almost imperceptible degradation, while demanding no multiplications and 56 fewer additions than the standard unmodified codec. The hardware realization of the proposed transform presented an improvement of more than 30% in area-time and area-time-square measures when compared to the lowest complexity competitor [36]. Potentially, the present approach can extended to derive 32- and 64-point approximations by means of the scaled approach introduced in [36].

Acknowledgments

Authors acknowledge CAPES, CNPq, FACEPE, and FAPERGS for the partial support.

References

- [1] V. Britanak, P. Yip, and K. R. Rao, Discrete Cosine and Sine Transforms. Academic Press, 2007.
- [2] K. R. Rao and P. Yip, Discrete Cosine Transform: Algorithms, Advantages, Applications. San Diego, CA: Academic Press, 1990.
- [3] R. J. Cintra, F. M. Bayer, and C. J. Tablada, "Low-complexity 8-point DCT approximations based on integer functions," *Signal Process.*, vol. 99, pp. 201–214, 2014.
- [4] W. B. Pennebaker and J. L. Mitchell, JPEG Still Image Data Compression Standard. New York, NY: Van Nostrand Reinhold, 1992.
- [5] International Telecommunication Union, "ITU-T recommendation H.261 version 1: Video codec for audiovisual services at $p \times 64$ kbits," ITU-T, Tech. Rep., 1990.
- [6] —, "ITU-T recommendation H.263 version 1: Video coding for low bit rate communication," ITU-T, Tech. Rep., 1995.
- [7] A. Luthra, G. J. Sullivan, and T. Wiegand, "Introduction to the special issue on the H.264/AVC video coding standard," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 13, no. 7, pp. 557–559, Jul. 2003.
- [8] W. H. Chen, C. Smith, and S. Fralick, "A fast computational algorithm for the discrete cosine transform," *IEEE Trans. Commun.*, vol. 25, no. 9, pp. 1004–1009, Sep. 1977.
- [9] Y. Arai, T. Agui, and M. Nakajima, "A fast DCT-SQ scheme for images," *IEICE Trans.*, vol. E-71, no. 11, pp. 1095–1097, Nov. 1988.
- [10] E. Feig and S. Winograd, "Fast algorithms for the discrete cosine transform," *IEEE Trans. Signal Processing*, vol. 40, no. 9, pp. 2174–2193, 1992.
- [11] H. S. Hou, "A fast recursive algorithm for computing the discrete cosine transform," *IEEE Trans. Acoust.*, Speech, Signal Processing, vol. 6, no. 10, pp. 1455–1461, 1987.
- [12] B. G. Lee, "A new algorithm for computing the discrete cosine transform," IEEE Trans. Acoust., Speech, Signal Processing, vol. ASSP-32, pp. 1243–1245, Dec. 1984.
- [13] C. Loeffler, A. Ligtenberg, and G. Moschytz, "Practical fast 1D DCT algorithms with 11 multiplications," in Proc. Int. Conf. on Acoustics, Speech, and Signal Process., 1989, pp. 988–991.
- [14] M. Vetterli and H. Nussbaumer, "Simple FFT and DCT algorithms with reduced number of operations," Signal Process., vol. 6, pp. 267–278, Aug. 1984.

- [15] Z. Wang, "Fast algorithms for the discrete W transform and for the discrete Fourier transform," IEEE Trans. Acoust., Speech, Signal Processing, vol. ASSP-32, pp. 803–816, Aug. 1984.
- [16] K. Lengwehasatit and A. Ortega, "Scalable variable complexity approximate forward DCT," IEEE Trans. Circuits Syst. Video Technol., vol. 14, no. 11, pp. 1236–1248, Nov. 2004.
- [17] T. I. Haweel, "A new square wave transform based on the DCT," Signal Process., vol. 82, pp. 2309–2319, 2001.
- [18] R. E. Blahut, Fast Algorithms for Signal Processing. Cambridge University Press, 2010.
- [19] T. D. Tran, "The binDCT: Fast multiplierless approximation of the DCT," *IEEE Signal Processing Lett.*, vol. 6, no. 7, pp. 141–144, 2000.
- [20] M. C. Lin, L. R. Dung, and P. K. Weng, "An ultra-low-power image compressor for capsule endoscope," *Biomed. Eng. Online*, vol. 5, no. 1, pp. 1–8, Feb. 2006.
- [21] S. Bouguezel, M. O. Ahmad, and M. N. S. Swamy, "Low-complexity 8×8 transform for image compression," *Electron. Lett.*, vol. 44, no. 21, pp. 1249–1250, sep 2008.
- [22] F. M. Bayer, R. J. Cintra, A. Edirisuriya, and A. Madanayake, "A digital hardware fast algorithm and FPGAbased prototype for a novel 16-point approximate DCT for image compression applications," *Meas. Sci. Technol.*, vol. 23, no. 8, pp. 114010–114019, 2012.
- [23] S. Bouguezel, M. O. Ahmad, and M. Swamy, "A fast 8×8 transform for image compression," in Int. Conf. on Microelectronics, Dec. 2009, pp. 74–77.
- [24] S. Bouguezel, M. O. Ahmad, and M. N. S. Swamy, "A novel transform for image compression," in Proc. 53rd IEEE Int. Midwest Symp. on Circuits and Systems, Aug 2010, pp. 509–512.
- [25] —, "A low-complexity parametric transform for image compression," in *Proc IEEE Int. Symp. on Circuits and Systems*, 2011.
- [26] —, "Binary discrete cosine and Hartley transforms," IEEE Trans. Circuits Syst. I, Reg. Papers1, vol. 60, no. 4, pp. 989–1002, 2013.
- [27] R. J. Cintra and F. M. Bayer, "A DCT approximation for image compression," *IEEE Signal Processing Lett.*, vol. 18, no. 10, pp. 579–582, Oct. 2011.
- [28] F. M. Bayer and R. J. Cintra, "DCT-like transform for image compression requires 14 additions only," *Electron. Lett.*, vol. 48, no. 15, pp. 919–921, 2012.
- [29] U. S. Potluri, A. Madanayake, R. J. Cintra, F. M. Bayer, and N. Rajapaksha, "Multiplier-free DCT approximations for RF multi-beam digital aperture-array space imaging and directional sensing," *Meas. Sci. Technol.*, vol. 23, no. 11, p. 114003, 2012.
- [30] U. S. Potluri, A. Madanayake, R. J. Cintra, F. M. Bayer, S. Kulasekera, and A. Edirisuriya, "Improved 8-point approximate DCT for image and video compression requiring only 14 additions," *IEEE Trans. Circuits Syst. I, Reg. Papers1*, vol. PP, no. 99, pp. 1–14, 2014.
- [31] T. L. T. da Silveira, F. M. Bayer, R. J. Cintra, S. Kulasekera, A. Madanayake, and A. J. Kozakevicius, "An orthogonal 16-point approximate DCT for image and video compression," *Multidim. Syst. Sign. P.*, pp. 1–18, 2014.
- [32] M. T. Pourazad, C. Doutre, M. Azimi, and P. Nasiopoulos, "HEVC: The new gold standard for video compression: How does HEVC compare with H.264/AVC?" *IEEE Trans. Consumer Electron.*, vol. 1, no. 3, pp. 36–46, Jul. 2012.
- [33] G. J. Sullivan, J.-R. Ohm, W.-J. Han, and T. Wiegand, "Overview of the high efficiency video coding (HEVC) standard," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 22, no. 12, pp. 1649–1668, Dec. 2012.

- [34] S. Bouguezel, M. O. Ahmad, and M. N. S. Swamy, "A multiplication-free transform for image compression," in Proc. 2nd Int. Conf. on Signals, Circuits and Systems, nov 2008, pp. 1–4.
- [35] R. K. Yarlagadda and J. E. Hershey, Hadamard Matrix Analysis and Synthesis With Applications to Communications and Signal/Image Processing. Kluwer Academic Publishers, 1997.
- [36] M. Jridi, A. Alfalou, and P. K. Meher, "A generalized algorithm and reconfigurable architecture for efficient and scalable orthogonal approximation of DCT," *IEEE Trans. Circuits Syst. I*, vol. 62, no. 2, pp. 449–457, 2015.
- [37] C. J. Tablada, F. M. Bayer, and R. J. Cintra, "A class of DCT approximations based on the Feig-Winograd algorithm," *Signal Process.*, vol. 113, pp. 38–51, 2015.
- [38] R. J. Cintra, "An integer approximation method for discrete sinusoidal transforms," Circ. Syst. Signal Pr., vol. 30, no. 6, pp. 1481–1501, 2011.
- [39] I. N. Herstein, Topics in Algebra, 2nd ed. John Wiley & Sons, 1975.
- [40] C.-K. Fong and W.-K. Cham, "LLM integer cosine transform and its fast algorithm," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 22, no. 6, pp. 844–854, 2012.
- [41] USC-SIPI, "The USC-SIPI image database," http://sipi.usc.edu/database/, 2011, University of Southern California, Signal and Image Processing Institute.
- [42] I.-M. Pao and M.-T. Sun, "Approximation of calculations for forward discrete cosine transform," IEEE Trans. Circuits Syst. Video Technol., vol. 8, no. 3, pp. 264–268, Jun. 1998.
- [43] Z. Wang, A. C. Bovik, H. R. Sheikh, and E. P. Simoncelli, "Image quality assessment: from error visibility to structural similarity," *IEEE Trans. Image Processing*, vol. 13, no. 4, pp. 600–612, Apr. 2004.
- [44] Joint Collaborative Team on Video Coding (JCT-VC), "HEVC reference software documentation," 2013, Fraunhofer Heinrich Hertz Institute. [Online]. Available: https://hevc.hhi.fraunhofer.de/
- [45] M. Budagavi, A. Fuldseth, G. Bjontegaard, V. Sze, and M. Sadafale, "Core transform design in the high efficiency video coding (HEVC) standard," *IEEE J. Sel. Top. Sign. Proces.*, vol. 7, no. 6, pp. 1029–1041, dec 2013.
- [46] Xiph.Org Foundation, "Xiph.org video test media," 2014, https://media.xiph.org/video/derf/.
- [47] J.-R. Ohm, G. J. Sullivan, H. Schwarz, T. K. Tan, and T. Wiegand, "Comparison of the coding efficiency of video coding standards - including high efficiency video coding (HEVC)," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 22, no. 12, pp. 1669–1684, Dec. 2012.