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Design of an Area and Power Efficient 8- Point Approximate DCT Architecture Requiring Only 14 Additions

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Abstract:

In video processing systems such as HEVC requiring low energy consumption needed for the multimedia market has lead to extensive development in fast algorithms for the efficient approximation of 2-D DCT transforms. The DCT is employed in a multitude of compression standards due to its remarkable energy compaction properties. Multiplier-free approximate DCT Transforms have been proposed that offer superior compression performance at very low circuit complexity. Such approximations can be realized in digital VLSI hardware using additions and Subtractions only, leading to significant reductions in chip area and power consumption compared to conventional DCTs and integer transforms. In this paper, we introduce a novel 8-point DCT approximation that requires only 14 addition operations and no multiplications. The proposed DCT approximation is a candidate for reconfigurable video standards such as HEVC. The proposed transform and several other DCT approximations are mapped to systolic-array digital architectures and physically realized as digital prototype circuits using FPGA Spartan 3 and it are implemented by verilog language.

Index Terms:

Approximate DCT, low-complexity algorithms, image compression, HEVC, low power consumption.

I. INTRODUCTION:

Recent years have experienced a significant demand for high dynamic range systems that operate at high resolutions [1]. In particular, high-quality digital video in multimedia devices and video-over-Internet protocol networks [2] are prominent areas where such requirements are evident. Other noticeable fields are geospatial remote sensing [3], traffic cameras, automatic surveillance, homeland security, automotive industry, and multimedia wireless sensor networks [4], to name but a few. Often hardware capable of significant throughput is necessary; as well as allowable area-time complexity [4]. In this context, the discrete cosine transform (DCT)[5] is an essential mathematical tool in both image and video coding [4], [5]–[15]. Indeed, the DCT was demonstrated to provide good energy compaction for natural images, which can be described by first-order Markov signals [6], [5], [7]. Moreover, in many situations, the DCT is a very close substitute for the Karhunen-Loève transform (KLT), which has optimal properties [5], [7], [8]. As a result, the two-dimensional (2-D) version of the 8-point DCT was adopted in several imaging standards such as JPEG [9], MPEG-1 [9], MPEG-2 [9], H.261 [11], H.263 [11] and H.264/AVC [12].Additionally, new compression schemes such as the High Efficiency Video Coding (HEVC) employs DCT-like integer transforms operating at various block sizes ranging from 4 to 32 pixels [13]–[14].

The distinctive characteristic of HEVC is its capability of achieving high compression performance at approximately half the bit rate required by H.264/AVC with same image quality [13]–[14]. Also HEVC was demonstrated to be especially effective for high-resolution video applications [14]. However, HEVC possesses a significant computational complexity in terms of arithmetic operations. In fact, HEVC can be 2–4 times more computationally demanding when compared to H.264/AVC. Therefore, low complexity DCT-like approximations may benefit future video codec's includes emerging HEVC/H.265 systems. Several efficient algorithms were developed and a noticeable literature is available [6]. Although fast algorithms can significantly reduce the computational complexity of computing the DCT, floating-point operations are still required [5]. Despite their accuracy, floating-point operations are expensive in terms of circuitry complexity and power consumption. Therefore, minimizing the number of floating-point operations is a sought property in a fast algorithm. One way of circumventing this issue is by means of approximate transforms.

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The aim of this paper is two-fold. First, we introduce a new DCT approximation that possesses an extremely low arithmetic complexity, requiring only 14 additions. This novel transform was obtained by means of solving a tailored optimization problem aiming at minimizing the transform computational cost. Second, we propose hardware implementations for several 2-D 8-point approximate DCT. The approximate DCT methods under consideration are (i) the proposed transform; (ii) the 2008 Bouguezel-Ahmad-Swamy (BAS) DCT approximation [16]; (iii) the parametric transform for image compression [17];(iv) the Cintra-Bayer (CB) approximate DCT based on the rounding-off function [18]; (v) the modified CB approximate DCT; and (vi) the DCT approximation proposed in the context of beam forming.

All introduced implementations are sought to be fully parallel time-multiplexed 2-D architectures for 8 data blocks. Additionally, the proposed designs are based on successive calls of 1-D architectures taking advantage of the reparability property of the 2-D DCT kernel. Designs were thoroughly assessed and compared.This paper unfolds as follows. In Section II, we discuss the role of DCT-like fast algorithms for video CODECs while proposing some new possibilities for low-power video processing where rapid reconfiguration of the hardware realization is possible. In Section III, we review selected approximate methods for DCT computation and describe associate fast algorithms in terms of matrix factorizations. Section IV details the proposed transform and its fast algorithm based on matrix factorizations. In Section V digital hardware architectures for discussed algorithms are supplied both for 1-D and 2-D analysis.

II.RECONFIGURABLE DCT-LIKE FAST ALGORITHMS IN VIDEO CODECS:

In current literature, several approximate methods for the DCT calculation have been archived [5].While not computing the DCT exactly, such approximations can provide meaningful estimations at low-complexity requirements. In particular, some DCT approximations can totally eliminate the requirement for floating-point operations—all calculations are performed over a fixed-point arithmetic framework. Prominent 8-point approximation- based techniques were proposed in [15], [16]. Works addressing 16-point DCT approximations are also archived in literature [19].

In general, these approximation methods employ a transformation matrix whose elements are defined over the set $\{0,\pm1/2,\pm1,\pm2\}$. This implies null multiplicative complexity, because the required operations can be implemented exclusively by means of binary additions and shift operations.Such DCT approximations can provide low-cost and low-power designs and effectively replace the exact DCT and other DCT-like transforms. Indeed, the performance characteristics of the low complexity DCT approximations appear similar to the exact DCT, while their associate hardware implementations are economical because of the absence of multipliers [14], [15], [16]–[19]. As a consequence, some prospective applications of DCT approximations are found in real-time video transmission and processing.

Emerging video standards such as HEVC provide for reconfigurable operation on-the-fly which makes the availability of an ensemble of fast algorithms and digital VLSI architectures a valuable asset for low-energy high-performance embedded systems. For certain applications, low circuit complexity and/or power consumption is the driving factor, while for certain other applications, highest picture quality for reasonably low power consumption and/or complexity may be more important. In emerging systems, it may be possible to switch modus operandi based on the demanded picture quality vs available energy in the device. Such feature would be invaluable in high quality smart video devices demanding extended battery life.Thus, the availability of a suite of fast algorithms and implementation libraries for several efficient DCT approximation algorithms may be a welcoming contribution.

III.REVIEW OF APPROXIMATE DCT METHODS:

In this section, we review the mathematical description of the selected 8-point DCT approximations. All discussed methods here consist of a transformation matrix that can be put in the following format:

[Diagonal matrix] X [low-complexity matrix]

The diagonal matrix usually contains irrational numbers in the form $1/\sqrt{m}$, where m is a small positive integer. In principle, the irrational numbers required in the diagonal matrix would require an increased computational complexity.

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However, in the context of image compression, the diagonal matrix can simply be absorbed into the quantization step of JPEG-like compression procedures [15]. Therefore, in this case, the complexity of the approximation is bounded by the complexity of the low-complexity matrix. Since the entries of the low complexity matrix comprise only powers of two in {0,±1/2,±1,±2}, null multiplicative complexity isachieved.In the next subsections, we detail these methods in terms of its transformation matrices and the associated fast algorithms obtained by matrix factorization techniques. All derived fast algorithms employ sparse matrices whose elements are the abovementioned powers of two.

A.Bouguezel-Ahmad-SwamyApproximate DCT[16]:

In a low-complexity approximate was introduced by Bouguezel et al. We refer to this approximate DCT as BAS-2008 approximation. The BAS-2008 approximation C1 has the following mathematical structure:

$$\mathbf{C}_1 = \mathbf{D}_1 \cdot \mathbf{T}_1$$
$$= \mathbf{D}_1 \cdot \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & -1 & -1 \\ 1 & \frac{1}{2} & -\frac{1}{2} & -1 & -1 & -\frac{1}{2} & \frac{1}{2} & 1 \\ 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 \\ \frac{1}{2} & -1 & 1 & -\frac{1}{2} & -\frac{1}{2} & 1 & -1 & \frac{1}{2} \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 \end{bmatrix}$$

Where $D_1 = \text{diag}\left({}^1/_{\sqrt{8}}, {}^1/_{\sqrt{4}}, {}^1/_{\sqrt{5}}, {}^1/_{\sqrt{2}}, {}^1/_{\sqrt{8}}, {}^1/_{\sqrt{4}}, {}^1/_{\sqrt{5}}, {}^1/_{\sqrt{2}}\right)$. A fast algorithm for matrix T_1 can be derived by means of matrix factorization.

Indeed, T1 can be written as a product of three sparse matrices having {0,±1/2,±1} elements as shown below [16]: T1 = A3. A2. A1, where

$$\mathbf{A}_1 = \begin{bmatrix} \mathbf{I}_4 & \bar{\mathbf{I}}_4 \\ \bar{\mathbf{I}}_4 & -\mathbf{I}_4 \end{bmatrix}$$

$$\mathbf{A}_2 = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \\ 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{A}_3 = \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2} & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

Matrices In and ~I¬n denote the identity and counter-identity matrices of order, respectively. It is recognizable that matrix A1 is the well-known decimation-in-frequency structure present in several fast algorithms [11].

B. Parametric Transform:

Proposed in 2011 by Bouguezel-Ahmad-Swamy[16], the parametric transform is an 8-point orthogonal transform containing a single parameter in its transformation matrix C(α) . In this work, we refer to this method as the BAS-2011 transform. It is given as follows:

$$\mathbf{C}^{(a)} = \mathbf{D}^{(a)} \cdot \mathbf{T}^{(a)}$$
$$= \mathbf{D}^{(a)} \cdot \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & -1 & -1 \\ 1 & a & -a & -1 & -1 & -a & a & 1 \\ 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 \\ a & -1 & 1 & -a & -a & 1 & -1 & a \end{bmatrix}$$

Where $D^{(\alpha)} = \text{diag}\left({}^1/_{\sqrt{8}}, {}^1/_2, {}^1/_{\sqrt{4+4\alpha^2}}, {}^1/_{\sqrt{2}}, {}^1/_{\sqrt{8}}, {}^1/_{\sqrt{2}}, {}^1/_2, {}^1/_{\sqrt{4+4\alpha^2}}\right)$.

Usually the parameter α is selected as a small integer in order to minimize the complexity of T(α) . In [17], suggested values are a€{0,1/2,1} .The value a=1/2 will not be considered in our analyses because in hardware it represents a right-shift which may incur in computational errors. Another possible value that furnishes a low-complexity, error-free transform is a=2. The matrixfactorization of T(α) that leads to its fast algorithm is [17]:

$$\mathbf{T}^{(\alpha)} = \mathbf{P}_1 . \mathbf{Q}^{(\alpha)} . \mathbf{A}_4 . \mathbf{A}_1, \text{ where}$$

$$\mathbf{Q}^{(a)} = \text{diag}\left(\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \begin{bmatrix} a & 1 \\ -1 & a \end{bmatrix}, \mathbf{I}_4\right)$$

$$\mathbf{A}_4 = \text{diag}\left(\begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ 1 & 0 & 0 & -1 \end{bmatrix}, \mathbf{I}_2, \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}\right).$$

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Matrix P1 performs the simple permutation (1) (2 5 6 4 8 7)(3), where cyclic notation is employed ([18], p. 77). This is a compact notation to denote permutation. In this particular case, it means that component indices are permuted according to 2->5->6->4->8->7->2. Indices 1 and 3 are unchanged. Therefore, P1 represents no computational complexity.

C. CB-2011 Approximation:

By means of judiciously rounding-off the elements of the exact DCT matrix, a DCT approximation was obtained and described in [20]. The resulting 8-point approximation matrix is orthogonal and contains only elements in $\{0,\pm1\}$. Clearly, it possesses very low arithmetic complexity. The matrix derived transformation matrix C2 is given by:

$$\mathbf{C_2} = \mathbf{D_2}\cdot\mathbf{T_2}$$
$$= \mathbf{D_2}\cdot\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & -1 & -1 & -1 \\ 1 & 0 & 0 & -1 & -1 & 0 & 0 & 1 \\ 1 & 0 & -1 & -1 & 1 & 1 & 0 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & -1 & 0 & 1 & -1 & 0 & 1 & -1 \\ 0 & -1 & 1 & 0 & 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & -1 & 1 & -1 & 1 & 0 \end{bmatrix}$$

Where $D_2 = \mathrm{diag}\,(1/\sqrt{8}, 1/\sqrt{6}, 1/2, 1/\sqrt{6}, 1/\sqrt{8}, 1/\sqrt{6}, 1/2, 1/\sqrt{6})$. An efficient factorization for the fast algorithm for T_2 was proposed in [20] as described below: $\mathbf{T_2 = P_2. A_6. A_5. A_1}$, where

$$\mathbf{A_5} = \mathrm{diag}\left(\begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ 1 & 0 & 0 & -1 \end{bmatrix}, \begin{bmatrix} -1 & 1 & -1 & 0 \\ -1 & -1 & 0 & 1 \\ 1 & 0 & -1 & 1 \\ 0 & 1 & 1 & 1 \end{bmatrix}\right)$$

and

$$\mathbf{A_6} = \mathrm{diag}\left(\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, -1, \mathbf{I}_5\right).$$

Matrix corresponds to the following permutation: (1) (2 5 8)(3 7 6 4).

D. Modified CB-2011 Approximation:

The transform proposed in [20] is obtained by replacing elements of the CB-2011 matrix with zeros. The resulting matrix is given by:

$$\mathbf{C_3} = \mathbf{D_3}\cdot\mathbf{T_3}$$
$$= \mathbf{D_3}\cdot\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & -1 & -1 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 0 & -1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 1 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 \end{bmatrix}$$

Where $D_3 = \mathrm{diag}(1/\sqrt{8}, 1/\sqrt{2}, 1/2, 1/\sqrt{2}, 1/\sqrt{8}, 1/\sqrt{2}, 1/2, 1/\sqrt{2})$. Matrix T_3 can be factorized into $\mathbf{T_3 = P_2. A_6. A_7. A_1}$, where

$$\mathbf{A_7} = \mathrm{diag}\left(\begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ 1 & 0 & 0 & -1 \end{bmatrix}, -\mathbf{I}_3, 1\right).$$

This particular DCT approximation has the distinction of requiring only 14 additions for its computation [39].

E. Approximate DCT in [18]:

In [18], a DCT approximation tailored for a particular radiofrequency (RF) application was obtained in accordance with an exhaustive computational search. This transformation is given by

$$\mathbf{C_4} = \mathbf{D_4}\cdot\mathbf{T_4}$$
$$= \mathbf{D_4}\cdot\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 2 & 1 & 1 & 0 & 0 & -1 & -1 & -2 \\ 2 & 1 & -1 & -2 & -2 & -1 & 1 & 2 \\ 1 & 0 & -2 & -1 & 1 & 2 & 0 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & -2 & 0 & 1 & -1 & 0 & 2 & -1 \\ 1 & -2 & 2 & -1 & -1 & 2 & -2 & 1 \\ 0 & -1 & 1 & -2 & 2 & -1 & 1 & 0 \end{bmatrix}$$

Where $D_4 = 1/2\ \mathrm{diag}\ (1/\sqrt{2}, 1/\sqrt{3}, 1/\sqrt{5}, 1/\sqrt{3}, 1/\sqrt{2}, 1/\sqrt{3}, 1/\sqrt{5}, 1/\sqrt{3})$. The fast algorithm for its computation consists of the following matrix factorization: $\mathbf{T_4 = P_3. A_9. A_8. A_1}$, where

$$\mathbf{A_9} = \mathrm{diag}\left(\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \begin{bmatrix} 1 & 2 \\ -2 & 1 \end{bmatrix}, \mathbf{I}_4\right)$$

$$\mathbf{A_8} = \mathrm{diag}\left(\begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ 1 & 0 & 0 & -1 \end{bmatrix}, \begin{bmatrix} 0 & 1 & 1 & 2 \\ -1 & -2 & 0 & 1 \\ 1 & 0 & -2 & 1 \\ -2 & 1 & -1 & 0 \end{bmatrix}\right)$$

and matrix P_3 denotes the permutation (1)(2 5)(3)(4 7 6)(8).

IV. PROPOSED TRANSFORM:

We aim at deriving a novel low-complexity approximate DCT. For such end, we propose a search over the 8 X 8 matrix space in order to find candidate matrices that possess low computation cost. Let us define the cost of a transformation matrix as the number of arithmetic operations required for its computation.

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One way to guarantee good candidates is to restrict the search to matrices whose entries do not require multiplication operations. Thus we have the following optimization problem:

$$\mathbf{T}^* = \arg\min_{\mathbf{T}} \operatorname{cost}(\mathbf{T}), \qquad (1)$$

Where T* is the sought matrix and cost(T) returns the arithmetic complexity of . Additionally, the following constraints were adopted:

1) Elements of matrix T must be in {0,±1,±2} to ensure that resulting multiplicative complexity is null;
2) We impose the following form for matrix T :

$$\mathbf{T} = \begin{bmatrix} a_3 & a_3 & a_3 & a_3 & a_3 & a_3 & a_3 & a_3 \\ a_0 & a_2 & a_4 & a_6 & -a_6 & -a_4 & -a_2 & -a_0 \\ a_1 & a_5 & -a_5 & -a_1 & -a_1 & -a_5 & a_5 & a_1 \\ a_2 & -a_6 & -a_0 & -a_4 & a_4 & a_0 & a_6 & -a_2 \\ a_3 & -a_3 & -a_3 & a_3 & a_3 & -a_3 & -a_3 & a_3 \\ a_4 & -a_0 & a_6 & a_2 & -a_2 & -a_6 & a_0 & -a_4 \\ a_5 & -a_1 & a_1 & -a_5 & -a_5 & a_1 & -a_1 & a_5 \\ a_6 & -a_4 & a_2 & -a_0 & a_0 & -a_2 & a_4 & -a_6 \end{bmatrix}$$

where $a_i \in \{0, 1, 2\}$, for $i = 0, 1 \ldots, 6$;

3) All rows of T are non-null;
4) Matrix T.TT must be a diagonal matrix to ensure orthogonality of the resulting approximation. Constraint 2) is required to preserve the DCT-like matrix structure. We recall that the exact 8-point DCT matrix is given by:

$$\mathbf{C} = \frac{1}{2} \cdot \begin{bmatrix} \gamma_3 & \gamma_3 & \gamma_3 & \gamma_3 & \gamma_3 & \gamma_3 & \gamma_3 & \gamma_3 \\ \gamma_0 & \gamma_2 & \gamma_4 & \gamma_6 & -\gamma_6 & -\gamma_4 & -\gamma_2 & -\gamma_0 \\ \gamma_1 & \gamma_5 & -\gamma_5 & -\gamma_1 & -\gamma_1 & -\gamma_5 & \gamma_5 & \gamma_1 \\ \gamma_2 & -\gamma_6 & -\gamma_0 & -\gamma_4 & \gamma_4 & \gamma_0 & \gamma_6 & -\gamma_2 \\ \gamma_3 & -\gamma_3 & -\gamma_3 & \gamma_3 & \gamma_3 & -\gamma_3 & -\gamma_3 & \gamma_3 \\ \gamma_4 & -\gamma_0 & \gamma_6 & \gamma_2 & -\gamma_2 & -\gamma_6 & \gamma_0 & -\gamma_4 \\ \gamma_5 & -\gamma_1 & \gamma_1 & -\gamma_5 & -\gamma_5 & \gamma_1 & -\gamma_1 & \gamma_5 \\ \gamma_6 & -\gamma_4 & \gamma_2 & -\gamma_0 & \gamma_0 & -\gamma_2 & \gamma_4 & -\gamma_6 \end{bmatrix}$$

where $\gamma_k = \cos(2\pi(k+1)/32), k = 0, 1, \ldots, 6.$

Above optimization problem is algebraically intractable. Therefore we resorted to exhaustive computational search. As a result, eight candidate matrices were found, including the transform matrix proposed in [18]. Among these minimal cost matrices, we separated the matrix that presents the best performance in terms of image quality of compressed images according the JPEG-like technique employed in [16] and briefly reviewed in next Section V.

An important parameter in the image compression routine is the number of retained coefficients in the transform domain. In several applications, the number of retained coefficients is very low. For instance, considering 8 image blocks, (i) in image compression using support vector machine, only the first 8–16 coefficients were considered [50]; (ii)Mandyam et al. proposed a method for image reconstruction based on only three coefficients; and (iii) Bouguezel et al. employed only 10 DCT coefficients when assessing image compression methods. Retaining a very small number of coefficients is also common for other image block sizes. In high speed face recognition applications, Pan et al. demonstrated that just 0.34%–24.26% out of 92 112 DCT coefficients are sufficient. Therefore, as a compromise, we adopted the number of retained coefficients equal to 10, as suggested in the experiments by Bouguezel et al. The solution of (1) is the following DCT approximation:

$$\mathbf{C}^* = \mathbf{D}^* \cdot \mathbf{T}^*$$
$$= \mathbf{D}^* \cdot \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & -1 & -1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

Where $D^* = \operatorname{diag}\left(\frac{1}{\sqrt{8}}, \frac{1}{\sqrt{2}}, \frac{1}{2}, \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{8}}, \frac{1}{\sqrt{2}}, \frac{1}{2}, \frac{1}{\sqrt{2}}\right)$.. Matrix T^* has entries in {0,±1} and it can be given a sparse factorization according to: $\mathbf{T}^* = \mathbf{P}_4 . \mathbf{A}_{12} . \mathbf{A}_{11} . \mathbf{A}_1$, where

$$\mathbf{A}_{11} = \operatorname{diag}\left(\begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ 1 & 0 & 0 & -1 \end{bmatrix}, \mathbf{I}_4\right)$$

$$\mathbf{A}_{12} = \operatorname{diag}\left(\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, -1, \mathbf{I}_5\right)$$

And P_4 is the permutation (1) (2 5 6 8 4 3 7).

V DIGITAL ARCHITECTURES AND REALIZATIONS:

In this section we propose architectures for the detailed 1-D and 2-D approximate 8-point DCT. We aim at physically implementing (2) for various transformation matrices. This section explores the hardware utilization of the discussed algorithms while providing a comparison with the proposed novel DCT approximation algorithm and its fast algorithm realization. Our objective here is to offer digital realizations together with measured or simulated metrics of hardware resources so that better decisions on the choice of a particular fast algorithm and its implementation can be reached.

A. Proposed Architectures:

We propose digital computer architectures that are custom designed for the real-time implementation of the fast algorithms described in Section III.

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The proposed architectures employs two parallel realizations of DCT approximation blocks, as shown in Fig. 1.

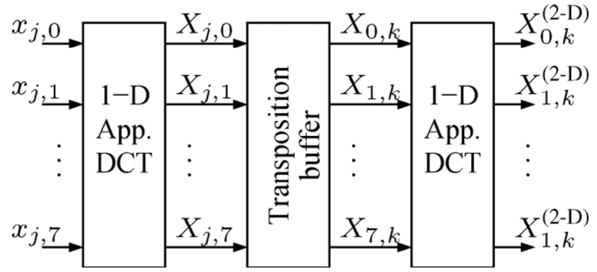


Fig.1: Two-dimensional approximate transform by means of 1-D approximate transform. Signal xk,0 , xk,1 , … corresponds to the rows of the input image; Xk,0 , Xk,1 , … indicates the transformed rows; X0,j , X1,j , … indicates the columns of the transposed row-wise transformed image; and X0,j(2-D) , X1,j(2-D) , … indicates the columns of the final 2-D transformed image. If i=0,1,2,3,.. then indices j and k satisfy j=i(mod 8) and k= [(↓8)i]/8(mod 8). The 1-D approximate DCT blocks (Fig. 5) implement a particular fast algorithm chosen from the collection described earlier in the paper. The first instantiation of the DCT block furnishes a row-wise transform computation of the input image, while the second implementation furnishes a column-wise transformation of the intermediate result.

The row- and column-wise transforms can be any of the DCT approximations detailed in the paper. In other words, there is no restriction for both row- and column-wise transforms to be the same. However, for simplicity, we adopted identical transforms for both steps.Between the approximate DCT blocks a real-time row-parallel transposition buffer circuit is required. Such block ensures data ordering for converting the row-transformed data from the first DCT approximation circuit to a transposed format as required by the column transform circuit. The transposition buffer block is detailed in Fig. 2.The digital architectures of the discussed approximate DCT algorithms were given hardware signal flow diagrams as listed below:

1) Proposed novel algorithm and architecture shown in Fig. 3(a);
2) BAS-2008 architecture shown in Fig. 3(b);
3) BAS-2011 architecture shown in Fig. 3(c);
4) CB-2011 architecture shown in Fig. 3(d);
5) Modified CB-2011 architecture shown in Fig. 3(e);
6) Architecture for the algorithm shown in Fig. 3(f).

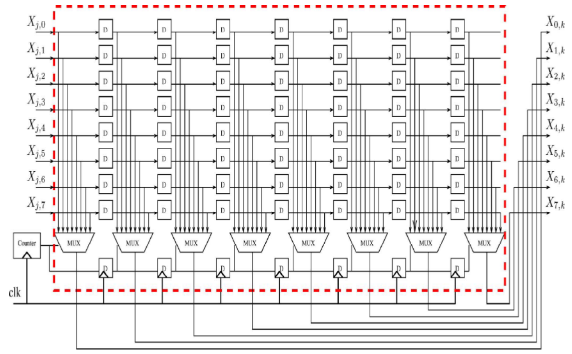
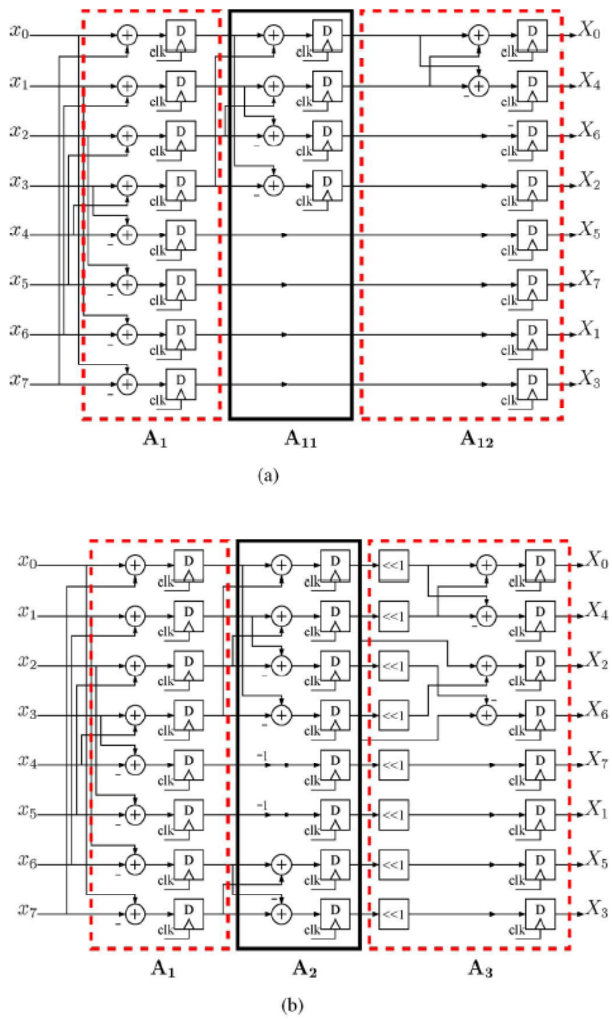


Fig.2: Details of the transposition buffer block.

The circuitry sections associated to the constituent matrices of the discussed factorizations are emphasized in the figures in bold or dashed boxes.



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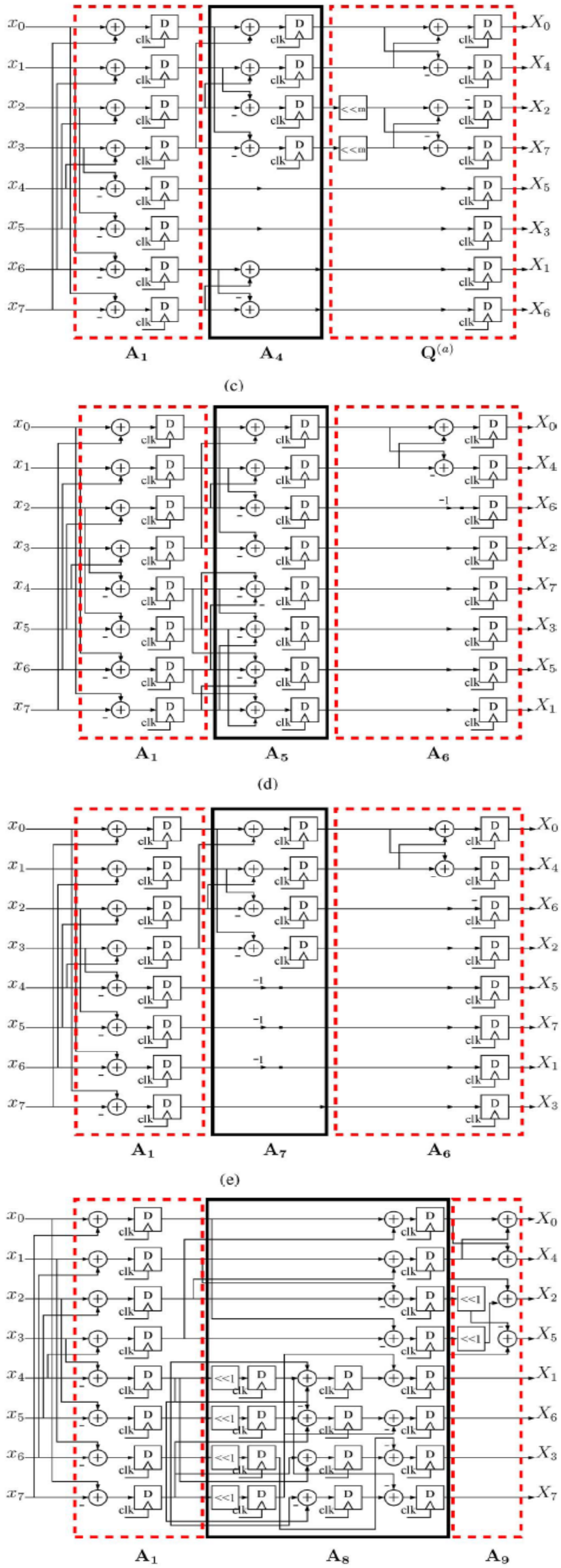

Fig.3: Digital architecture for considered DCT approximations. (a) Proposed approximate transform (T*), (b) BAS-2008 approximate DCT (T1), (c) BAS-2011 approximate DCT (T(α))where m Є{-α,0,1} , (d) CB-2011 approximate DCT(T2) , (e) Modified CB-2011 approximate DCT (T3), (f) Approximate DCT(T4) .

VI. SIMULATION RESULTS:

The simulation of the proposed designs is carried out by using Verilog HDL language in Xilinx ISE simulator tool. The following figure shows the simulated results and synthesis report of the proposed design.

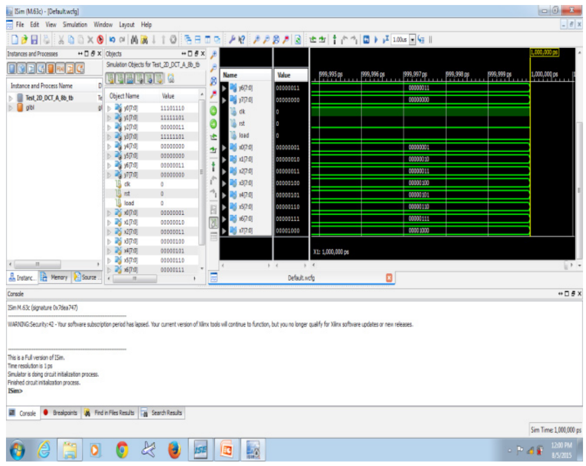

Fig.4: Simulated results of the proposed design.

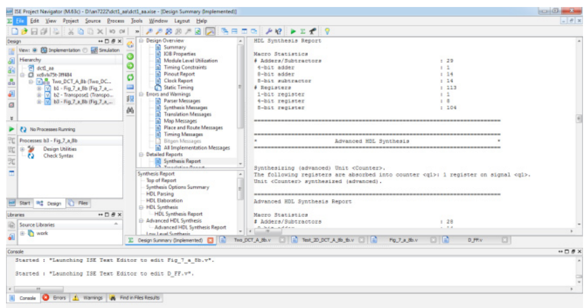

Fig.5: Synthesis report of the proposed design

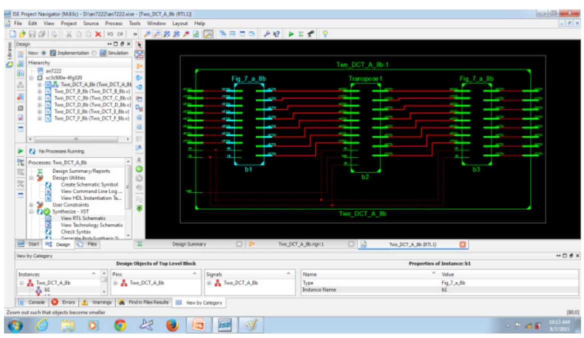

Fig.6: Proposed schematic diagram

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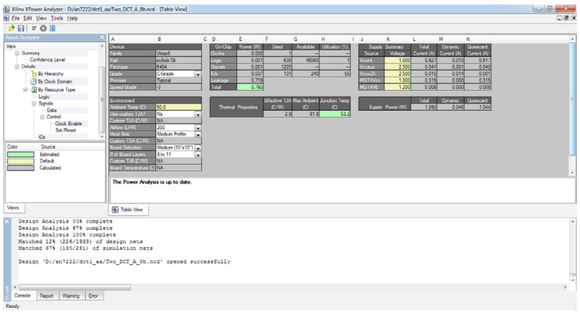

Fig.7:Xilinx XPower Analyzer Report

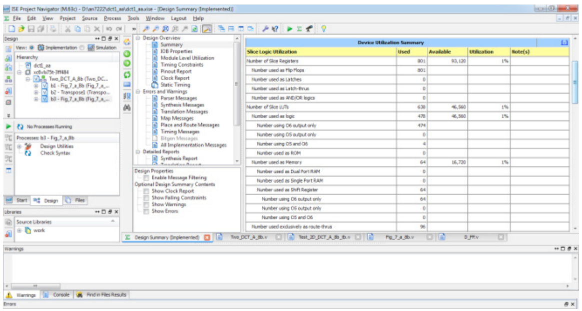

TABLE III
HARDWARE RESOURCE CONSUMPTION USING XILINX VIRTEX-6 XC6VSX475T-2FF1156 DEVICE

L	CLB	FF	Q_p (W)	D_p (W)	T_{cpd}	$F_{\max}$
			BAS-2008 Algorithm			
4	395	784	5.154	0.918	2.350	401.7
8	613	1123	5.168	1.105	2.573	367.1
12	821	1523	5.184	1.301	2.930	337.8
16	1029	1915	5.187	1.344	3.254	284.0
			BAS-2011 for $a = 0$			
4	335	877	5.142	0.767	2.340	386.4
8	535	1276	5.161	1.015	2.600	356.2
12	728	1732	5.180	1.260	2.822	337.4
16	919	2187	5.198	1.486	2.981	325.2
			BAS-2011 for $a = 1$			
4	387	1019	5.146	0.811	2.413	396.7
8	605	1453	5.165	1.065	2.513	361.4
12	813	1949	5.179	1.247	2.962	329.4
16	1021	2445	5.198	1.483	2.987	316.9
			BAS-2011 for $a = 2$			
4	385	1019	5.146	0.818	2.371	402.9
8	603	1453	5.163	1.042	2.584	364.7
12	812	1950	5.190	1.378	2.618	353.1
16	1019	2445	5.201	1.527	3.006	326.5
			CB-2011 Algorithm			
4	452	883	5.141	0.750	2.518	363.4
8	702	1257	5.151	0.876	3.065	303.1
12	950	1709	5.162	1.029	3.466	270.6
16	1198	2162	5.187	1.341	3.610	256.0
			Approximate DCT in [40]			
4	513	1040	5.158	0.972	2.545	387.8
8	779	1471	5.173	1.170	2.769	351.0
12	1036	1968	5.181	1.262	2.945	314.9
16	1291	2463	5.200	1.514	3.205	298.0
			Modified CB-2011 approximation			
4	297	652	5.153	0.903	2.384	399.7
8	481	961	5.177	1.214	2.523	391.2
12	657	1329	5.191	1.390	2.693	354.0
16	834	1698	5.219	1.752	2.829	345.5
			Proposed Transform			
4	303	651	5.146	0.818	2.344	404.0
8	487	963	5.167	1.092	2.470	385.1
12	663	1329	5.185	1.322	2.524	353.7
16	839	1697	5.203	1.551	2.818	341.8

In proposed system the value of the power, Flip Flops and LUT's are:
On-Chip Power utilization - 0.765W
Number used as Flip-Flops - 801
Number of slice LUT's - 638

VII. CONCLUSION:

In this paper, we proposed (i) a novel low-power 8-point DCT approximation that requires only 14 addition operations to computations and (ii) hardware implementation for the proposed transform and several other prominent approximate DCT methods, including the designs by Bouguezel-Ahmad-Swamy. We obtained that all considered approximate transforms perform very close to the ideal DCT. However, the modified CB-2011 approximation and the proposed transform possess lower computational complexity and are faster than all other approximations under consideration. In terms of area and power utilization the proposed transform could outperform the modified CB-2011 algorithm. Hence the new proposed transform is the best approximation for the DCT in terms of computational complexity, less area, low power consumption and speed among the approximate transform examined.

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