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An Efficient DCT Computational Algorithm Suitable For VLSI Implementation

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ABSTRACT: This paper proposes an efficient Discrete Cosine Transformation (DCT) computational algorithm by using a novel coordinate rotation digital computer (CORDIC)- based fast radix-2 algorithm. It has some distinguish advantages, such as Coolwey-Tukey Fast Fourier Transformation (FFT) like regular data flow, uniform post-scaling factor, in-place computation and arithmetic sequence rotation angles. Compared to existing DCT algorithms the proposed algorithm has lower computational complexity. Furthermore the proposed algorithm is efficient, less complex, reliable and suitable for VLSI implementation

KEYWORDS: Discrete Cosine Transformation, Coordinate Rotation Digital Computer (CORDIC), Coolwey-Tukey Fast Fourier Transformation.

I. INTRODUCTION

Algorithms in the non radix category attempt to reduce computational complexity and make computations more efficient, such as matrix factorization directly deduced from signal flow graphs , and coordinate rotation digital computer (CORDIC) -based fast algorithms. Due to extensive design optimization for cost reduction and performance enhancement, these DCT algorithms are often complicated and hardly scalable to more than 8-point DCTs.

Compared to non radix algorithms, a radix algorithm allows generating higher-order DCTs from lower-order DCTs. Furthermore, radix algorithms generally have a regular computational structure, which reduces implementation complexity. However, due to their recursive nature, radix algorithms are difficult to realize pipeline and are not suitable for high-speed applications. The project combines both the CORDIC algorithm and radix2 algorithm to reduce the computational complexity and to get efficient results, highly suitable for VLSI implementation since it is built using shifters and adders only. Here the approximation of DCT is computed using binary shift and addition operation only.

II. RADIX ALGORITHM

Since the discrete cosine transformation (DCT) was proposed by Ahmed, various fast algorithms have been reported in the literature. Existing fast algorithms can be classified into non radix and radix categories. Algorithms in the non radix category attempt to reduce computational complexity and make computations more efficient, such as matrix factorization directly deduced from signal flow graphs , and coordinate rotation digital computer (CORDIC) -based fast algorithms.

Due to extensive design optimization for cost reduction and performance enhancement, these DCT algorithms are often complicated and hardly scalable to more than 8-point DCTs. Compared to non radix algorithms, radix algorithms allow us to generate higher-order DCTs from lower-order DCTs. Furthermore, radix algorithms generally have a regular computational structure, which reduces implementation complexity. However, due to their recursive nature, radix algorithms are difficult to realize pipeline and are not suitable for high-speed applications. Among radix algorithms, the radix-2 algorithm is the most popular because of its computational efficiency and structural simplicity. Based on the proposed algorithm, signal flows of DCTs and inverse DCTs (IDCTs) are developed and deduced using their orthogonal properties, respectively.



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III. CORDIC ALGORITHM

As the name suggests the CORDIC algorithm was developed for rotating coordinates, a piece of hardware for doing real-time navigational computations in the 1950's. The CORDIC uses a sequence like successive approximation to reach its results. The nice part is it does this by adding/subtracting and shifting only. Suppose we want to rotate a point(X,Y) by an angle(Z).

The coordinates for the new point (X_{new} , Y_{new}) are

$$X_{new} = X * \cos(Z) - Y * \sin(Z)$$

$$Y_{new} = Y * \cos(Z) + X * \sin(Z)$$

or rewritten:

$$X_{new} / \cos(Z) = X - Y * \tan(Z)$$

$$Y_{new} / \cos(Z) = Y + X * \tan(Z)$$

It is possible to break the angle into small pieces, such that the tangents of these pieces are always a power of 2.

This results in the following equations:

$$X(n+1) = P(n) * (X(n) - Y(n) / 2^n)$$

$$Y(n+1) = P(n) * (Y(n) + X(n) / 2^n)$$

$$Z(n) = \text{atan}(1/2^n)$$

The $\tan(1/2^n)$ has to be pre-computed, because the algorithm uses it to approximate the angle. The P(n) factor can be eliminated from the equations by pre-computing its final result. If we multiply all P(n)'s together we get the aggregate constant.

$$P = \cos(\text{atan}(1/2^0)) * \cos(\text{atan}(1/2^1)) * \cos(\text{atan}(1/2^2)) \dots \cos(\text{atan}(1/2^n))$$

This is a constant which reaches 0.607... depending on the number of iterations and the number of bits used. The final equations look like this:

$$X_{new} = 0.607... * \text{Sum}(X(n) - Y(n) / 2^n)$$

$$Y_{new} = 0.607... * \text{Sum}(Y(n) + X(n) / 2^n)$$

Now it is clear how we can simply implement this algorithm, it only uses shifts and adds/subs. Or in a program-like style:

```
For i=0 to n-1
if (Z(n) >= 0) then
X(n + 1) := X(n) - (Yn/2^n);
Y(n + 1) := Y(n) + (Xn/2^n);
Z(n + 1) := Z(n) - atan(1/2^i);
else
X(n + 1) := X(n) + (Yn/2^n);
Y(n + 1) := Y(n) - (Xn/2^n);
Z(n + 1) := Z(n) + atan(1/2^i);
end if;
end for;
```

Where 'n' represents the number of iterations.

IV. DCT BLOCK



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A discrete cosine transform (DCT) expresses a finite sequence of data points in terms of a sum of cosine functions oscillating at different frequencies. DCTs are important to numerous applications in science and engineering, from lossy compression of audio (e.g. MP3) and images (e.g. JPEG) (where small high-frequency components can be discarded), to spectral methods for the numerical solution of partial differential equations. The use of cosine rather than sine functions is critical in these applications: for compression, it turns out that cosine functions are much more efficient (as described below, fewer functions are needed to approximate a typical signal), whereas for differential equations the cosines express a particular choice of boundary conditions.

In particular, a DCT is a Fourier-related transform similar to the discrete Fourier transform (DFT), but using only real numbers. DCTs are equivalent to DFTs of roughly twice the length, operating on real data with even symmetry (since the Fourier transform of a real and even function is real and even), where in some variants the input and/or output data are shifted by half a sample. There are eight standard DCT variants, of which four are common.

The most common variant of discrete cosine transform is the type-II DCT, which is often called simply "the DCT", its inverse, the type-III DCT, is correspondingly often called simply "the inverse DCT" or "the IDCT". Two related transforms are the discrete sine transforms (DST), which is equivalent to a DFT of real and odd functions, and the modified discrete cosine transforms (MDCT), which is based on a DCT of overlapping data.

V. CORDIC BASED FAST DCT ALGORITHM

For an N-point signal as shown in fig 2.1, the DCT is defined as,

$$c(k) = \alpha[k] \sum_{n=0}^{N-1} x[n] \cos \left[\frac{(2n+1)k\pi}{2N} \right] \quad (1)$$

Where $\alpha[0] = 1/\sqrt{N}$ if $k = 0$, and $\alpha[k] = \sqrt{2}/N$ otherwise

According to(1), neglecting the post-scaling factor without loss of generality, the main operation of an N – point DCT denoted as DCT can be written as,

$$c(k) = \sum_{n=0}^{N-1} x[n] \cos \left[\frac{(2n+1)k\pi}{2N} \right] \quad (2)$$

where $k=0,1,2,\dots,N-1$.

A length N input sequence $x[n]$, with N is power-of-two, can be decomposed into $x_L[n]$ and $x_H[n]$, which are defined as:

$$x_L[n] = 1/2 \{x[2n] + x[2n+1]\} \text{ and} \quad (3)$$

$$x_H[n] = 1/2 \{x[2n] - x[2n+1]\}; \quad (4)$$

where $n=0, 1, 2, \dots, (N/2)-1$.

So the original signal $x[n]$, can be obtained from $x_L[n]$ and $x_H[n]$ as follows:

$$x[2n] = x_L[n] + x_H[n] \quad (5)$$

$$x[2n+1] = x_L[n] - x_H[n] \quad (6)$$

Substituting (5) and (6) into (2), (2) can be rewritten as:

$$C[k] = \cos(\pi k/2N) \sum_{n=0}^{(N/2)-1} x_L[n] \cos \left[\frac{(2n+1)k\pi}{2N} \right], (k = 0, \dots, N-1)$$

+

$$2\sin(\pi k/2N) \sum_{n=0}^{(N/2)-1} x_L[n] \cos \left[\frac{(2n+1)k\pi}{2N} \right], (k =$$

$0, \dots, N-1)$

(7)

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Where $k=0, \dots, N-1$

Since

$$\cos \left[\frac{(2n+1)(\frac{N-k}{2})\pi}{N} \right] = \sin \left(2n + \frac{1}{2\pi} \right) \sin \left(2n + \frac{1}{Nk\pi} \right) \quad (8)$$

We get (9) and (10)

$$C[k] = 2 \cos \left(\frac{\pi k}{2N} \right) \sum_{n=0}^{\left(\frac{N}{2}\right)-1} xL[n] \cos \left[\frac{2n+1}{N} k\pi \right] + 2 \sin \left(\frac{\pi k}{2N} \right) \sum_{n=0}^{\left(\frac{N}{2}\right)-1} (-1)^n xH[n] \cos \left[(2n+1) \left(\frac{N}{2} - k \right) \pi \right] \quad (9)$$

$$C[N-k] = -2 \sin \left(\frac{\pi k}{2N} \right) \sum_{n=0}^{\left(\frac{N}{2}\right)-1} xL[n] \cos \left[\frac{2n+1}{N} k\pi \right] + 2 \cos \left(\frac{\pi k}{2N} \right) \sum_{n=0}^{\left(\frac{N}{2}\right)-1} (-1)^n xH[n] \cos \left[\frac{(2n+1) \left(\frac{N}{2} - k \right) \pi}{N} \right] \quad (10)$$

Where $k=0 \dots N/2-1$

From (9) and (10), we find that each equation has two $N/2$ -point DCT with two different coefficients, and the four coefficients just make one CORDIC. Hence, we combine the two equations to realize a CORDIC based fast DCT algorithm.

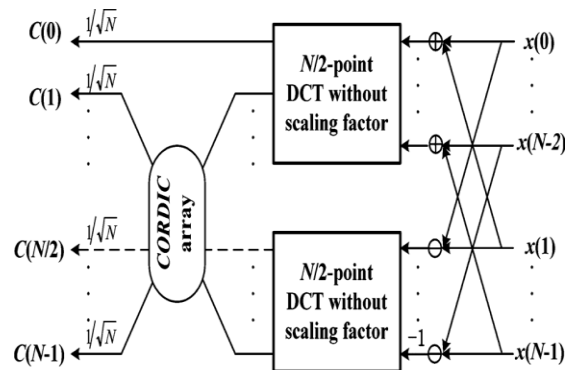


Fig.2.1 Signal flow of an n-point fast discrete cosine transformation

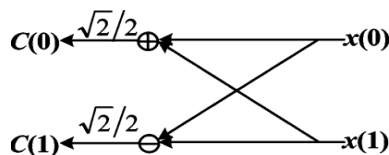


Fig 2.2 Signal flow of a 2-point fast discrete cosine transformation (DCT)

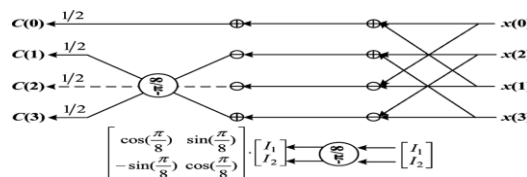


Fig.2.3 Signal flow of a 4-point fast discrete cosine transformation (DCT).

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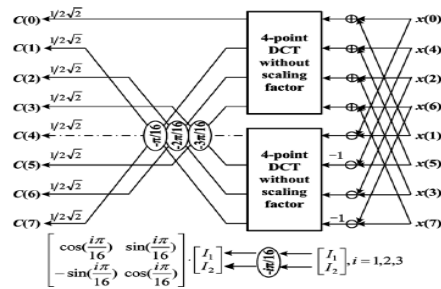


Fig.2.4 Signal flow of a 8-point fast discrete cosine transformation (DCT).

Let

$$\hat{x}_H[n] = (-1)^n x_H[n]$$

Combining the constant values 2 and $\sqrt{2}$ in recursively decomposing stages with the post-scaling factor, the DCT can be written as:

The above diagram (fig 2.4) equation

$$C(k) = \frac{1}{\sqrt{N}} \begin{cases} \tilde{C}_L[0], k = 0 \\ \tilde{C}_H[0], k = \frac{N}{2} \\ \begin{bmatrix} \tilde{C}(k) \\ \tilde{C}(N-k) \end{bmatrix} = \begin{bmatrix} \cos(\frac{k\pi}{2N}) & \sin(\frac{k\pi}{2N}) \\ -\sin(\frac{k\pi}{2N}) & \cos(\frac{k\pi}{2N}) \end{bmatrix} \\ \cdot \begin{bmatrix} \tilde{C}_L(k) \\ \tilde{C}_H(\frac{N}{2}-k) \end{bmatrix}, k = 1, \dots, \frac{N}{2} - 1 \end{cases}$$

Application

CORDIC uses simple shift-add operations for several computing tasks such as the calculation of trigonometric, hyperbolic and logarithmic functions, real and complex multiplications, division, square-root calculation, solution of linear systems, eigen value estimation, singular value decomposition, QR factorization and many others. As a consequence, CORDIC has been utilized for applications in diverse areas such as signal and image processing, communication systems, robotics and 3-D graphics apart from general scientific and technical computation.

DCT and IDCT signal flow based on proposed algorithm

The general signal-flow graph for the proposed fast DCT algorithm given while the signal-flow graphs of 2-point DCT, 4-point DCT, and 8-point DCT are respectively represented where the angles in the circles are used to represent CORDICs with this rotation angles.

There are two separate -point DCTs and one CORDIC array. As mentioned above, the CORDIC array has CORDICs with arithmetic-sequence rotation angles. The inputs are addressed in bit-reverse order and the outputs are addressed in natural order. It also supports in-place computation like the FFT. Regular and pure feed-forward data paths of the signal flow make them suitable for pipelined VLSI implementation. For special applications, a double-angle formula can be used to reduce CORDIC types. Hence, the architecture based on the signal flow is highly modular. Furthermore, the modified unfolded CORDIC, which presented in our previous work, can be used to speed up computations and overcome recursive problems in conventional CORDICs.

Similarly, the fast algorithm for the -point IDCT can be deduced like the fast DCT algorithm. Alternatively, it can be obtained more easily using their orthogonal property. As is known, the DCT and IDCT are orthogonal transformations, and the signal flow of the -point IDCT can be easily obtained by inverting the transfer function of each building block shown in Table 2.1 and reversing the signal flow direction.

Table 2.1 transfer function of DCT and IDCT



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Symbol	DCT	IDCT
Butterfly	$x_{out} = x_{in} + y_{in}$ $y_{out} = x_{in} - y_{in}$	$x_{out} = (x_{in} + y_{in})/2$ $y_{out} = (x_{in} - y_{in})/2$
Multiply constant	$\leftarrow K \times$	$\times \frac{1}{K} \rightarrow$
CORDIC	Clockwise ($-\theta$)	Anticlockwise (θ)

The CORDICs in the DCT and IDCT have the same rotation angle but opposite rotation directions. When changing the CORDIC from a clockwise to an anticlockwise rotation with the same angle, the only thing that is required is to change all adders to subtractors and subtractors to adders in the rotation iteration stage. This results in an easy way to implement a reconfigurable or unified architecture for DCTs and IDCTs. Notice that the proposed fast IDCT algorithm has the same arithmetic complexity as does the DCT.

IV. FEATURES OF PROPOSED CORDIC-BASED FAST DCT ALGORITHM.

Hardware complexity:

The CORDIC-based algorithm is highly suitable for VLSI implementation, since it is built using shifters and adders only. Liang *et al.* [7] propose lifting scheme-based fast multiplierless approximation of the DCT using only binary shift and addition operations. This results in a very low hardware complexity VLSI implementation. We use the modified unfolded CORDIC to realize a low hardware complexity VLSI implementation also using only binary shift and addition operations. Moreover, the computational accuracy can be selected based on the trade-off between the hardware complexity and approximation error. In addition, since our proposed algorithm has uniform post-scaling factor, it is also suitable for scaled DCT implementation. The block diagram and the corresponding layout view of the proposed 8-point DCT after placement and routing based on SMIC 0.18 standard cell library. This design (excluding the I/O pads) has area of 627738 with power consumption of 12.5 mW under operating frequency of 66.7 MHz.

Scalability:

Many CORDIC-based algorithms are limit to short-length DCT, such as the algorithms based on Loeffler's DCT. Our proposed algorithm provides much easier and more regular way to realize the scalability, which can be easily extended to compute long-length DCTs as long as the transform length is power-of-two.

Modularity:

For N -point DCT, our proposed algorithm requires CORDICs with only different CORDIC types. Furthermore, the rotation angles of the CORDICs in our proposed algorithm are arithmetic-sequence, the double-angle formula can be used to reduce the number of the CORDIC types and make this algorithm highly modular. Compared to the CORDIC-based architectures, our architecture has better modularity.

Pipelinability:

The architectures is recursive in nature, thus making them difficult to realize pipeline. We use the modified unfolding CORDIC to overcome this problem. Moreover, the regular and purely feed forward data path makes our proposed algorithm based architecture suitable for pipelined VLSI implementation.

Reconfigurability:

In a method for mapping the type-IV DCT to the type II-DCT is presented. However the method required additional arithmetic computation. We present an easy way to implement a reconfigurable architecture for DCT and IDCT with the same arithmetic complexity by taking the orthogonal.

V. FAST DCT ALGORITHM

Forward DCT



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The DCT of a sequence $\{x[m], (m=0, \dots, N-1)\}$ can be implemented by FFT. First we define a new sequence: $\{y[m], (m=0, \dots, N-1)\}$

$$\begin{cases} y[m] \triangleq x[2m] \\ y[N-1-m] \triangleq x[2m+1] \quad (i = 0, \dots, \frac{N}{2} - 1) \end{cases}$$

Then the DCT of $x[n]$ can be written as the following (the coefficient $a[n]$ is dropped for now for simplicity):

$$X[n]: \sum_{m=0}^{N-1} x[m] \cos\left(\frac{(2m+1)n\pi}{2N}\right)$$

$$: \sum_{m=0}^{\frac{N}{2}-1} x[2m] \cos\left(\frac{(4m+1)n\pi}{2N}\right) + \sum_{m=0}^{\frac{N}{2}-1} x[2m+1] \cos\left(\frac{(4m+3)n\pi}{2N}\right)$$

$$: \sum_{m=0}^{\frac{N}{2}-1} y[m] \cos\left(\frac{(4m+1)n\pi}{2N}\right) + \sum_{m=0}^{\frac{N}{2}-1} y[N-1-m] \cos\left(\frac{(4m+3)n\pi}{2N}\right)$$

where the first summation is for all even terms and second all odd terms. We define for the second summation, then the limits of the summation 0 and $N/2-1$ for m becomes $N-1$ and $N/2$ form m' , and the second summation can be written as

$$\sum_{m=N/2}^{N-1} y[m] \cos\left(2n\pi - \frac{(4m'+1)n\pi}{2N}\right) = \sum_{m'=\frac{N}{2}}^{N-1} y[m'] \cos\left(\frac{(4m'+1)n\pi}{2N}\right)$$

Now the two summations in the expression of $x[n]$ can be combined

$$X[n] = \sum_{m=0}^{N-1} y[m] \cos\left(\frac{(4m+1)n\pi}{2N}\right)$$

Next, consider the DFT of $y[m]$:

$$Y[n] = \sum_{m=0}^{N-1} y[m] e^{-\frac{j2\pi mn}{N}} = \sum_{m=0}^{N-1} y[m] \left[\cos\left(\frac{2\pi mn}{N}\right) - j \sin\left(\frac{2\pi mn}{N}\right) \right]$$

If we multiply both sides by

$$e^{-jn\pi/2N} = \cos\left(\frac{n\pi}{2N}\right) - j \sin\left(\frac{n\pi}{2N}\right)$$

and take the real part of the result (and keep in mind that both $x[m]$ and $y[m]$ are real), we get:

$$\operatorname{Re} \left[e^{-\frac{jn\pi}{2N}} Y[n] \right] = \sum_{m=0}^{N-1} y[m] \left[\cos\left(\frac{2\pi mn}{N}\right) \cos\left(\frac{n\pi}{2N}\right) - \sin\left(\frac{2\pi mn}{N}\right) \sin\left(\frac{n\pi}{2N}\right) \right] = \sum_{m=0}^{N-1} y[m] \cos\left(\frac{(4m+1)n\pi}{2N}\right)$$

The last equal sign is due to the trigonometric identity:

$$\cos(\alpha + \beta) = \cos \alpha \cos \beta - \sin \alpha \sin \beta$$

This expression for $\operatorname{Re} \left[e^{-\frac{jn\pi}{2N}} Y[n] \right]$ is identical to that for $X[n]$ above, therefore we get



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$$X[n] = Re[e^{-\frac{jn\pi}{2N}} Y[n]]$$

where $Y[n]$ is the DFT of $y[m]$ (defined from $x[m]$) which can be computed using FFT algorithm with time complexity $O(N \log_2 N)$.

In summary, fast forward DCT can be implemented in 3 steps:

- **Step 1:** Generate a sequence $y[m]$ from the given sequence $x[m]$:

$$\begin{cases} y[2m] = x[2m] \\ y[N-1-m] = x[2m+1] \quad (i = 0, \dots, \frac{N}{2} - 1) \end{cases}$$

- **step 2:** Obtain DFT $Y[n]$ of $y[m]$ using FFT. (As $y[m]$ is real, $Y[n]$ is symmetric and only half of the data points need be computed.)

$$Y[n] = F[y[m]]$$

- **step 3:** Obtain DCT $X[n]$ from $Y[n]$ by

$$X[n] = Re[e^{-\frac{jn\pi}{2N}} Y[n]]$$

Inverse DCT

The most obvious way to do inverse DCT is to reverse the order and the mathematical operations of the three steps for the forward DCT: [8]

- **step 1:** Obtain $Y[n]$ from $X[n]$. In step 3 above there are N equations but $2N$ variables (both real and imaginary parts of $Y[n]$). However, note that as $y[m]$'s are *real*, the real part of its spectrum $Y[n]$ is even ($N+1$ independent variables) and imaginary part odd ($N-1$ independent variables). So there are only N variables which can be obtained by solving the N equations. [10-13]

$$X[n] = Re \left[e^{-\frac{jn\pi}{2N}} Y[n] \right] \quad (n = 0, \dots, N-1)$$

- **step 2:** Obtain $y[m]$ from $Y[n]$ by inverse DFT also using FFT in $N \log_2 N$ complexity.

$$y[m] = F^{-1}[Y[n]]$$

- **Step 3:** Obtain $x[m]$ from $y[m]$ by

$$\begin{cases} x[2m] = y[m] \\ x[2m+1] = y[N-1-m] \quad (i = 0, \dots, \frac{N}{2} - 1) \end{cases}$$

However, there is a more efficient way to do the inverse DCT. Consider first the real part of the inverse DFT of the sequence: $X[n]e^{jn\pi/2N}$

$$Re \left[\sum_{n=0}^{N-1} X[n] e^{\frac{jn\pi}{2N}} e^{\frac{j2\pi mn}{N}} \right] = Re \left[\sum_{n=0}^{N-1} X[n] e^{\frac{j(2m+1)n\pi}{2N}} \right] = \sum_{n=0}^{N-1} X[n] \cos \left(\frac{(4m+1)n\pi}{2N} \right) = x[2m]$$

This equation gives the inverse DCT of all $N/2$ even data points $x(2m)$

($m = 0 \dots N/2-1$). To obtain the odd data points, recall that $x[m] = x[2N-m-1]$, and all odd data points

$$x[2m+1] = x[2N - (2m+1) - 1] = x[2(N-m-1)] \quad (m = 0, \dots, \frac{N}{2} - 1)$$

can be obtained from the second half of the previous equation in reverse order [9]

($m = N-1, N-2, \dots, N/2$).

In summary, we have these steps to compute IDCT:

The mathematically equivalent to the steps of the first method

- **step 1:** Generate a sequence $Y[n]$ from the given DCT sequence $X[n]$:

$$Y[n] = X[n] e^{\frac{jn\pi}{2N}} \quad (n = 0, \dots, N-1)$$



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- **Step 2:** Obtain $y[m]$ from $Y[n]$ by inverse DFT also using FFT. (Only the real part need be computed.)
 $y[m] = \text{Re}\{F^{-1}[Y[n]]\}$

- **Step 3:** Obtain $x[m]$'s from $y[m]$'s by

$$\begin{cases} x[2m] = y[m] \\ x[2m + 1] = y[N - 1 - m] \end{cases} \left(i = 0, \dots, \frac{N}{2} - 1 \right)$$

VI. IMPLEMENTATION CONSIDERATION AND COMPARISONS

The N -point proposed DCT algorithm needs two-point DCTs, CORDICs, and additions. Therefore, the number of CORDICs required by the proposed algorithm is

$$C(N) = \sum_{n=1}^{\log_2 N - 1} 2 \log_2^{N-1} - 2^{n-1} = \frac{N}{2} \log_2 N - N + 1$$

and the number of additions is $A(N) = N \log_2 N$

VII. RESULT AND ANALYSIS

The proposed algorithm can generate the next higher-order DCT from two identical lower-orders DCTs. After simulation the result of 2-point DCT and 4-point DCT are shown in fig4.1 and fig 4.2.

CORDIC-based fast radix-2 DCT algorithm requires $N \log_2 N$ additions and $N/2 \log_2 N - N + 1$ CORDICs.

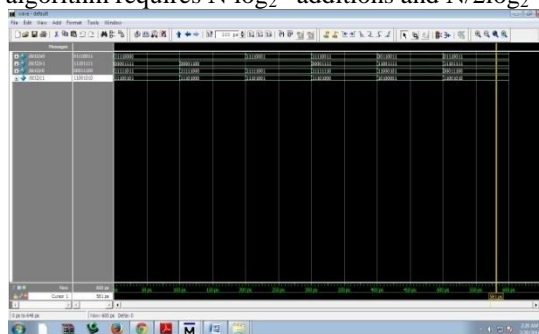


Fig 4.1 simulation of 2-point DCT

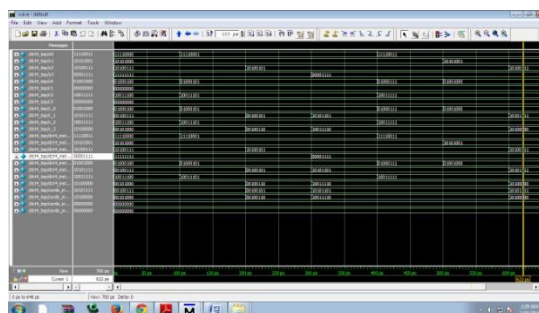


Fig 4.2 simulation of 4-point DCT

VIII. CONCLUSION



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A novel CORDIC-based radix-2 fast DCT algorithm was proposed. This algorithm can generate the next higher order DCT from two identical lower-order DCTs. Compared to existing DCT algorithms, our proposed algorithm has several distinct advantages, such as low computational complexity, and being highly scalable, modular, regular, and able to admit efficient pipelined implementation.

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