

Lifting-based Discrete Wavelet Transform for Real-Time Signal Detection

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Abstract

Background: Discrete Wavelet Transform (DWT) is extensively useful in different Digital Signal Processing (DSP) applications. In this paper, Lifting scheme is introduced in three mother wavelets, which are Haar wavelet, Daubechies (db4) and Cohen-Daubechies-Feauveau (CDF) 9/7-tap wavelet also known as db9/7 wavelet. **Method:** In this work each of the architecture is compared with its Direct form. Haar wavelet is used to design the basic DWT architecture. Daubechies DWT (db4) orthogonal filters and Cohen-Daubechies-Feauveau (CDF) 9/7 bi-orthogonal wavelet filters are considered for DWT construction. Due to the uncomplicated design, lifting scheme provides less power consumption. Instead of set of filters, simple predict and update mechanism is introduced. The IEEE 754 floating point standard is used to represent the filter coefficients. The architectures are described in Verilog HDL and simulation is performed in Xilinx for FPGA implementation. All the architectures are synthesized in Cadence RC for 180 nm technology. **Findings:** The Lifting Scheme has 75-82% less power consumption and 27% area-efficiency than conventional DWT architectures. FPGA implementation is done using Altera Cyclone IV FPGA kit. Maximum operating frequency is 33.3MHz and 45MHz for 3-level and 1-level of decomposition respectively in DWT implementation. **Conclusion:** Due to the uncomplicated design, lifting scheme provides less power consumption. DWT designs are compared with respect to power consumption and area.

Keywords: Cohen-Daubechies-Feauveau (CDF) 9/7 wavelet, Daubechies Wavelet (db4), Discrete Wavelet Transform (DWT), Lifting Scheme

1. Introduction

Wavelet Transform is one of the proposed solutions while working on non-stationary signals. Wavelet Transform is widely used in signal analysis, denoising and compression for its excellent locality in time-frequency domain. Discrete Wavelet Transform (DWT) was first defined by Mallat¹. It performs a multi-resolution signal analysis, in which locality is adjustable in both time and frequency domains. Correlation between local maxima of high frequency components are extracted from multi-scale wavelet decomposition of the signal. DWT can be designed by different choice of wavelet families² and basis functions. Traditional DWT comprises of decomposition of Finite Impulse Response (FIR) filters and sub sampling them. Because of the large computations required in the

traditional DWT method, many techniques are proposed to design a rapid and low-power DWT³⁻⁵.

In 1996, Sweldens defined a new approach to design wavelet transform which is called Lifting Scheme⁶. Lifting scheme⁷⁻¹⁰ is based on the spatial interpretation of the wavelet transform. It can be easily designed in hardware because of the reduced computations. In lifting scheme, a new wavelet is derived from the mother wavelets based on the domain features.

Odd samples are derived from the even samples and filters are replaced with simple prediction and update blocks. The Inverse Discrete Wavelet Transform (IDWT) can be designed in a similar way. It does not require complex mathematical calculations that are required in traditional methods. It requires half number of computations as compare to traditional convolution based discrete

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wavelet transform. The lifting scheme allows a fully in-place calculation of the wavelet transform¹¹. In other words, no auxiliary memory is needed and the original signal can be replaced with its wavelet transform.

There are numerous mother wavelets that can be used for DWT. The mother wavelet defines the characteristics of the resulting transform. As a result, details of a particular application should be taken into consideration while selecting the mother wavelet. Haar wavelet is the simplest and Daubechies wavelet^{12,13} is the most popular in the wavelet family. Daubechies wavelet transform was implemented by Huang et al.¹⁴ for power system disturbances. The wavelets are selected according to their shapes and their capacity to analyze the signal for the given application. Pipelining in Lifting scheme was introduced¹⁵, which provides less power consumption but affects the clock frequency.

This paper is organized as follows. In Section 2, different structures of DWT are discussed. Section 3 presents Lifting Scheme for DWT. Section 4 provides Information about Daubechies Wavelet Transform. Proposed architecture in which Lifting Scheme applied in Daubechies (db4 and db9/7) transform is discussed in Section 5. Performance and results are discussed in Section 6. Conclusion is given in Section 7.

2. Discrete Wavelet Transform (DWT)

The Discrete Wavelet Transform (DWT) is designed by successive low-pass and high-pass filtering of the discrete time-domain signal shown in Figure 1. It is called as the Mallat algorithm or Mallat-tree decomposition. In the figure, the sequence $x[n]$ denotes input signal, where n is an integer. The low pass filter is given by G_o , while the high pass filter is given by H_o . At each decomposition level, the low pass filter produces coarse approximations $a[n]$, while the high pass filter produces detail information $d[n]$ of the signal. The filter banks used in Forward Wavelet Transform

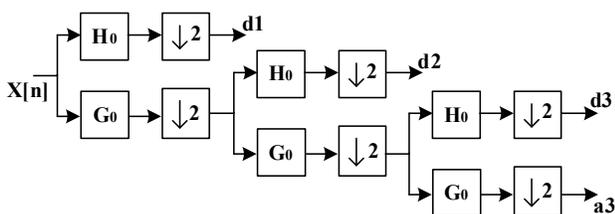


Figure 1. 3-level decomposition DWT.

is called analysis filters and the filter banks used in Inverse Wavelet Transform is called synthesis filters.

There are various architectures for implementing a filter bank i.e. Direct form, Polyphase, Lattice structure and Lifting Scheme. A filter bank basically consists of a low pass filter and a high pass filter followed by decimators or expanders and delay elements.

2.1 Direct Form Structure

The Direct form analysis filters has set of low pass and high pass filters followed by decimators. The inverse synthesis filter contains up-samplers followed by the low pass and high pass filters as shown in Figure 2.

3. Lifting Scheme for DWT

Lifting scheme is a very effective way to design a DWT. Complex multiplier and accumulator units used in FIR filters shown in Figure 2 are designed using simple prediction technique. It consists of three steps: Split, Predict and Update. The Lifting scheme is shown in Figure 3.

3.1 Split

In this step, the input is divided into odd ($\gamma[k]$, and even ($\lambda[k]$, samples.

$$f[k] = \begin{cases} \lambda[k] = f[2k] \\ \gamma[k] = [2k + 1] \end{cases} \quad (1)$$

3.2 Predict

The predict step uses a function that approximates the odd samples. It is also called dual lifting. It gives the

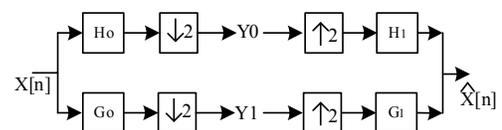


Figure 2. Analysis and synthesis filter banks for DWT.

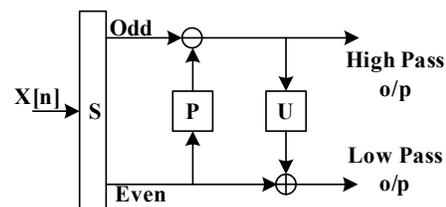


Figure 3. Lifting scheme for DWT.

interpolation on even samples. The differences between the approximation and the actual values replace the odd samples of the data set. It provides high pass filtered component. The odd value is “predicted” from the even value, which is described by the Equation 2 given below.

$$\gamma[k] = \lambda[k] - P(\lambda[k]) \tag{2}$$

3.3 Update

In the update step, scaling is done to smooth the data and then added with even samples to provide low pass filtered values for the DWT. It is also called primal lifting. This results in a smoother input for the next step of the wavelet transform shown in Equation 3.

$$\lambda[k] = \lambda[k] - U(\gamma[k]) \tag{3}$$

4. Daubechies Wavelet Transform

While using wavelet transform, it is imperative to choose a suitable wavelet family. Ingrid Daubechies was the first to introduce the Daubechies wavelet filters¹³. It is the most popular wavelet family because of their desirable characteristics. The frequency response of the filters gives maximum flatness at 0 and π , they are also called Maxflat filters. The method involves convolution of input signal and filter coefficients. If N input samples are given, the result is given by N/2 approximate values and N/2 detail values.

4.1 Daubechies (db4) Wavelet Filter

This filter is widely used due to its orthogonal properties. It is also easy to implement as it is a short filter. They gives perfect reconstruction properties. Daubechies wavelets are not comprised by a single mathematical equation but it is given by set of filter coefficients. The filter coefficients are shown in Table 1.

4.2 Daubechies (db9/7) Wavelet Filter

The Cohen-Daubechies-Feauveau (CDF) 9/7-tap bi-orthogonal filter are also called Daubechies (db9/7)

Table 1. Filter coefficients for Daubechies (DB4) WT

Tap	Low Pass Filter	High Pass Filter
0	0.4829629	0.1294095
1	0.8365163	0.2241439
2	0.2241439	-0.8365163
3	-0.1294095	0.4829629

Wavelet Filters. They have symmetric scaling and wavelet functions. Because of these properties, they are very popular for image compression applications. FBI Fingerprint Compression Standard uses the Daubechies 9/7 filters and it is the default filter for compression in the JPEG 2000 standard. The filter coefficients are shown in Table 2.

5. Proposed Lifting Scheme for Daubechies (db4 and db9/7) WT

In the proposed technique, lifting scheme is exercised on two types of wavelets: Daubechies db4 and db9/7.

5.1 Lifting Scheme on Daubechies (db4) WT

The lifting scheme for Daubechies (db4) have of four-step operations: update1, predict1, update2 and normalization. The lifting scheme is memory efficient and does not require a temporary storage as the general Daubechies db4 does. As shown in Figure 4, the split operation separates input signal into even ($\lambda[n]$) and odd ($\gamma[n]$) samples. All the operations are given in Equations 4–8. Normalization is done at the end.

$$\text{Update1: } \lambda[n] = \lambda[n] + 1.732 * \gamma[n] \tag{4}$$

$$\text{Predict1: } \gamma[n] = \gamma[n] - 0.433 * \lambda[n] + 0.067 * \lambda[n-1] \tag{5}$$

$$\text{Update2: } \lambda[n] = \lambda[n] - \gamma[n+1] \tag{6}$$

$$\text{Normalization1: } \lambda[n] = 0.5176 * \lambda[n] \tag{7}$$

$$\text{Normalization2: } \lambda[n] = 1.9319 * \gamma[n] \tag{8}$$

Table 2. Filter coefficients of Daubechies (Db9/7) WT

Taps	Low Pass Filter	Taps	High Pass Filter
0, 8	0.026748757410	0, 6	0.091271763114
1, 7	-0.016864118442	1, 5	-0.057543526228
2, 6	-0.078223266528	2, 4	-0.591271763114
3, 5	0.266864118442	3	1.111508705245
4	0.602949018326		

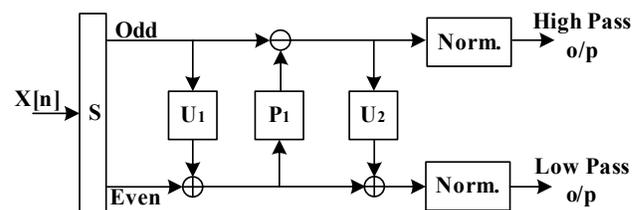


Figure 4. Lifting scheme for Daubechies (db4) DWT.

5.2 Lifting Scheme on Daubechies (db9/7) WT

The lifting scheme for Daubechies (db9/7) have two lifting steps. It contains 5 operations: predict1, update1, predict2, update2 and normalization as shown in Figure 5. As the filter coefficients increase, the lifting steps are more than Daubechies (db4) and so is the complexity. The values of constants are given in Table 3.

$$\text{Predict 1: } I_{2i+1} = X_{j,2i+1} + \alpha (X_{j,2i} + X_{j,2i+2}) \quad (9)$$

$$\text{Update 1: } I_{2i} = X_{j,2i} + \beta (I_{j,2i-1} + I_{j,2i+1}) \quad (10)$$

$$\text{Predict 2: } P_{j-1,i} = I_{2i-1} + \gamma (I_{2i-2} + I_{2i}) \quad (11)$$

$$\text{Update 2: } U_{j-1,i} = I_{2i} + \delta (P_{j-1,i} + P_{j-1,i+1}) \quad (12)$$

$$\text{Normalization 1: } H_{j-1,i} = K * (P_{j-1,i}) \quad (13)$$

$$\text{Normalization 2: } G_{j-1,i} = (1/K) * (U_{j-1,i}) \quad (14)$$

6. Results and Discussion

In this section, power consumption and area requirement results for all DWT architectures are discussed. IEEE 754 floating point half precision standard is used to define the coefficients. The coefficients are represented in 16 bits, in which 1 bit is sign bit, 5 bits contains exponents and 10

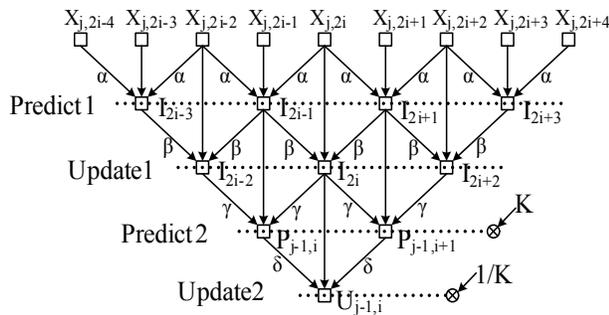


Figure 5. Lifting scheme for Daubechies (db9/7) DWT.

Table 3. Filter coefficients for Daubechies (Db4) WT

Coefficients	Floating Point Value	Coefficients	Floating Point Value
α	-1.586134342	β	-0.052980118
γ	0.882911075	δ	0.443506852
$-K$	-1.230174105	$1/K$	0.812893066

bits are mantissa. All the architectures are synthesized in Cadence RC for 180 nm technology.

In Figure 6 and Figure 7, power dissipation and area requirement are compared for each technique for 1-level of decomposition. Due to the simple addition and multiplications rather than complex design, lifting scheme DWT has advantage over conventional DWT in power consumption and cell area.

In Figure 8 and Figure 9, 3-level of decomposition DWT is compared for power consumption and cell area. Higher level of decomposition has more accurate detail and approximate values as an output from the DWT.

Pipelining is implemented for the coherent working between two DWT decomposition-level blocks. For designing lifting scheme in Daubechies (db9/7) DWT, intermediate pipelining can also be implemented between two lifting steps so that to reduce the power consumption, but it will decrease the maximum operating

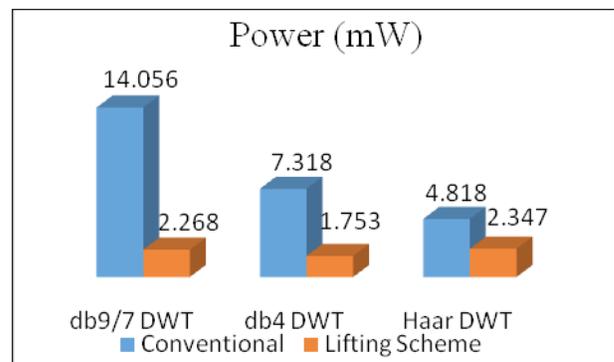


Figure 6. Comparison of power consumption by DWT Architectures for 1-level of Decomposition.

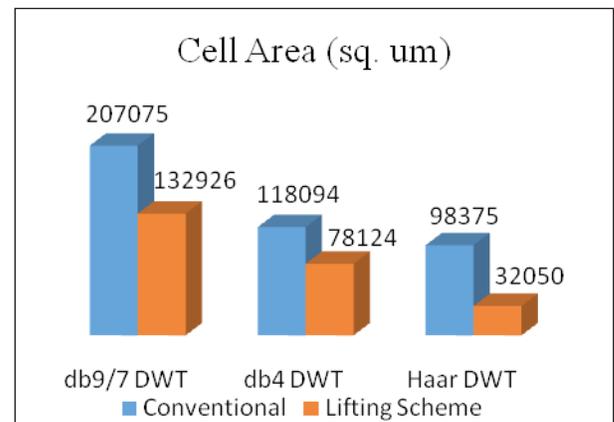


Figure 7. Cell area comparison of DWT Architectures for 1-level of Decomposition.

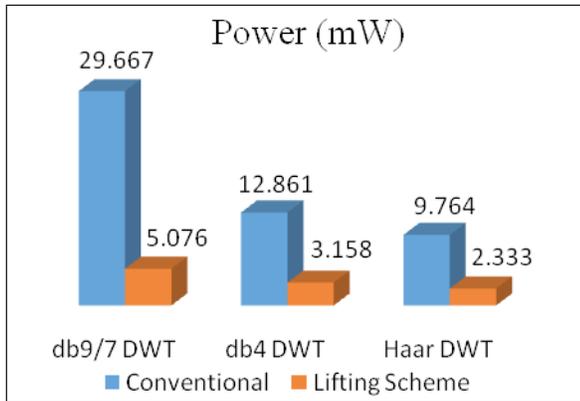


Figure 8. Comparison of power consumption by DWT Architectures for 3-level of Decomposition.

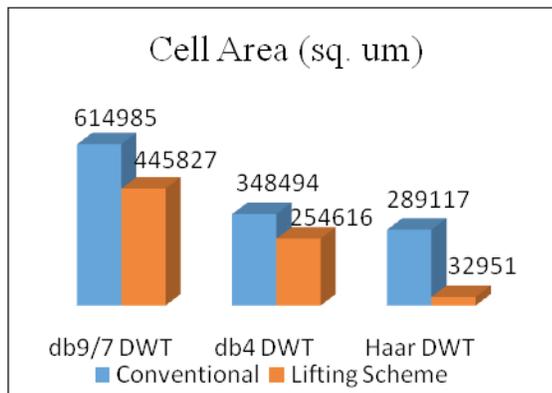


Figure 9. Cell area comparison of DWT Architectures for 3-level of Decomposition.

frequency. All architectures are simulated in ModelSim and synthesized in Cadence RC tool.

FPGA implementation is done on Altera Cyclone IV FPGA kit. Maximum operating frequency is 33.3MHz for 3-level of decomposition DWT while 45MHz is the maximum operating frequency for 1-level of decomposition DWT.

7. Conclusion

Different techniques are discussed for designing Discrete Wavelet Transform (DWT) with low-complexity and low power. Haar wavelet is approached to design the basic DWT architecture. Daubechies DWT (db4) orthogonal filters and Cohen-Daubechies-Feauveau (CDF) 9/7 bi-orthogonal wavelet filters are considered for DWT construction. Lifting Scheme is introduced in DWT to decrease the complexity of the design. All DWT

architectures are designed using lifting scheme. Due to the uncomplicated design, lifting scheme provides less power consumption. DWT designs are compared with respect to power consumption and area.

As shown in Figures 6 and 8, Power consumption is drastically reduced to 75% to 82% by introducing lifting scheme in various DWT families. As shown in Figures 7 and 9, area requirement is reduced by 27% approximately.

8. References

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