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HDL Implementation of 2-D Lifting-based Discrete Wavelet Transform

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***Abstract* – The digital data can be transformed using Discrete Wavelet Transform (DWT). The images need to be transformed without loosing of information. The Discrete Wavelet Transform (DWT) was based on time-scale representation, which provides efficient multi-resolution. The lifting based scheme (5, 3) (Here 5 Low Pass filter coefficients and the 3 High Pass filter coefficients) filter give lossless mode of information as per the JPEG 2000 Standard. The lifting based DWT are lower computational complexity and reduced memory requirements. Since Conventional convolution based DWT is area and power hungry which can be overcome by using the lifting based scheme. The discrete wavelet transform (DWT) is being increasingly used for image coding. Recently, a lifting-based scheme that often requires far fewer computations has been proposed for the DWT. In this paper, the design of Lossless 2-D DWT (Discrete Wavelet Transform) using Lifting Scheme Architecture will be modeled using the Verilog HDL and its functionality were verified using the Modelsim tool and can be synthesized using the Xilinx tool. Recently, a lifting-based scheme that often requires far fewer computations has been proposed for the DWT.**

***Keywords* – Discrete Wavelet Transform (DWT), Lifting Scheme, Fourier Transform, Symmetrical Boundary Conditions, VLSI Architecture.**

I. INTRODUCTION

The fundamental idea behind wavelets is to analyze according to scale. Indeed, some researchers in the wavelet field feel that, by using wavelets, one is adopting a perspective in processing data. Wavelets are functions that satisfy certain mathematical requirements and are used in representing data or other functions. This idea is not new. Approximation using superposition of functions has existed since the early 1800's, when Joseph [10]

Fourier discovered that he could superpose sines and cosines to represent other functions [2]-[3]. However, in wavelet analysis, the scale that we use to look at data plays a special role. Wavelet algorithms process data at different scales or resolutions.Fourier Transform (FT) with its fast algorithms (FFT) is an important tool for analysis and processing of many natural signals. FT has certain limitations to characterize many natural signals, which are non-stationary (e.g. speech). Though a time varying, overlapping window based FT namely STFT (Short Time FT) is well known for speech processing applications, a time-scale based Wavelet Transform [4] is a powerful mathematical tool for non-stationary signals. Wavelet Transform uses a set of damped oscillating functions known as wavelet basis. WT in its continuous (analog) form is represented as CWT. CWT with various deterministic or non-deterministic basis is a more effective representation of signals for analysis as well as characterization. Continuous wavelet transform is powerful in singularity detection. A discrete and fast implementation of CWT (generally with real valued basis) is known as the standard DWT [8]-[9] (Discrete Wavelet Transform).With standard DWT, signal has a same data size in transform domain and therefore it is a non-redundant transform. A very important property was Multi-resolution Analysis (MRA) allows DWT to view and process.The wavelet transform is computed separately for different segments of the time-domain signal at different frequencies.[5] Multi-resolution analysis: analyzes the signal at different frequencies giving different resolutions. Multi-resolution analysis is designed to give good time resolution and poor frequency resolution at high frequencies and good frequency resolution and poor time resolution at low frequencies. Good for signal having high frequency components for short durations and low frequency components for long duration, e.g. Images and video frames.

A 'wavelet' is a small wave which has its energy concentrated in time. It has an oscillating wavelike characteristic but also has the ability to allow simultaneous time and frequency analysis and it is a suitable tool for transient, non-stationary or time-varying phenomena.

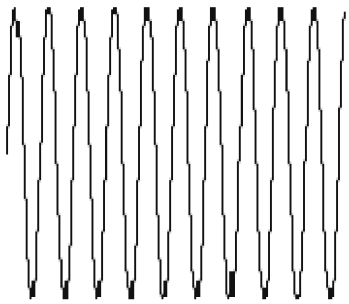

Fig.1. Representation of a wave

The difference between wave (sinusoids) and wavelet is shown in figure 1 Waves are smooth, predictable and everlasting, whereas wavelets are of limited duration, irregular and may be asymmetric. Waves are used as deterministic basis functions in Fourier analysis for the expansion of functions (signals), which are time-invariant, or stationary. The important characteristic of wavelets is that they can serve as deterministic or non-deterministic basis for generation and analysis of the most natural signals to provide better time-frequency representation, which is not possible with waves using conventional Fourier analysis. The wavelet analysis [10] procedure is to adopt a wavelet prototype function, called an 'analyzing

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wavelet' or 'mother wavelet'. Temporal analysis is performed with a contracted, high frequency version of the prototype wavelet, while frequency analysis is performed with a dilated, low frequency version of the same wavelet. Mathematical formulation of signal expansion using wavelets gives Wavelet Transform (WT) pair, which is analogous to the Fourier Transform (FT) pair. Discrete-time and discrete-parameter version of WT is termed as Discrete Wavelet Transform (DWT).Recursive filtering[2] process of the one-dimensional DWT is shown in Figure 1, where z is the input data-stream, *a* and *d* are approximation (low-pass filter output) and difference (high-pass filter output) data-streams respectively. The subscript values show the "level" of output.

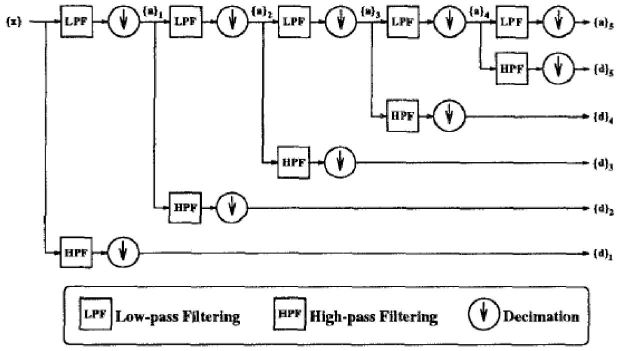

Fig.2. The DWT filtering process

The filtering steps are multiply and accumulate operations. A filter in the algorithmic, discrete sense is a number of "coefficient" values. The number of these values is referred to as the "filter width" and these coefficients are also referred to as "taps". At each data-word of the input, the filter spans across that data-word and its neighboring data-words as a "window". The values within this window are multiplied by their corresponding filter coefficient and all the results are added together to give the filtered result for this data-word. The filtering operation extracts certain frequency information from the data depending on the characteristics of the filter. This filtering operation can be done with a systolic array. It is simple to implement a systolic array for each level of the DWT, but the arrays are poorly utilized due to the decreasing data-rates of the levels. It is possible, through some complex timing, to use a single array to perform all levels of the DWT.The discrete wavelet transform (DWT) is being increasingly used for image coding.[7] This is due to the fact that DWT supports features like progressive image transmission (by quality, by resolution), ease of compressed image manipulation, region of interest coding, etc. DWT has traditionally been implemented by convolution. Such an implementation demands both a large number of computations and a large storage features that are not desirable for either high-speed or low-power applications. Recently, a lifting-based scheme that often requires far fewer computations has been proposed for the DWT. The main feature of the lifting based DWT scheme is to break up the high pass and low pass filters into a sequence of upper and lower triangular matrices and convert the filter implementation into banded matrix multiplications. Such a scheme has several advantages, including "in-place" computation of the DWT, integer-to-integer wavelet transform (IWT), symmetric forward and inverse transform, etc. Therefore, it comes as no surprise that lifting has been chosen in the upcoming.

The proposed architecture [4]-[6] computes multilevel DWT for both the forward and the inverse transforms one level at a time, in a row-column fashion. There are two row processors to compute along the rows and two column processors to compute along the columns. While this arrangement is suitable or filters that require two banded-matrix multiplications filters that require four banded-matrix multiplications require all four processors to compute along the rows or along the columns. The outputs generated by the row and column processors (that are used for further computations) are stored in memory modules. The memory modules are divided into multiple banks to accommodate high computational bandwidth requirements. The proposed architecture is an extension of the architecture for the forward transform that was presented.

A number of architectures have been proposed for calculation of the convolution-based DWT. The architectures are mostly folded and can be broadly classified into serial architectures (where the inputs are supplied to the filters in a serial manner) and parallel architectures (where the inputs are supplied to the filters in a parallel manner). Recently, a methodology for implementing lifting-based DWT that reduces the memory requirements and communication between the processors, when the image is broken up into blocks. For a system that consists of the lifting-based DWT transform followed by an embedded zero-tree algorithm, a new interleaving scheme that reduces the number of memory accesses has been proposed. Finally, a lifting-based DWT architecture capable of performing filters with one lifting step, i.e., one predict and one update step. The outputs are generated in an interleaved fashion. [3] DWT can be a Mathematical tool, which is also used in image processing applications like image compression and image Restoration.DWT may be implemented in 3D.

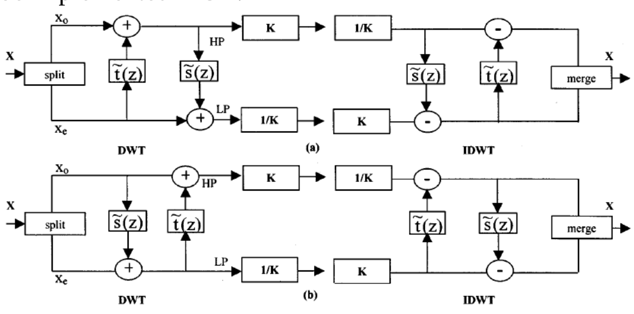

Fig.3. Lifting Schemes. (a) Scheme (b) Scheme 2.

The basic principle of the lifting scheme is to factorize the poly phase matrix of a wavelet filter into a sequence of alternating upper and lower triangular matrices and a diagonal matrix. This leads to the wavelet implementation by means of banded-matrix multiplications.

Let $\tilde{h}(z)$ and $\tilde{g}(z)$ be the low pass and high pass analysis filters, and let $h(z)$ and $g(z)$ be the low pass

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and high pass synthesis filters. The corresponding poly-phase matrices are defined as

$$\tilde{P}(z) = \begin{bmatrix} \tilde{h}_e(z) & \tilde{h}_o(z) \\ \tilde{g}_e(z) & \tilde{g}_o(z) \end{bmatrix} \quad \text{and} \quad P(z) = \begin{bmatrix} h_e(z) & g_e(z) \\ h_o(z) & g_o(z) \end{bmatrix}$$

If $(\tilde{h}, \tilde{g})$ is a complementary filter pair, then can always be factored into lifting steps as

$$\tilde{P}_1(z) = \begin{bmatrix} K & 0 \\ 0 & \frac{1}{K} \end{bmatrix} \prod_{i=1}^{m} \begin{bmatrix} 1 & \tilde{s}_i(z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \tilde{t}_i(z) & 1 \end{bmatrix}$$

$$\tilde{P}_2(z) = \begin{bmatrix} K & 0 \\ 0 & \frac{1}{K} \end{bmatrix} \prod_{i=1}^{m} \begin{bmatrix} 1 & 0 \\ \tilde{t}_i(z) & 1 \end{bmatrix} \begin{bmatrix} 1 & \tilde{s}_i(z) \\ 0 & 1 \end{bmatrix}$$

Where K is a constant. The two types of lifting schemes are shown in Figure Scheme 1 $\tilde{P}_1(z)$ which corresponds to the factorization consists of three steps:

- *Predict* step, where the even samples are multiplied by the time domain equivalent of $\tilde{t}(z)$ and are added to the odd samples.
- *Update* step, where updated odd samples are multiplied by the time domain equivalent of $\tilde{s}(z)$ and are added to the even samples.
- *Scaling* step, where the even samples are multiplied by 1/k and odd samples by k.

The inverse DWT is obtained by traversing in the reverse direction, changing the factor K to 1/K, K factor to i/K, and reversing the signs of coefficients in $\tilde{t}(z)$ and $\tilde{s}(z)$. In Scheme 2 which corresponds to the $\tilde{P}_2(z)$ factorization, the odd samples are calculated in the first step, and the even samples are calculated in the second step. The inverse is obtained by traversing in the reverse direction. The lifting scheme is a technique for both designing wavelets and performing the discrete wavelet transform. Actually it is worthwhile to merge these steps and design the wavelet filters while performing the wavelet transform. This is then called the second generation wavelet transform. The technique was introduced by Wim Sweldens.

The discrete wavelet transform applies several filters separately to the same signal. In contrast to that, for the lifting scheme the signal is divided like a zipper. Then a series of convolution-accumulate operations across the divided signals is applied.The basic idea of lifting is the following: If a pair of filters (h,g) is complementary, that is it allows for perfect reconstruction, then for every filter[3]-[4] Sthepair (*h*', *g*) with

$$h'(z) = h(z) + s(z^2) \cdot g(z)$$

allows for perfect reconstruction, too. Of course, this is also true for every pair (*h*,*g*') of the form

$$g'(z) = g(z) + t(z^2) \cdot h(z).$$

The converse is also true: If the filter banks (*h*,*g*) and (*h*',*g*) allow for perfect reconstruction, then there is a unique filter Swith

$$h'(z) = h(z) + s(z^2) \cdot g(z).$$

Each such transform of the filter bank (or the respective operation in a wavelet transform) is called a lifting step. A sequence of lifting steps consists of alternating lifts, that is, once the low pass is fixed and the high pass is changed and in the next step the high pass is fixed and the low pass is changed. Successive steps of the same direction can be merged. [6].One dimensional DWT can be easily extended to two dimensions which can be used for the transformation of two dimensional images. A two dimensional digital image which can be represented by a 2-D array X [m,n] with m rows and n columns, where m, n are positive integers. First, a one dimensional DWT is performed on rows to get low frequency L and high frequency H components of the image. Then, once again a one dimensional DWT is performed column wise on this intermediate result to form the final DWT coefficients LL, HL, LH, HH. These are called sub-bands. The LL sub-band can be further decomposed into four sub-bands by following the above procedure. This process can continue to the required number of levels. This process is called multi level decomposition. A three level decomposition of the given digital image is as shown**.** High pass and low pass filters are used to decompose the image first row-wise and then column wise. Similarly, the inverse DWT is applied which is just opposite to the forward DWT to get back the reconstructed image, shown .

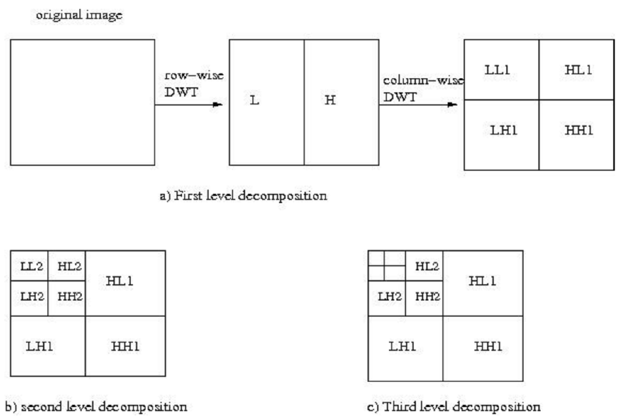

Fig.4. Row-column computation of 2-D DWT

II. Results and Analysis

The test bench is developed in order to test the modeled design. This developed test bench will automatically force the inputs and will make the operations of algorithm to perform.This is first of all simulation steps; those are encountered throughout the hierarchy of the design flow. This simulation is performed before synthesis process to verify RTL (behavioral) code and to confirm that the design is functioning as intended. Behavioral simulation can be performed on either VHDL or Verilog designs. In this process, signals and variables are observed, procedures and functions are traced and breakpoints are set. This is a very fast simulation and so allows the designer to change the HDL code if the required functionality is not met with in a short time period. Since the design is not yet synthesized to gate level, timing and resource usage properties are still unknown. Results shown in the following pages.DWT1, DWT2, DWT3 were shown with Xilinx software.(Model sim is also used for simulation)

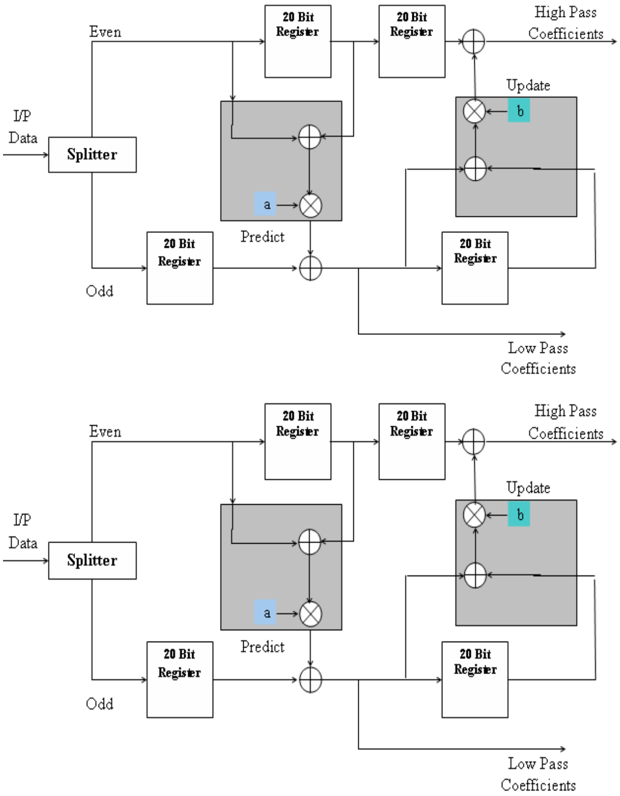

Fig.5. Computation of Basic (5, 3) DWT Block in which 'a' and 'b' are lifting coefficients (a = -1/2 and b = 1)

III. Simulation Diagrams

DWT Block The initial block of the design is that the Discrete Wavelet Transform (DWT) block which is mainly used for the transformation of the image. In this process, the image will be transformed and hence the high pass coefficients and the low pass coefficients were generated. Since the operation of this DWT block has been discussed in the previous chapter, here the snapshots of the simulation results were directly taken in to consideration and discussed. The input is 16 bits each input bit width is 20 bit width. The DWT consists of registers and adders. Whenever the input is send, the data divided into even data and odd data. The even data and odd data is stored in the temporary registers. When the reset is high the temporary register value consists of zero whenever the reset is low the input data split into the even data and odd data. The input data read up to sixteen clock cycles after that the data read according to the lifting scheme. The output data consists of low pass and high pass elements. This is the 1-D discrete wavelet transform. The 2-D discrete wavelet transform is that the low pass and the high pass again divided into LL, LH and HH, HL. The output is verified in the Model sim. For this DWT block, the clock and reset were the primary inputs. The pixel values of the image, that is, the input data will be given to this block and hence these values will be split in to even and odd pixel values. In the design, this even and odd were taken as a array which will store its pixel values in it and once all the input pixel values over, then load will be made high which represents that the system is ready for the further process.Once the load signal is set to high, then the each value from the even and odd array will be taken and used for the Low Pass Coefficients generation process. Hence each value will be given to the adder and in turn given to the multiplication [2] process with the filter coefficients. Finally the Low Pass Coefficients will be achieved from the addition process of multiplied output and the odd pixel value. Again this Low Pass Coefficient will be taken and it will be multiplied with the filter coefficients. The resultant will be added with the even pixel value which gives the High Pass Coefficient. Hence all the values from even and odd array will be taken and then above said process will be carried out in order to achieve the High and Low Pass Coefficients of the image.Now these low pass coefficients and the high pass coefficients were taken as the input for the further process. Hence for the DWT-2 process, low pass coefficients will be taken as the inputs and will do the process in order to calculate the low pass and high pass coefficients from the transform The device utilization summery is shown below in which its gives the details of number of devices used from the available devices and also represented in %. Hence as the result of the synthesis process, the device utilization in the used device and package is shown above.

Timing Summary: *Speed Grade: -4*
Minimum period: 10.081ns (Maximum Frequency: 99.197MHz)
Minimum input arrival time before clock: 4.252ns
Maximum output required time after clock: 14.421ns
Maximum combinational path delay: No path found

In timing summery, details regarding time period and frequency is shown are approximate while synthesize. After place and routing is over, we get the exact timing summery. Hence the maximum operating frequency of this synthesized design is given as 99.197 MHz and the minimum period as 10.081ns. Here, OFFSET IN is the minimum input arrival time before clock and OFFSET OUT is maximum output required time after clock.

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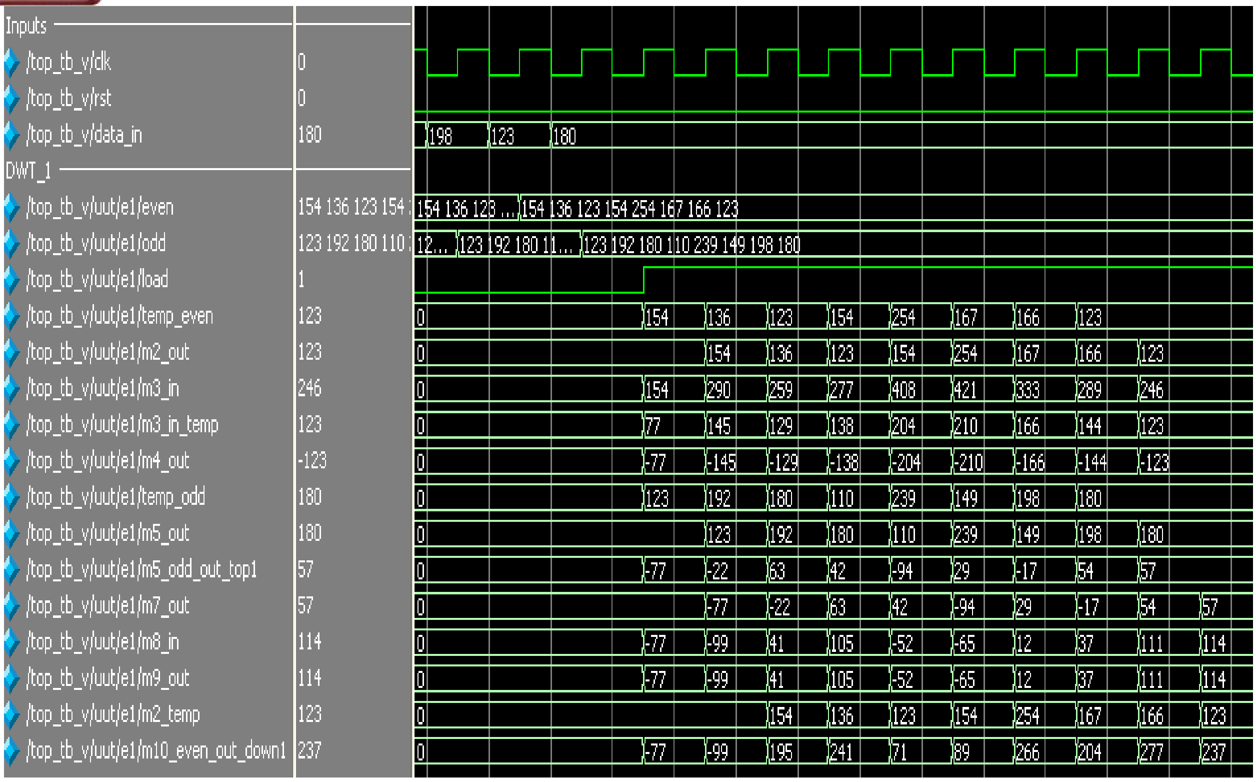

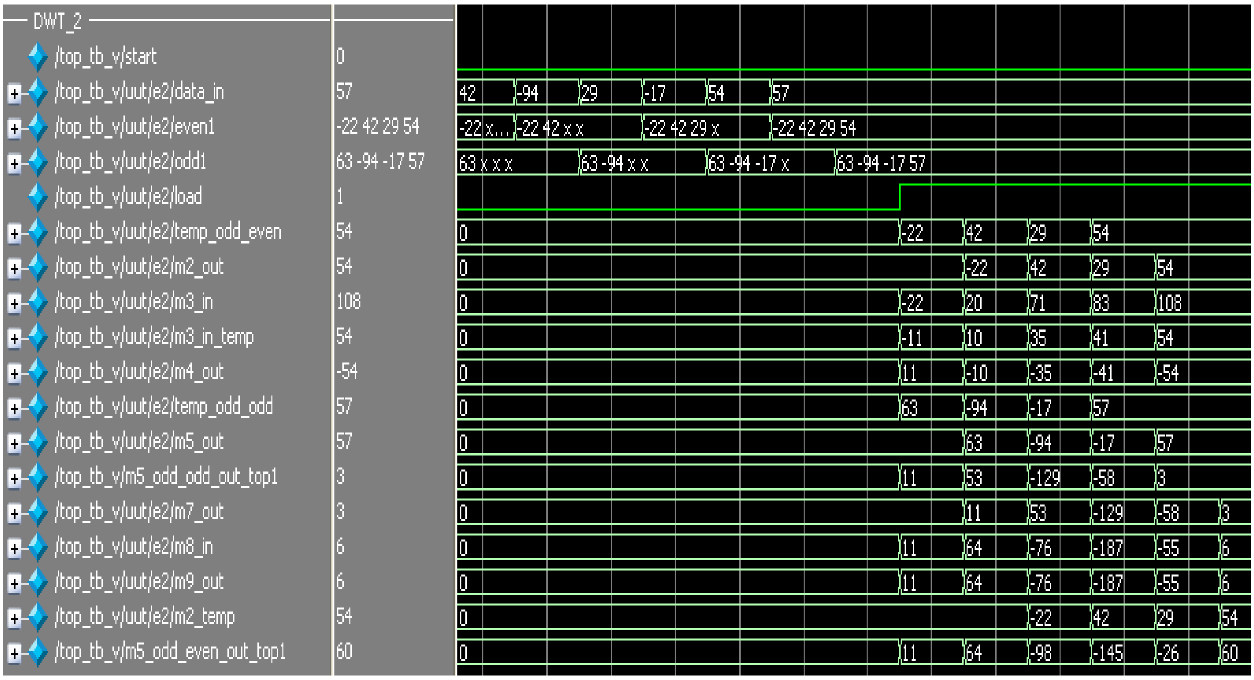

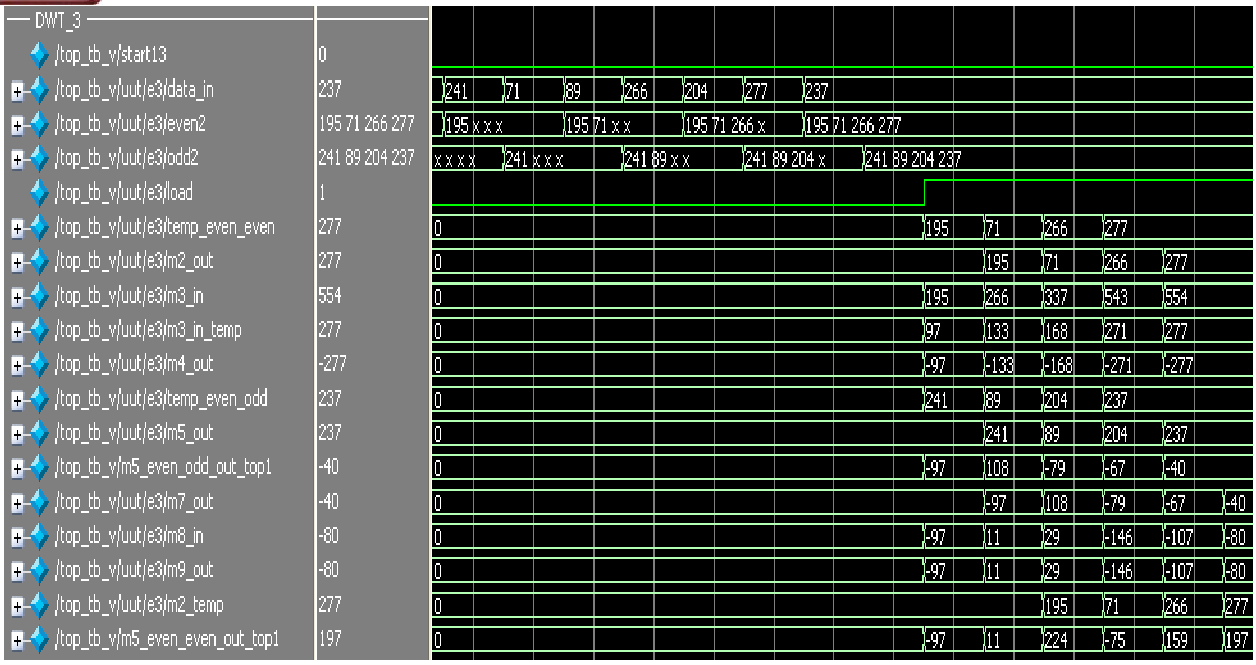

Summary

tst1 Project Status (04/21/2010 - 17:41:36)			
Project File:	tst1.ise	**Current State:**	Placed and Routed
Module Name:	top_dwt	• **Errors:**	No Errors
Target Device:	xc3s500e-4fg320	• **Warnings:**	5 Warnings
Product Version:	ISE 10.1 - Foundation Simulator	• **Routing Results:**	All Signals Completely Routed
Design Goal:	Balanced	• **Timing Constraints:**	All Constraints Met
Design Strategy:	Xilinx Default (unlocked)	• **Final Timing Score:**	0 (Timing Report)

tst1 Partition Summary	[-]
No partition information was found.	

Device Utilization Summary				[-]
Logic Utilization	**Used**	**Available**	**Utilization**	**Note(s)**
Number of Slice Flip Flops	386	9,312	4%	
Number of 4 input LUTs	532	9,312	5%	
Logic Distribution				
Number of occupied Slices	446	4,656	9%	
Number of Slices containing only related logic	446	446	100%	
Number of Slices containing unrelated logic	0	446	0%	
Total Number of 4 input LUTs	532	9,312	5%	
Number used as logic	292			
Number used for Dual Port RAMs	240			
Number of bonded IOBs	104	232	44%	
Number of BUFGMUXs	1	24	4%	

IV. Conclusion

Basically the medical images need more accuracy without loosing of information. The Discrete Wavelet Transform (DWT) was based on time-scale representation, which provides efficient multi-resolution. The lifting based scheme (5, 3) (The high pass filter has five taps and the low pass filter has three taps) filter give lossless mode of information. A more efficient approach to lossless whose coefficients are exactly represented by finite precision numbers allows for truly lossless encoding.

This work ensures that the image pixel values given to the DWT process which gives the high pass and low pass coefficients of the input image. The simulation results of DWT were verified with the appropriate test cases. Once the functional verification is done, discrete wavelet transform is synthesized by using Xilinx tool in Spartan 3E FPGA family. Hence it has been analyzed that the discrete wavelet transform (DWT) operates at a maximum clock frequency of 99.197 MHz respectively.

As future work,

- This work can be extended in order to increase the accuracy by increasing the level of transformations.

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- This can be used as a part of the block in the full fledged application, i.e., by using these DWT, the applications can be developed such as compression, watermarking, etc.

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