HARDWARE IMPLEMENTATION OF SATELLITE IMAGE COMPRESSION FILTER USING LIFTING BASED5/3 WAVELETS

[1]SENDAMARAI P., [2]DR GIRIPRASAD M.N.,

[1]Assistant Professor Nagarjuna College of Engineering and Technology, xxx, YYY

[2]Professor & HOD ECE JNTU

E-mail: [1]sendamarai17@gmail.com, [2]mahendragiri1960@gmail.com

ABSTRACT

Most of the satellite missions are of the remote sensing type used to image the places of interest on the Earth. With improving technology, the imaging payloads are become complex and as a result the data generated by these payloads is increasing exponentially. With limited on board resources and capabilities, it is important to process the data on board and compression of payload data is one of the important and crucial requirements. Lossless data compression is required as the raw data is of extreme importance and any loss of information cannot be afforded. This work presents a Le Gall 5/3 Wavelet based image compression implementation using Lifting technique in an FPGA for onboard payload data compression. The compression core achieves an operating frequency of 251MHz with a power consumption of 384mW. The image compression performance metrics are also evaluated and a PSNR of 29dB and compression ratio of 2.2 is achieved.

Keywords: *Remote Sensing, image compression, Le Gall 5/3, lifting, PSNR*

1.   INTRODUCTION

Remote sensing is an important application of the satellite missions. The earth observation missions are increasing in complexity with the improving payloads used for imaging. The earth observation has seen dramatic changes from panchromatic images to multispectral to hyperspectral imaging over the past several years. The increasing complexity of payloads and improvements in the spatial resolution of the payloads, the volumes of payload data generated by these missions is also increasing. An appreciation of the fact can be obtained from the   TOPSAT mission which provides PAN images at 2.5m GSD with 8000 pixels and MS images in three bands each at 5m GSD with around 2100 pixels. Each square PAN image and a square MS image acquisition generates 600Mbits of data and the satellite downlink is having a data rate of 11Mbps [Laycock et al. 2004]-[Cawley 2005] .

Most of the remote sensing missions are in the Low Earth Orbit and   operate on a store and forward paradigm. As the   LEO satellite has limited ground station availabil- ity, the payload data needs to be stored on board and   then transmitted at a later stage. The increased volumes of data hence puts stringent demands on the   on board data storage and data transmission link to the ground. Due to constraints on the downlink bandwidth and satellite visibility period, it may need more than one satellite pass for complete data transmission [Dawood et al. 2001]. With limited on board storage and limited data transmission rates, it is imperative that the on board raw payload data be suitably compressed, stored and then transmitted to the ground.

Image compression compensates for the limited storage memory and   limited down- link bandwidth. Hence, data compression is becoming an integral part of payload data processing unit of any satellite. French Space Agency CNES has done an exclusive survey on the on board compression systems   [Lambert-Nebout and Moury 1999]. An- other limitation of an onboard system is the limited computing hardware as the space grade processors have limited computation capacity. This puts a serious limitation on the complexity of any   algorithm that can be implemented in on-board system. Most of the computing hardware is dedicated to the critical spacecraft operations like com- munications and control. Reconfigurable logic devices like CPLDs

and FPGAs combine the flexibility of the software with the performance of hardware [Vestrum 2000]. Small satellite development is further enabled by the development of radiation hardened FPGAs [Dawood and Bergmann 2001], [DeHon 2000].

Image compression algorithms are of two types: lossy and lossless. In a lossless compression, the reconstructed image quality is the sameas the original image without any loss of information. The entropy measured by the lowest compression bit rate per pixel gives a theoretical boundary for lossless compression [Phamdo 2003]. On the other hand reconstruction from alossy compression leads to varying degree of information loss. Compression algorithms take advantage of several types of redundancies present in an imagelike the spatial redundancy, statistical redundancy and humanvision redundancy. Compression is achieved by removing one or all of these redundancies.

Many image compression techniques have been discussedin literature. Based on spatial decorrelation, the compression techniques can be classifiedinto prediction, DCT and DWT-based systems. Prediction based methods are DPCM [Jayant and Noll 1985] and adaptive DPCM. DWT based methods include the JPEG2000 [jpe 2000], SPIHT [Said et al. 1996]. Different DWT based compression systems like H-compress JPEG2000, ICER are used in the Mars exploration rovers. University of Idaho'sCAMBR is developing an ASIC for implementing CCSDS-IDC [Yeh et al. 2005]. An- other mission PLEIADES-HR will be using a DWT transform implemented in an ASIC [Thiebaut and Camarero 2012]. JPEG2000 standard is also used in IMS-1 [Srinivasan and Subramanian 2012]. GEZGIN another DSP card attainshigh throughput and maintains real timeoperation [Yüksel et al. 2005]. It implements the wavelet transform consisting of 5/3 coefficient integer filtering and signal decomposition and entropycoding and formatting.

Discrete wavelet transform have been used inthe image resolution enhancement of satellite images. Demirel et.al [Demirel and Anbarjafari 2011] applied interpolation of high frequency subbands obtained by discrete wavelet transform for image resolution enhancement. Image compression in case of Multispectral satellite images is achieved by removing spectral redundancy in Multispectral images through inter band spectral correlation [Saghri et al. 1995], [Benierbah and Khamadja 2006]. Hyperspectral satellite images require high speed data processing because of higher number of spectral bands [Abousleman et al. 1995].

Comparison of lossless image comparison between traditional and lifting based wavelets is presented by Reddy et al [Reddy and Narayana 2012].

2. DISCRETE WAVELET TRANSFORM

Single stage of image decomposition into low frequency and high frequency components can be implemented using successive row and column transforms. In principle one level of DWT involves high pass and low pass filtering operations on row and column data separately. The filtering operation is followed by downsampling by a factor of 2. The downsampling operation removes the redundant information generated by filtering operation. A typical one level DWT is represented by Fig. 1.
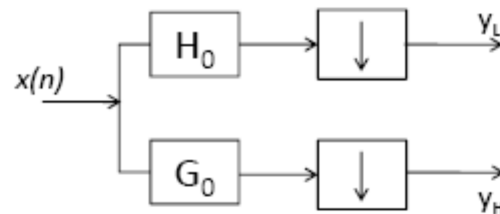

Figure 1.1-D DWT Operation

In a two dimensional DWT, the signal isprocessed separately for rows and columns. The rows and column data represent the two dimensional image data. Representation of the same is shown in Fig 2. A 2-D DWT can be considered as a combination of two1-D DWT in the x, and ydirections. A 2-D DWT processor is designed by building1D DWT modules composed of high-pass and low-pass filters. These filters perform the convolution of filter coefficients and input data stream. After a one-level of 2-D discrete wavelet transform, the volume of image is decomposed into HH (High-High), HL (High-Low), LH (Low-High) and LL (Low-Low) signals as shown in Fig. 2.
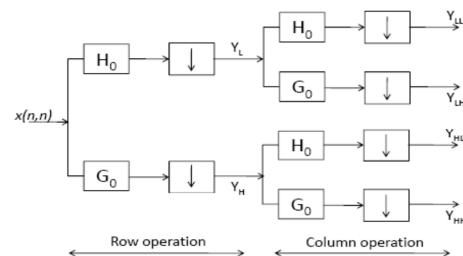

Figure. 2. 2-D DWT Operation

The Le Gall's 5/3 filter is an accepted standard filter for lossless data compression in the JPEG2000 standard and is widely used in image compression applications. Le Gall's 5/3 wavelet filter is from the family of Cohen-Daubechies-Feauveau (CDF) wavelets where a B-spline is used as a primary generator polynomial for the CDFwavelets.All the generators and wavelets in this family are symmetric. For every positiveinteger A there exists a unique polynomial$Q_A(X)$ of degree $A - 1$ satisfying theidentity.

Table 1 CDF Wavelet Construction

Class	A	$Q_A(X)$	$q_{prim}(X)$	$q_{dual}(X)$
LeGall's 5/3	2	1+X	1	1+X
Daubechies 9/7	4	$1 + 2X + 5/2X^2 + 5/2X^3$	1-cX	$1+(c+2)X+ (c^2 + 2c+5/2)X^2$

$$(1 − X/2)A \, QA \, (X) + (X/2)A \, QA \, (2 − X) = 1 \quad (1)$$

This polynomial is used for the construction of CDF wavelets with QA (X) factorizedas

$$QA \, (X) = qprime \, (X)qdual \, (X) \quad (2)$$

Then, Equation 3 forms a biorthogonal pair of scaling sequences.

$$a_{prim}(Z) = 2Z^d \left(\frac{1+Z}{2}\right)^A q_{prim}\left(1 - \frac{Z + 1/Z}{2}\right)$$

$$a_{dual}(Z) = 2Z^d \left(\frac{1+Z}{2}\right)^A q_{dual}\left(1 - \frac{Z+1/Z}{2}\right) \quad (3)$$

Substituting A = 2, gives the Le-Gall's 5/3 filter as tabulated in Table I. Higher values of A (eg A=4) give lossy filters like the Daubechies 9/7.

Filters obtained from higher values of A result in a better compression ratio but at the same time the data loss is also higher. Le Gall's 5/3 filter has low latency, pro- vides lesser image compression but is a Lossless filter. Most of the applications in remote sensing, the raw data (uncompressed data) is of high value and any loss of such data cannot be afforded. Hence, lossless compression is the solution for such ap- plications. Another distinction for image compression using discrete wavelet transform is the manner in which the filter is realized. The following section compares the two implementation methods for DWT.

3. CONVOLUTIONAL VERSUS LIFTING METHOD

There are two main approaches of implementing a 1-D DWT: the traditional convo-lutional based implementation [Mallat 1989] and the lifting based implementation [Daubechies and Sweldens 1998; Andra et al. 2002].

3.1. Convolutional 1D DWT

In convolution based 1D DWT, two analysis filters, low pass (h) and high pass (g) are used. The data stream x[n] is decomposed into the low frequency and the high fre- quency signal components. Downsampling operation follows the filtering and is done at the full sampling rate. In this method half of the calculated coefficients have to be discarded because of redundancy. An improvement over this made in the filter bank de-sign where the execution is faster using a polyphase matrix of filter bank instead of the conventional filtering-downsampling structure. Here, downsampling is done prior to filtering and hence the requirement to compute redundant coefficients does not arise. The polyphase components of the signal are filtered by the corresponding filter coeffi- cients parallely. The polyphase matrix is defined as:

$$E_0(z) = \begin{bmatrix} H_e(z) & H_o(z) \\ G_e(z) & G_o(z) \end{bmatrix} \quad (4)$$

The He (z) and Ho (z) denote the even and odd polyphase components of the low pass analysis filter and Ge (z) and Go (z) denote the even and odd polyphase components ofthe high pass analysis filter. With the polyphase matrix, the wavelet decomposition for the signal can be expressed as:

$$\begin{bmatrix} LP(z) \\ HP(z) \end{bmatrix} = E_o(z) \begin{bmatrix} X_e(z) \\ X_o(z) \end{bmatrix} \quad (5)$$

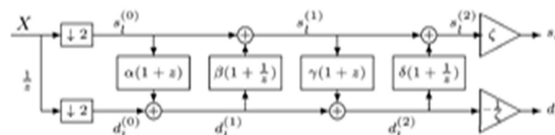Hardware Implementation of Satellite Image Compression Filter using Lifting based5/3 Wavelets :5

Figure 3. Lifting Based 1-D DWT Implementation

3.2. Lifting based 1-D DWT

In lifting based implementation, the computational complexity of the convolutional transformation is reduces by factoring the polyphase matrix of DWT into elementary matrices. For a perfect

reconstruction filter pair (H, G), [Daubechies and Sweldens 1998] proved that it is possible to factor the polyphase matrix Eo (z) into lifting steps as:

$$E(z) = \begin{bmatrix} K & 0 \\ 0 & 1/K \end{bmatrix} \prod_{i=1}^{m} \begin{bmatrix} 1 & U_i(z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -P_i(z) & 1 \end{bmatrix}$$

(6)

where K is a constant and m is the number of predict and update steps.

The forward lifting scheme is depicted in Fig. 3 and consists of the following steps.

(1) Decomposition: This step splits a signal (of even length) into two sets of coefficients, with even index indicated by evenj+1 and odd index indicated by oddj+1 . This is called the lazy wavelet transform.

(2) Prediction: As the even and odd coefficients are correlated, we can predict one from the other. More specifically, a prediction operator P is applied to even coefficients and the result is subtracted from the odd coefficients to get the detail signal d^{j+1}

$$d^{j+1} = odd^{j+1} - P(even^{j+1}) \tag{7}$$

(3)Update: An update operator U is applied to the odd coefficients and added to the even coefficients to define c^{j+1}

$$c^{j+1} = even^{j+1} + U(d^{j+1}) \tag{8}$$

(4) Scaling: To ensure normalization, the approximation band c^{j+1} is scaled by a factor of K, and the detail band d^{j+1} by a factor of 1/K

The defining equations for the lifting method are given by Equations 9-11.

Table 2: Lifting Coefficient for Le-Gall 5/3 DWT

	α	β	γ	δ	ζ
Le-Gall 5/3 [An-gelopoulou et al. 2008]	-1/2	1/4	0	0	1

$$d_i^1 = \alpha[x_e(i) + x_e(i+1)] + x_o(i) \tag{9}$$

$$a_i^1 = \beta[d_i^1 + d_{i-1}^1] + x_e(i)$$

$$d_i^2 = \gamma(a_i^1 + a_{i+1}^1) + a_i^1$$

$$a_i^2 = \delta(d_i^2 + d_{i-1}^2) + a_i^1 \tag{10}$$

$$Y_L = \zeta a_i^2$$

$$Y_L = (1/\zeta) d_i^2 \tag{11}$$

Equation 9 gives the predict (P1:d_i^1) and the update (U1:a_i^1) values for the first stage of lifting and equation 10 gives the predict (P2:d_i^2) and update (U2: a_i^2) values for the second stage of lifting. Equation 11 is the scaling equation.

The beauty of the lifting transform is that the inverse DWT transform can be imple- mented by simply computing from right to left and switching the signs of the predict and update operators and scaling factors. The lifting based DWT implementation is prefered because of the lower computational complexity and the flexibility offered in terms of factorization and perfect reconstruction property.

A comparison of wavelet filter implementation using the convolutional and the lift- ing method [K. et al. 2005] shows that the lifting architecture results in smaller and faster hardware with lower energy consumption compared to the convolutional archi- tecture.

4. PROPOSED ARCHITECTURE FOR IMAGE COMPRESSION

Le Gall's 5/3 DWT filter implemented with lifting architecture is designed for image compression application for satellite images. The filter design has the following salient features.

(1) Lifting Based Implementation: The wavelet architectures for 5/3 filter is imple- mented using lifting scheme as against the convolutional implementation in [Amit and Joseph 2012].

(2) Scaled Coefficients: The filters design uses rounding and scaling of the coefficients.The advantage of this process is that the arithmetic units operate on integer sam- ples and thus reduces complexity of the hardware.

(3) Multiplier less Architecture: The filter architecture does not require any multipli- ers. All multiplication operations are implemented by shift operations. Multiplier less architecture improves the operating speed and reduces the complexity of im- plementation.

The basic lifting method is described by the predict, update and the scaling equations operating on even and odd samples of the input data stream. The lifting coefficients for the Le-Gall 5/3 are tabulated in Table II.

Basic lifting algorithm uses fractional coefficients and hence requires adders and multipliers to operate upon fixed/ floating point numbers. The proposed modified lift- ing method

uses integer coefficients and hence the mathematical operations use inte- gers and are simpler to implement. Moreover the multiplication operations are imple- mented using shift operations. The equations for the lifting based Le Gall 5/3 DWT are given in Equation 12. The architecture uses the backbone of the basic lifting architec- ture for computing the Le-Gall 5/3 DWT.

Table 3: Synthesis Result

Parameter	Value
Clock Speed	251.4 MHz
Set up time	3.126 ns
Hold time	3.253 ns
Adders	4
Multipliers	0
Slice Registers	367
Slice LUTs	296
Power	5.23mW(dynamic)
	378.99mW(static)

$$H\,P[2n+1] = X[2n+1] - \left[\frac{X[2n]+X[2n+2]}{2}\right]$$

$$L\,P[2n] = X[2n] - \left[\frac{H\,P[2n-1]+X[2n+1]+2}{4}\right] \quad (12)$$

where X[.] are the signal samples, HP and LP are the high frequency and low frequency outputs. The division by 2 and 4 are realized using shift operations.

The salient modifications proposed in the present architecture as compared to the conventional lifting architecture are as follows:

(1) Multiplication and division operations are decomposed into shifting operations which eliminates the requirement of multipliers.

(2) The architecture uses integer lifting coefficients. Hence the mathematical opera- tions use integer operands

5. IMPLEMENTATION RESULTS

This section presents results for the performance of Le-Gall's 5/3 filter in image com- pression of satellite imagery. The test images are obtained from high resolution satel- lite scene databse of Wuhan University [Zhang Xun]. The design is implemented in a XILINX XC5VLX30 FPGA hardware.

The performance of the image compression core is evaluated in terms of the compres- sion quality which is expressed in terms of the performance metrics like Mean Square Error, Peak Signal to Noise Ratio and Compression Ratio. The hardware implemen- tation is evaluated in terms of the utilization of the FPGA resources, the maximum operating frequency and the power consumption.

The quantitative results for the performance of the image compression DWT core are presented in this section along withthe image reconstruction performance and FPGA resource utilization.

5.1. Synthesis

The synthesis results of proposed architecture are tabulated in Table 3. The proposed design achieves a clock frequency of 251.4 MHz. As is obvious fromthe analytical equations, four addersare used. As the multiplication operations are carriedout by shift operations no dedicated multiplier is used. The totalpower consumption of the architecture is 384mW.

Table 4: Image Reconstruction Quality for the Proposed Le Gall 5/3 Image Compression

Test Image	MSE	PSNR Le-Gall 5/3(dB)	Compression Ratio
Airport	79.81	29.11	2.4
Park	102.1	28.04	2.4
Port	234.24	24.43	2.4
Railway Station	481.98	21.30	2.4

5.2. Synthesis

The proposed compression architecture was evaluated for different test images for the image reconstruction quality studies. The image reconstruction was achieved by forward and inverse DWT transformation implemented in the same hardware. Results of the test are compiled in Table IV. The design achieves a good PSNR value for the test images in the range of 29dB for Le-Gall 5/3 filter.

The salient features of the present work are summarized in the following bullets.

(1) The work presents the results of the actual hardware implementation of the proposed architecture on XILINX XC5VLX30 FPGA Hence, the results present a more realistic and reliable performance.

(2) In this work, dedicated adders are used for all addition operations and no multipliers are used as all the multiplication and division operations are implemented using shift operations.

(3) This work achieves a clock frequency of 251MHz with an operating power consumption of 384mW.

6.   CONCLUSION

An image compression core using the Le Gal's 5/3 wavelets is presented for satellite image compression applications. The design of the compression core is in accordance with the wavelet based JPEG2000 standard. The design is implemented in a XILINX FPGA and the design results are presented. This work presents a detailed analysis of the compression performance of image compression including the hardware implementation result

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