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Modified Lifting Based DWT/IDWT Architecture for OFDM on Virtex-5 FPGA

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Keywords : OFDM, DWT, MULTIWAVELETS, DMWT.

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Strictly as per the compliance and regulations of:

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Anitha.K [α], Dr.Dharmistan.K.Varugheese [σ] & Dr N.J.R.Muniraj [ρ]

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Keywords : OFDM,DWT ,MULTIWAVELETS,DMWT.

I. Introduction

Wireless communication systems, limited bandwidth allocations coupled with a potentially large group of users restrict the bandwidth availability to the users. The success of wirelesses communication systems thus depends heavily on the development of bandwidth efficient data transmission schemes. Wireless multicarrier modulation *(MCM-OFDM)* is a technique of transmitting data by dividing the input data stream into parallel sub streams where each stream is modulated and multiplexed onto the channel at different carrier frequencies [1]. In OFDM, the message which is symbol mapped using QAM scheme is modulated using complex carrier which introduces orthogonality between multiple carrier signals. The orthogonally modulated signal is transmitted in the channel with narrow band requirements, thus improving throughput as well as high data rate.

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At the receiver, the inverse transform is performed to retrieve message symbols from the orthogonally modulated data. Currently FFT is used for forward and inverse transform operation performing orthogonal modulation at the receiver and transmitter respectively. The limitations of FFT such as ISI and bandwidth occupation due to cyclic prefix can be minimized with use of Wavelet Transform. Wavelets are known to have compact support (localization) both in time and frequency domain, and possess better orthogonality [8]. A hopeful application of wavelet transform is in the field of digital wireless multicarrier communication where they can be used to generate waveforms that are fit for transmission over fading channels [1, 2, 3, 4, 30].

The major advantage of wavelet based OFDM is its optimal performance over conventional OFDM (FFT based OFDM). Wavelet bases therefore appear to be a more logical choice for building orthogonal waveform sets usable in communication. In this work we study orthogonal wavelet bases OFDM. Inter Symbol Interference (ISI) and Inter Carrier Interference (ICI) causes by loss of orthogonality between the carriers is reduced by using orthogonal wavelets. The work addresses performance of wavelet OFDM using different orthogonal wavelet basis families such as Haar, Daubechies, Symlets, Coiflets and Discrete Meyer over wireless channels and tries to investigate a suitable wavelet based OFDM for its better performance.

II. Review of Related Research

There are several papers reporting the advantages of DWT over FFT for orthogonal modulation. Wornell and Oppenheim outlined the design of the transmitter and receiver for wavelet modulation (WM) [30]. They proved that the estimate of the received bit becomes more accurate as the number of noisy observations is increased. Haixia Zhag et al. based on tharfeeir work titled research of discrete Fourier transform based OFDM (DFT-OFDM) and discrete wavelet transform based OFDM (DWT-OFDM)on different Transmission Scenarios concluded that DWT-OFDM performs much better than DFT-OFDM .But they observed an error floor in DWT- OFDM systems [2]. They suggested that it may be resulted from the Haar wavelet base, since different wavelet base is of different characteristics.

Some other wavelet bases are expected to be employed to improve performance of DWT- OFDM [2]. Akansu et al. [24] emphasized the relation between filter banks and transmultipxer theory and predicted that wavelet packet based modulation has a role to play in future communication systems. Dereje Hailemariam [3] investigated the performance of MultiCarrier-CDMA in the three transmission scenarios and in his direction to the future work he predicts that designing of wavelet filters which are better suited to OFDM left as an area to be explored. Yesuf Shiferaw [32] showed that Daubechies wavelet family can be a viable alternative suitable basis for future OFDM communication scheme. It reduced the probability of bit error rates, providing better performance gains. Mohammed Aboud kadhim and Widad Ismail [33] proved that proposed DWT-OFDM design achieved much lower bit error rates and better performance than FFT-OFDM. The proposed system obtains higher spectral efficiency, therefore this structure can be considered an alternative to the conventional OFDM, and can be used at high transmission rates with better performance. Mohamed H. M. Nerma et al. [34]

Dual–Tree Complex Wavelet Transform (DT-CWT) is used to replace the fast Fourier transform (FFT) in the conventional OFDM and also to the wavelet packet modulation (WPM) based OFDM system. With considerable improvement in terms of bit error rate (BER) and achieves better peak–to–average power ratio (PAPR) performance at acceptable increase in computational complexity. Most of the work reported in literature is based on software simulations carried out. However, for practical implementation of DWT based OFDM, the major bottleneck is the hardware efficient architecture for DWT and IDWT. In this paper, we propose a modified DWT/IDWT architecture that reduces the computation complexity and improves throughput and latency is designed and implemented on FPGA. Section III provides a brief introduction to Wavelet Transforms, Section IV discusses lifting scheme based DWT architecture, section V discusses modified lifting based DWT. Results and discussion is presented in section V and conclusion in section VI.

III. Discrete Wavelet Transform

Discrete Wavelet Transform (DWT) wavelets are better localized in both time and frequency with desirable characteristics. DWT possess the property of orthogonality across scale and translation. The discrete wavelet transform (DWT) provides a means of decomposing sequences of real numbers in a basis of compactly supported orthonormal sequences each of which is related by being a scaled and shifted version of a single function. The DWT of a signal $x(t)$ is the set of coefficients $X\,(m,\ k)$ *DWT* for m and k obtained as the inner product of the signal $x(t)$ and the wavelet function, $\boldsymbol{\Psi}_{m,k}$. The discrete wavelet and inverse discrete representation of a signal $x(t)$ is given by (3.1) and (3.2) respectively

$$X_{DWT}{}_{k}^{m} = \int_{-\infty}^{\infty} x(t) 2^{\frac{m}{2}} \psi(2^m t\text{-}k)dt \qquad (3.1)$$

$$X_{IDWT}(t) = \sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} X_k^m 2^{\frac{m}{2}} \psi(2^m t\text{-}k)dt \qquad (3.2)$$

Where is $\boldsymbol{\Psi}_{m,k}$ the wavelet function [30]. Mallat's fast wavelet transform (FWT) provides a computationally efficient, practical, discrete time *algorithm* for computing the DWT.

IV. Properties of Wavelets

The most important properties of wavelets are the *admissibility* and the *regularity* conditions and these are the properties which gave wavelets their name.

a) Admissibility

The square integral function $\Upsilon(t)$ satisfying the *admissibility condition*,

$$\int \frac{|\psi(\omega)|^2}{|\omega|} d\omega < +\infty \qquad (3.3)$$

Can be used to first analyze and then reconstruct the signal without loss of information. In the above equation $\Upsilon(w)$ is the Fourier Transform of $\Upsilon(t)$. The admissibility condition implies that the Fourier Transform of $\Upsilon(t)$ vanishes at zero frequency, i.e.

$$\int \frac{|\psi(\omega)|^2}{|\omega|} d\omega < +\infty \qquad (3.4)$$

This means that wavelets must have a band-pass like spectrum. A zero at the zero frequency also means that the average value of the wavelet in time domain must be zero,

$$|\psi(\varpi)|^2|_{w=0} = 0 \qquad (3.5)$$

Therefore it must be oscillatory. That is $\Upsilon(t)$ must be a wave.

b) Regularity

As can be seen from equation below

$$X_{CWT}(s,\tau) = \int x(t)\, \psi_{s,\tau}(t) dt \qquad (3.6)$$

The wavelet transform of a one-dimensional function is two-dimensional. The time-bandwidth product of the wavelet transform is the square of the input signal and for most practical applications this is not a desirable property. Therefore one imposes some additional conditions on the wavelet functions in order to make the wavelet transform decrease quickly with decreasing scale **s**. These are the ***regularity*** conditions and they state that the wavelet function should have some smoothness and concentration in both time and frequency domains. Regularity is a quite complex concept and we will try to explain it a little using the concept of vanishing moments (approximation order).

c) Vanishing moments

If we expand the wavelet transform (2.1) into the Taylor series at t=0 until order n (let τ =0 for simplicity) we get

$$X(s,o) = \frac{1}{\sqrt{s}}[\sum_{p=0}^{N} x^{(p)}\ (0)\frac{t^p}{p!}\psi(\frac{t}{s})dt + R(n+1)] \quad (3.7)$$

Here $x^{(p)}$ stands for the p^{th} derivative of x and $R(n+1)$ means the rest of the expression. Now if we define the moments of the wavelet by

$$N_p = \int t^p\ \psi(t)dt \quad (3.8)$$

Then we can write the equation (2.49) into the finite development

$$X(s,0) = \frac{1}{\sqrt{s}}[x(0)N_0 s + \frac{x^{(1)}(0)}{1!}N_1 s^2 + \cdots \frac{x^{(n)}(0)}{n!}N_n s^{n+1} + R(s^{n+2}) \quad (3.9)$$

From the admissibility condition we already have that the 0th moment $N0 = 0$ so that the first term in the right hand side of (2.50) is zero. If we now manage to make the other moments up zero, then the wavelet transform coefficients $x(s,t)$ will decay as fast as s^{n+2} for a smooth signal $x(t)$. This is known in as the vanishing moments or approximation order. If a wavelet has N vanishing moments, then the approximation order of the wavelet transform is also *N*. With increasing number of vanishing moments the wavelet becomes smoother or more regular. Summarizing, the ***admissibility*** condition gave us the wave, ***regularity*** and *vanishing moments* gave us the fast decay or the let, and put together they give us the wavelet.

V. Software Reference Model

In order to compare the performances of OFDM model using DWT, in this work Simulink model is developed to compute BER performances of FFT OFDM with DWT OFDM. A sinusoidal signal of 10-100 MHz frequency is preprocessed and is symbol mapped. The symbol mapped data is modulated using IFFT as well as IDWT and the modulated data is transmitted through a noisy channel. A gain factor is used to improve the transmission gain at the transmitter. The received data is demodulated and BER computation is carried out. Table 1 shows the software simulation results of BER values for FFT-OFDM and DWT-OFDM using different modulations. From the results obtained it is found that DWT based OFDM achieves better BER for most of the modulation schemes.

Modulation schemes	FFT-OFDM	DWT-OFDM
16-QAM	0.9688	0.9196
32-QAM	0.9031	0.8703
64-QAM	0.9987	0.8547
128-AM	1	0.8704
512-AM	0.7071	0.6911
64-PSK	0.9774	0.8889
128-PSK	0.9921	0.8897

Table 1 : BER comparison of OFDM schemes (FFT vs. DWT)

The BER for FFT based OFDM and DWT based OFDM are almost closer thus it would be very difficult to conclude the performances. Thus in order to estimate the performances, the channel noise and gain factor were varied to the worst cases to prove the performances of DWT to be better than FFT. In FFT the basis function is complex sine wave, in DWT there are multiple basis functions. Thus in order to identify a suitable wavelet, an experimental setup is developed to compare the performances of various wavelet functions in OFDM. We limit our performance analysis to wavelet OFDM based on widely used wavelet families such as Haar, Daubechies, Symlets, Coiflets Meyer& biorthogonal. The primary wavelet family we have been focusing is the one that satisfies the characteristics which are demanded features for representing the signal in wireless transmission over fading channels as in the table 2. Daubechies, the asymmetric wavelet family satisfies these characteristics which are demanded feature for representing the signal in communication.

Wavelets	AWGN	Rayleigh Fading	Rician Fading
Haar	0.9762	0.991 6	0.9754
Daubechies	0.9773	0.990 0	0.9858
Symlets	0.9773	0.990 0	0.9858
Coiflets	0.9767	0.997 7	0.9855
Biorthogonal	0.9762	0.991 6	0.9754
Discrete Meyer	0.9765	0.986 6	0.9823

Table 2 : BER values for DWT-OFDM in Different channels using 64-QAM

Table2. BER Comparisons between AWGN channel and Rayleigh Fading Channel using 64-QAM the results obtained, it is found that Haar wavelet

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achieves better BER compared with other techniques. Hardware implementation of Haar is complex and thus biorthogonal filter is adopted for hardware implementation as it achieves BER closer to haar. In the next section, a detailed discussion on design and implementation of 9/7 wavelet filter for OFDM is presented.

VI. Dwt Based Ofdm System

Figure 1 shows the block diagram of a typical OFDM transceiver. The digital data is to be transmitted by the transmitter section. Then it is applied into a mapping of subcarrier amplitude and phase. Then by using an Inverse Fast Fourier Transform (IFFT) it transforms this spectral representation of the data into the time domain.

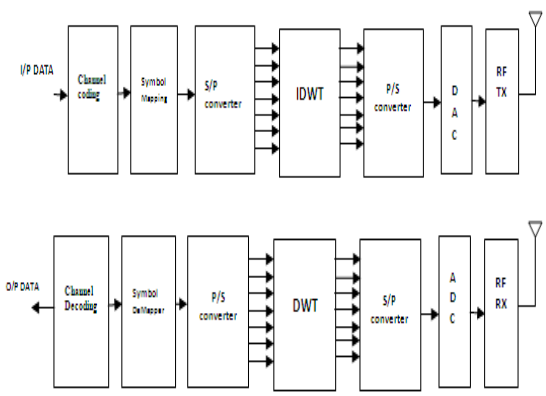

Figure 1 : Complete OFDM system

To modulate the data bits on the sub carriers, different modulation techniques are used. The N sub blocks are created by dividing the stream of bits. By using constellation modulator such as QPSK and QAM the n sub blocks are mapped. Depends on the quality of communication channel the modulators are selected. The calculated time domain signal is mixed up to the required frequency to transmit the OFDM signal.

The reverse operation of the transmitter is performed by the receiver section. The Conversion of RF signal to base band is done by using the mixing process. To analyze the signal in the frequency domain Fast Fourier Transform (FFT) is used.

Transmitted data is typically in the form of a serial data stream. In OFDM, each symbol typically transmits 40 - 4000 bits, and so a serial to parallel conversion stage is needed to convert the input serial bit stream to the data to be transmitted in each OFDM symbol. The parallel to serial converter is the reverse process. Robustness against multi path delay is one of the most important properties of OFDM.

The accomplishment is done by adding the guard period between transmitted symbols. The most successful guard period is a “cyclic prefix”, which is appended at the front of every OFDM symbol. To eliminate the inter symbol interference (ISI) completely; the guard time is needed for each OFDM symbol. The chosen guard time is to be larger than the estimated delay spread, such that the multipath components from one symbol do not interfere with next symbol. A copy of the last part of the OFDM symbol is cyclic prefix, and is of equal or greater length than the maximum delay spread of the channel.

VII. Improved Dwt Architecture

Daubechies (9,7) wavelet filter with N=2 is used for architecture development. Lifting scheme is used for the development of architecture. Here N=2 means, we will be having two stages of lifting scheme i.e predict1, update1 and in second stage predict2, update2.

VIII. Lifting Based Dwt Architecture

The convolution-based 1-D DWT requires both a large number of arithmetic computations and a large memory for storage. Such features are not desirable for either high speed or low-power applications. Recently, a new mathematical formulation for wavelet transformation has been proposed by Swelden as a light-weighted computation method for performing wavelet transform. The main feature of the lifting-based wavelet transform is to break-up the high pass and the low pass wavelet filters into a sequence of smaller filters. The lifting scheme requires fewer computations compared to the convolution based DWT. Therefore the computational complexity is reduced to almost a half of those needed with a convolution approach. The lifting-based wavelet transform basically consists of three steps, which are called split, lifting, and scaling, respectively, as shown in Figure 2

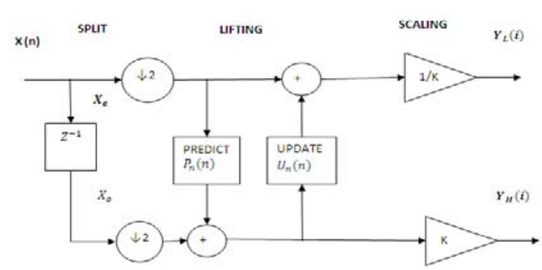

Figure 2 : The lifting scheme implementation of 1D-DWT [11]

The basic idea of lifting scheme is first to compute a trivial wavelet (or lazy wavelet transform) by splitting the original 1-D signal into odd and even indexed sub sequences, and then modifying these values using alternating prediction and updating steps. The lifting scheme algorithm can be described as follow:

1. **Split step:** The original signal, *X(n)*, is split into odd and even samples (lazy wavelet transform).

2. Lifting step: This step is executed as N sub-steps (depending on the type of the filter), where the odd and even samples are filtered by the prediction and update filters, *Pn(n)* and *Un(n)*.

3. Normalization or Scaling step: After N lifting steps, a scaling coefficients K and 1/K are applied respectively to the odd and even samples in order to obtain the low pass band (YL(i)), and the high-pass sub-band (YH(i)). Fig. 4.2 illustrates how the lifting scheme can be implemented using these steps. The diagram shows the lifting scheme for Daubechies (9, 7) biorthogonal filter.

The lifting scheme algorithm to the (9,7) filter is applied as:

a) Split step

Xe ← X(2i) *Even Samples* ....equation 4.1.1

Xo ← X(2i+1) *Odd Samples* ....equation 4.1.2

b) Lifting Steps

For (9, 7) filter, N=2

Predict P1: D(i) = Xo(i) + a [Xe(i) + Xe(i+1)] ....equation 4.1.3

Update U1: S(i) = Xe(i) + b [D(i-1) + D(i)] ....equation 4.1.4

Predict P2: Y_H(i) = D(i) + c [S(i) + S(i+1)] ....equation 4.1.5

Update U2: Y_L(i) = S(i) + d [Y_H(i-1) + Y_H(i)] ....equation 4.1.6

c) Scaling Step

YH(i) = K Y_H(i) ....equation 4.1.7

YL(i) = 1/K Y_L(i) ....equation 4.1.8

where a=-1.586134342, b=-0.0529801185, c=0.882911076, d=-0.443506852, and K=1.1496043 98. These fractional values are multiplied by a factor of 128 to convert them to decimal values.

Stage1: In this stage even and odd bits are considered accordingly and equation 4.1.3 is computed to get predict1 output D[i].

Stage 2: The predict1 output (D[i]) along with even position of initial inputs are taken to compute equation 4.1.4, which results in update1 output S[i].

Stage 3: Predict1 (D[i]) and Update1(S[i]) outputs are taken to compute equation 4.1.5, which results in Predict2 output Y_H[i].

Stage 4: Predict2 (Y_H[i]) and Update1 (S[i]) outputs are taken to compute equation 4.1.6, which results in Update2 output Y_L[i].

Just reverse operation of this with corresponding sign change is carried out to to compute IDWT.

IX. Modified Dwt for Ofdm

From the lifting scheme equation presented in the previous section, it is found that the final scaling and dilation coefficients are interdependent on predict and update outputs, thus there is s a delay and also affects throughput. In order to improve the latency and throughput of DWT computation it is required to minimize the interdependence of partial outputs of lifting scheme, thus a modified lifting scheme is derived. The modified equations for a_i and d_i can be obtained by substituting eqn. (4.1.1)-(4.1.6) in (4.1.7) and (4.1.8). The lifting coefficients were substituted and the results were scaled by multiplying with 256 to avoid decimal and to round off the values. The modified lifting scheme equation is as follows:

The approximation coefficient is:

a_i= 294*(8(6*x_{2i}+4*x_{2i-2}+x_{2i+4}+x_{2i+4}+x_{2i-4}+4*x_{2i+2}) -

5*(3*x_{2i+1}+x_{2i+3}+x_{2i3}+3*x_{2i-1})+

100*(2*x_{2i}+x_{2i+2}+x_{2i+2})-

180*(2*x_{2i}+x_{2i+2}+x_{2i+2})+

113*(x_{2i+1}+x_{2i+1}) +

21*(2*x_{2i}+x_{2i+2}+x_{2i+2}) -

13*(x_{2i+1})+x_{2i}+x_{2i-1}). ------------- eqn 4.1.9

The detail coefficient is:

d_i=19*(3*x_{2i}+3*x_{2i+2}+x_{2i+4}+x_{2i-2})+

(-12)*(2*x_{2i+1}+x_{2i-1}+x_{2i+3}) +

226*(x_{2i}+x_{2i+2}) –

406*(x_{2i}+x_{2i+2}) +x_{2i+1} --------------------eqn 4.1.10

By substituting i=2 for the above equations we get,

a2=294*(8*((6* x4)+(4* 2)+(2*x8)+x0+(4*x6)) –

5*((3*x5)+(2*x7)+(3*x4))+

100*((2*x4)+(2*x6)) –

180*((2*x4)+(2*x6))+

(226*x5)+42*(x4+x6)-

(13*x5)+x4+x3)---------- eqn 4.1.11

d2= 19*((3*x4)+(3*x6)+x8+x6) –

12*((2*x5)+x3+x7) +

226*(x4+x6) -406*(x4+x6)+x5-------eqn 4.1.12

The modified lifting scheme equations are realized using multipliers, adders and intermediate registers. Wallace tree multiplier is chosen for faster multiplication operation. Carry save adder is adopted for addition operation as it uses minimum gates and also has very less delay compared with ripple carry adder. The input samples are loaded into the input data register, after every 9 clock cycles the multiplication and addition operations are performed. Computation of ai and di coefficients requires 4 clock cycles. Thus the latency of the proposed architecture is 13 clock cycles (9 + 4), and the throughput is 5 clock cycles. The modified lifting based DWT architecture is faster than generic DWT architecture by 4 clock cycles.

The equation shown above for i=2, computation of ai and di requires input samples x8 to x0, thus a serial in parallel out 8-bit shift register is used to load the input data after 9 clock cycles, the input samples are multiplied by the coefficients and wavelet coefficients are computed. Thus the modified architecture shown in the figure above has a initial latency of 9 clock cycles and throughput of 0.5. By interchanging the coefficients of low pass and high pass, IDWT can be computed.

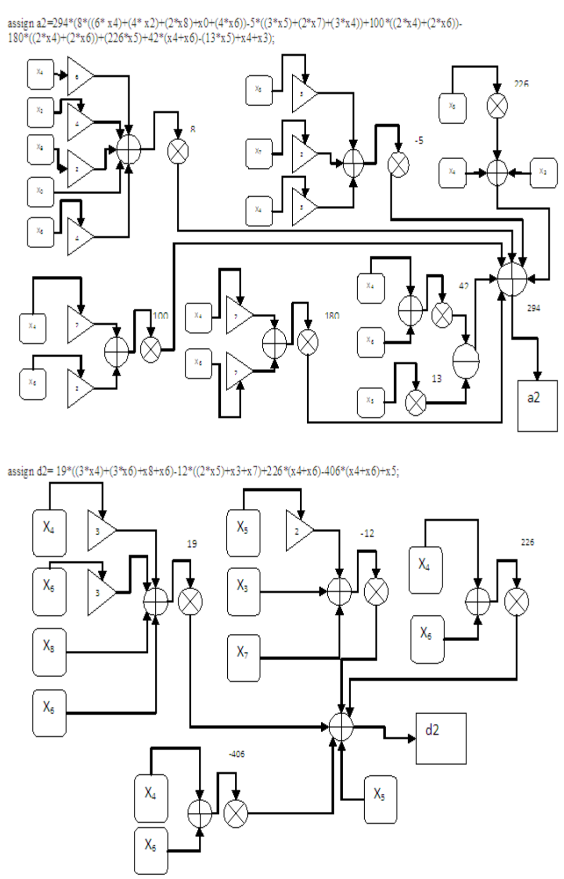

Figure 3 : Modified architecture for Lifting Discrete Wavelet Transform

Thus the proposed architecture is better in terms of latency and throughput when compared with generic lifting scheme architecture. The modified lifting scheme is model using HDL and is functionally verified using ModelSim. The functionally correct HDL model is synthesized using Xilinx ISE targeting Virtex-5. For OFDM, the QAM modulated output is stored in intermediate memory and the samples are sequentially read and modulated using IDWT, the modulated data is stored in output memory. At the receiver, the data stored in memory is further processed using DWT, and is demodulated using QAM demodulator.

X. FPGA Implementation of DWT for OFDM

Synthesis is the transformation of design from higher level of abstraction to lower level of abstraction .The DWT design using Lifting Scheme is carried out on Virtex5 FPGA development kit. In our implementation, Xilinx Virtex5 using device xc2vp30-7-ff896 with 1000K gate count FPGA is used. It has total 10K numbers of configurable logic blocks (CLBs) arranged in 32 X 28 matrix fashion. Each CLB has four slices and two of them are named as SLICEM and rest two as SLICEL. Each SLICEM can be used as 16 bit (embedded)shifregister(SRL16).i.e

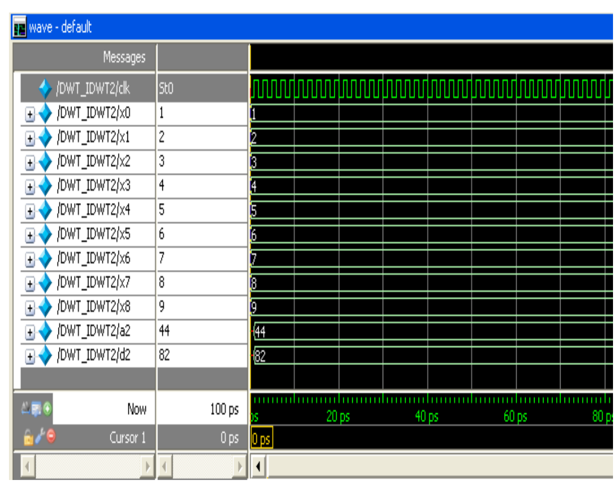

Figure 4 : Post Place and Route Simulation

It is seen in figure 4 that the pre-simulation and post place and route simulation results match, thereby proving that the design is perfectly mapped onto FPGA meeting the required design specifications.

a) Synthesis on Virtex5

The design summary is shown below highlighting the major device utilization in terms of LUT's and slices. Device utilization summary:

Selected Device : 2vp30ff896-7

- Number of Slices: 114 out of 13696 0%
- Number of 4 input LUTs:220 out of 27392 0%

- Number of IOs: 89
- Number of bonded IOBs: 73 out of 556 13%
- IOB Flip Flops: 8
- Number of MULT18X18s: 12 out of 136 8%
- Number of GCLKs: 1 out of 16 6%
- Total CPU time to Xst completion: 31.44secs
- Total delay:3.459ns
- Total estimated power consumption 28mW

b) RTL Schematic of the design

Figure 6 below shows the RTL schematic of the proposed design with interconnects between the various blocks. It is a technology independent schematic.

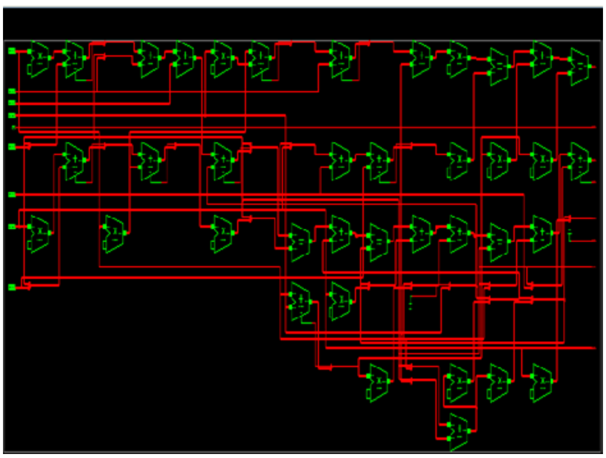

Figure 5 : RTL Schematic

c) HDL Co-Simulation

The HDL co simulation of the design is performed using matlab simulation which is shown in Figure 6 below.

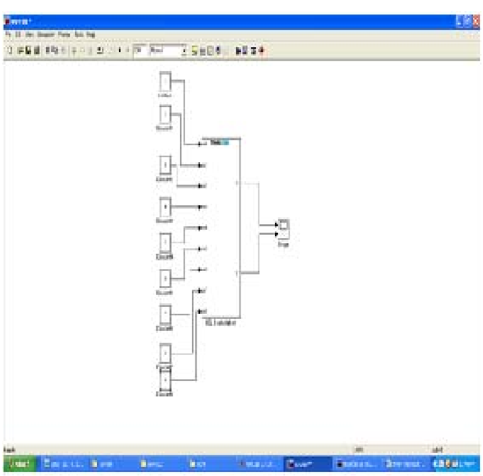

Figure 6 : HDL Co-Simulation

XI. Conclusion

DWT based OFDM is finding importance due to its performance in terms of ISI and bandwidth compatibility over FFT based OFDM. The DWT-OFDM outperformed FFT-OFDM by approximately 6dB gain in BER, Haar wavelet showed best performance over Biorthogonal (bior3.3, bior5.5), Daubechies (db2,db4), reverse biorthogonal (rbior3.3, rbior5.5) by approximately 2dB. However, computation complexity of DWT restricts use of DWT for OFDM due to its hardware requirements on VLSI platform. In this work, lifting based DWT is modified and a new architecture is derived that can compute DWT in less than 3.429ns, and consumes power of less than 28 mW. The modified DWT is realized on Virtex II FPGA and occupies resources less than 114 slices. Thus the proposed DWT architecture is suitable for OFDM application. The performance of DWT architecture can be further enhanced by introducing parallel processing and pipelining schemes to improve throughput and latency.

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