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Design and Implementation of Third Order Low Pass Digital FIR Filter using Pipelining Retiming Technique

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***Abstract:** This paper presents design and implementation of 3rd order low pass digital FIR filter using pipelining retiming technique. Aim of this paper is to apply pipelining retiming technique on low pass digital FIR filter and compare with the existing second order retimed FIR filter and third order broadcast, non-broadcast low pass FIR filter. MATLAB FDA tool is used to calculate digital FIR filter coefficients. Hamming and Kaiser window methods are used to find out the coefficients of the FIR filter. Broadcast and non broadcast third order low pass FIR filter architectures are used for pipelining retiming .Cutset and feed forward pipelining retiming techniques are used to retime the third order low pass digital FIR filter. We design our algorithm in VHDL and implemented on Xilinx Vivado xc7a35tcpg261-1. Area (LUT), speed and power are calculated using Xilinx Vivado 2015.2 tool. Synthesis and simulation results are discussed in this paper. Speed and area (LUT) of proposed third order low pass FIR filter is improved in comparison with existing designs.*

***Keywords:** FIR, Hamming, Kaiser, MATLAB FDA tool, Pipelining Retiming technique.*

I. INTRODUCTION

FIR filters i.e., Finite Impulse Response filters are non -recursive type filter which impulse response is of finite period.IIR i.e., Infinite Impulse response are recursive filter which impulse response is of infinite period. By non-recursive type filter we mean the filter output sample depends on the present input sample and previous input sample. Recursive type filters reuses one or more of its outputs as an input. The impulse response of FIR filter is of finite period because it settles to zero in finite time.FIR filter is important as it have the capability of no phase distortion. In digital processing application FIR filters are preferred over IIR.FIR filter are always stable and easily designed with exact linear phase.FIR filter are also less sensitive to filter quantization errors. While implementing FIR filters this is a much require factor.

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Retiming is main and powerful technique to digital circuit performance optimization and it decreases the critical delays of a circuit by varying its location so that combinational path delay are balance across the entire design[1].Retiming is a method in which without altering the input-output of the characteristic of the circuit , the positions of delay elements are changed[2]. It helps in lowering the clock period of the circuit, lowering power consumption, and logic synthesis[2].It is used to increase the clock rate of the circuit[2]. It is also used to lower the power consumption by reducing switching and that may lead to effective power dissipation in static CMOS circuits[8].Speed is one of the important parameters in the performance of a device. To meet the demand of high speeds, digital signal processing systems are used which uses different techniques like pipelining, parallel processing ,retiming, unfolding, etc[3].

Design of third order low pass FIR filter using Hamming and Kaiser Window method is given in section III. Introduction to retiming technique is discussed in Section IV. Sections V contain designing of 3rd order low pass FIR filter using retiming techniques. Sections VI contain experimental results and comparison. Section VII contains the conclusion**.**

II. EXISTING WORK RELATED TO FIR

In [1] the author uses retiming technique to design and implement FIR filter. The results show the improvement of proposed methods in terms of no. of registers, no. of LUT, delay (in ns) and power (mW) in comparison with the existing method. In [2] the author uses folding and registers minimization transformation on DSP filter. The author uses techniques like retiming, folding, register minimization, etc. The results show the advantage of register minimization over folding on a second IIR filter. In [3] the author uses VHDL for the implementation of word level parallel processing unfolding algorithm. The author uses unfolding algorithm to FIR and IIR filter and compare with original filter and parallel processing filters architecture. The results show that proposed technique reduces the critical path delay in comparison with existing designs and speed of 3-unfolded IIR filter is more than 3-parallel IIR filters. In [4] the author uses VHDL to design and implement combined pipelining and parallel processing architecture for FIR and IIR filters. The author compares the proposed architecture with the original FIR and IIR filter. The results show that for combined architecture FIR filter, there is decrease in area, power and reduce in delay.

In case of combined architecture IIR filter there is slight increase in area, power consumption is reduced and delay is also reduced. In [5] the author uses VLSI implementation of area efficient 2-parallel FIR digital filter. The author compares primary 2-parallel FIR digital filter and area efficient 2-parallel FIR digital filter. The results show that area and speed of area efficient 2- parallel filter are improved. In[10] the author explain about the comparative study on Direct form-1, Broadcast and Fine grain structure of FIR digital filter. The author design digital filter using MATLAB FDA tool and implement using direct form-1, broadcast and fine grain. The experimental results show that to design an area optimized filter we should use fine grain pipeline structure, where as for high speed, we should use direct form-1 structure of digital filter.

III. DESIGN OF THIRD ORDER LOW PASS FIR FILTER USING HAMMING AND KAISER WINDOW METHOD

A.FIR Filter

Finite Impulse Response (FIR) filter plays an important role in digital signal processing systems. Its output sample depends on the present input sample and previous input sample. So it is a non recursive filter .It always stable and can easily be designed with exactly linear phase.

The difference equation for the FIR filter is given as

$$y(n) = b_0\, x(n)+b_1 x(n-1) +\ldots\ldots.+ b_N\, x(n-N) \quad (1)$$

Equation (1) defines the relation of the input signal to the output signal.

It can also be expressed as

$$y(n) = \sum_{i=0}^{N} b_i\, x(n-i) \quad (2)$$

Where x(n) is the input signal, y(n) is the output signal, b_i is the filter coefficient and N is the filter order[4][9]

B. Hamming Window

Hamming window is a type of raised cosine window. The window sequence of cosine window is of the form [13]

$$w_\alpha(n) = \alpha + (1-\alpha)\cos\frac{2\pi n}{N-1}$$

$$\text{for } -(N-1)/2 \leq n \leq (N-1)/2. \quad (3)$$

$$= 0 \text{ otherwise}$$

Where $w_\alpha(n)$ is the frequency response

The equation for Hamming window can be obtained by substituting α = 0.54 in equation 1.

$$wH_\alpha(n) = 0.54 + 0.46\cos\frac{2\pi n}{N-1}$$

$$\text{for } -(N-1)/2 \leq n \leq (N-1)/2. \quad (4)$$

$$= 0 \qquad \text{otherwise}$$

C. Kaiser Window

Kaiser Window generates a sharp central peak. It reduces side lobes and transition band is narrowed.

The Kaiser window is given by

$$w_k(n) = \frac{Io[\alpha\sqrt{1-(2n/N-1)^2}]}{Io(\alpha)}$$

$$\text{for } |n| \leq \frac{N-1}{2} \quad (5)$$

$$= 0 \qquad \text{otherwise}$$

Where α is the adjustable parameters and $I_o(x)$ is the modified zeroth- order Bessel function.[13]

D.MATLAB FDA tool

To design low pass FIR filter for both Hamming and Kaiser window we have used MATLAB FDA tool.FDA tool i.e., Filter Design and Analysis Tool is a powerful GUI(Graphical User Interface) for designing and analysing filter quickly.FDA tool enables to design digital FIR or IIR filter .FDA tool is use in MATLAB by typing >>fdatool in command window. The specification used to design the filter on this paper is given in Table I. Depending upon the specification, the transfer function coefficient of both Hamming and Kaiser are given in Table II and Table III respectively. The magnitude and phase plot of Hamming and Kaiser are shown in Figure 1 and Figure 2 respectively [10].

Table I: The specification used to design the filter

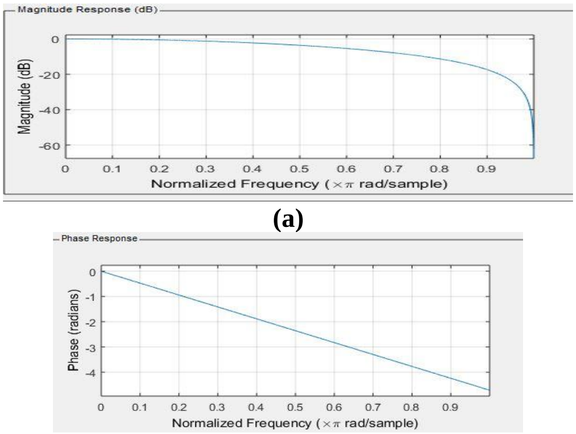
Properties	**Specification**
Response	**Low pass**
Design	**FIR**
Order	**3^{rd}**
Window	**Hamming and Kaiser**
Cut-off frequency	**0.5 (normalised)**
Attenuation at cut-off frequency	**6 db**

Table II: Transfer function coefficient of Hamming

Transfer function	**Coefficient**
h(0)	**0.016**
h(1)	**0.486**
h(2)	**0.486**
h(3)	**0.16**

Table III: Transfer function coefficient of Kaiser

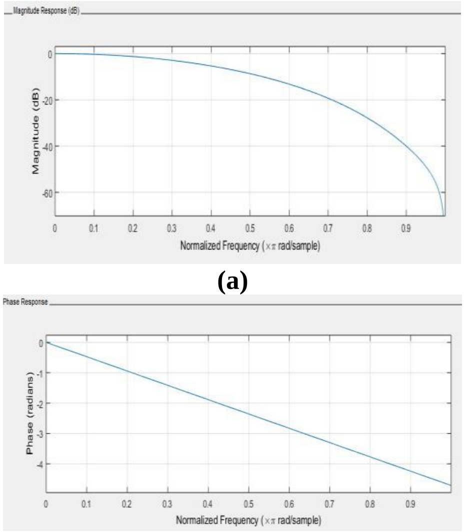
Transfer function	**Coefficient**
h(0)	**0.119**
h(1)	**0.380**
h(2)	**0.380**
h(3)	**0.119**



(a)

(b)

Figure1: (a) Magnitude and (b) Phase plot of Hamming



(a)

(b)

Figure 2: (a) Magnitude and (b) Phase plot of Kaiser

IV. INTRODUCTION TO RETIMING TECHNIQUE

Retiming is a transformation technique used to change the delay elements locations in a circuit without affecting the input/output characteristics of the circuit. By reducing the computation time of the critical path, retiming can be used to increase the clock rate of a circuit. Retiming can also be used to decrease the number of registers in a circuit. In synchronous circuit design, retiming has many applications. Applications includes reducing the clock period of the circuit, reducing power consumption of the circuit, reducing the clock period of the circuit and logic synthesis[8]

Retiming will not affect the input/output characteristics of the circuit by changing the delay elements locations. For example; consider the filter in Figure 3(a).This filter is described by

$$w(n) = ay(n-1) + by(n-2)$$
$$y(n) = w(n-1) + x(n)$$
$$= ay(n-2) + by(n-3) + x(n)$$

The filter in Figure 3(b) is described by

$$w_1(n) = ay(n-1)$$
$$w_2(n) = by(n-2)$$
$$y(n) = w_1(n-1) + w_2(n-1) + x(n)$$
$$= ay(n-2) + by(n-3) + x(n)$$

Although the filter in Figure 3(a) and Figure 3(b) have delays at different locations, they have the same input/output characteristics. Using retiming these filters can be derived from one another [8].

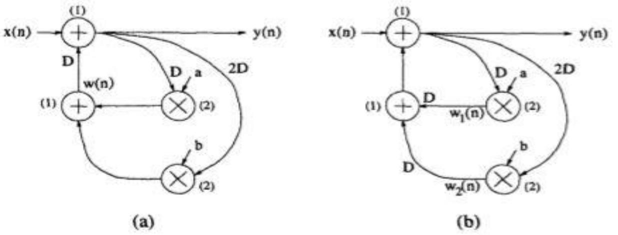


Figure 3: (a) A DFG of a filter, (b) The retimed DFG of the filter.

We will consider the retiming technique which will be used in designing the filters. There are two special cases of retiming namely, cutset and pipelining. These retiming techniques will help to minimize the clock period and the number of registers that are require implementing circuit.

A.Cutset Retiming

Cutset retiming is a special case of retiming technique where a data flow graph is retime by applying a suitable cutset line. A cutset is a set of edges that can be removed from the graph to create two disconnected sub graphs.Cutset retiming only affects the weights of the edges in the cutset. If the two disconnected sub graphs are labelled G and G2,then cutset retiming consist of adding k delays to each edge from G1 and G2 and removing k delays from each edge from G2 to G1[1][8].

B. Pipelining

Pipelining is a special case of cutset retiming .In pipelining there are no edges in the cutset from the sub graphs G2 to sub graphs G1.This means that pipelining applies to graphs without loops. These cutsets are referred to as feed-forward cutsets. [1][8].

C. Feed-forward Cutset

A feed-forward cutset is a type of cutset where the data moves in the forward direction on all the edges of cutset.

V. DESIGNING OF 3RD ORDER LOW PASS FIR FILTER USING RETIMING TECHNIQUES

In this paper we use cutset pipeline retiming and feed-forward retiming techniques.DFG for 3rd order non broadcast and broadcast low pass FIR filter are shown in Figure 4 and Figure 5 respectively. Unretimed DFG for broadcast 3rd order low pass FIR filter with cutset is shown in Figure 6. DFG for cutset pipelining retiming for 3rd order broadcast low pass FIR filter when k=1 and when k=2 are shown in Figure 7 and Figure 8 respectively. Unretimed DFG for 3rd order non broadcast low pass FIR filter with a cutest is shown in Figure 9. DFG for cutest pipelining retiming for 3rd order non broadcast low pass FIR filter when k=1 and when k=2 is shown in Figure 10 and Figure 11 respectively. Unretimed DFG for 3rd order non broadcast low pass FIR filter with a feed-forward cutest is shown in Figure 12. DFG for feed-forward cutset retiming for 3rd order non broadcast low pass FIR filter when k=1 and when k=2 are shown in Figure 13 and Figure 14 respectively. Unretimed DFG for 3rd order broadcast low pass FIR filter with a feed forward cutest is shown in Figure 15. DFG for feed-forward cutset retiming for 3rd order broadcast low pass FIR filter when k=1 and when k=2 are shown in Figure 16 and Figure 17 respectively. The k we use is the number of delay.

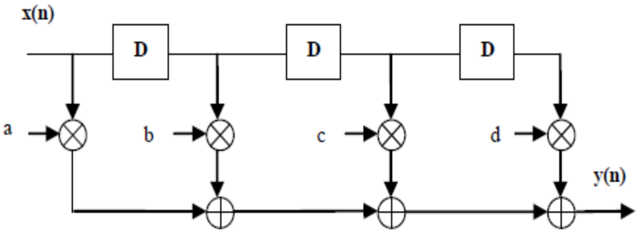


Figure 4: DFG for 3rd order non broadcast low pass FIR filter

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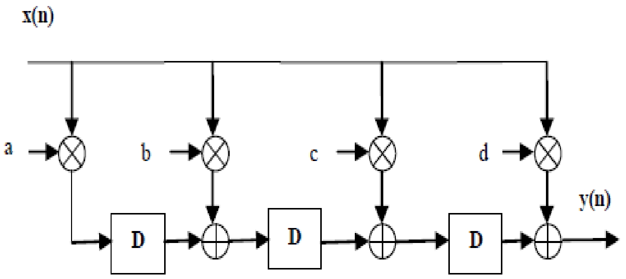

Figure 5: DFG for 3rd order low pass FIR filter

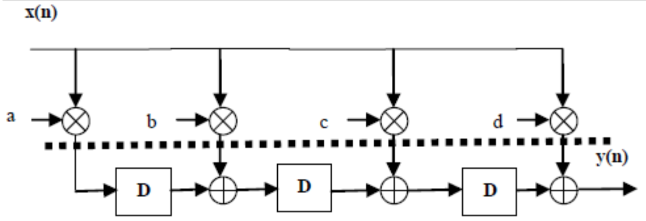

Figure 6: Unretimed DFG for broadcast 3rd order low pass FIR filter with a cutest.

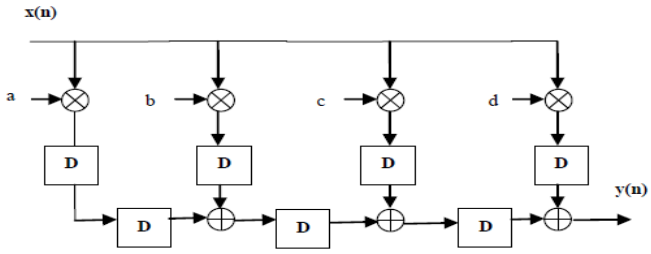

Figure 7: DFG for cutset pipelining retiming for 3rd order broadcast low pass FIR filter when k=1

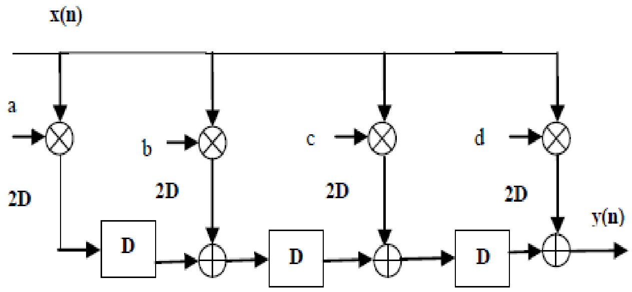

Figure 8: DFG for cutset pipelining retiming for 3rd order broadcast low past FIR filter when k=2

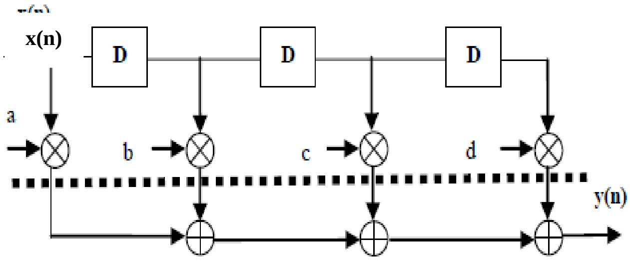

Figure 9: Unretimed DFG for 3rd order non broadcast low pass FIR filter with a cutest.

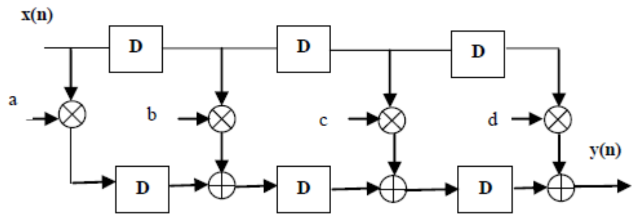

Figure 10: DFG for cutest pipelining retiming for 3rd order non broadcast low pass FIR filter when k=1

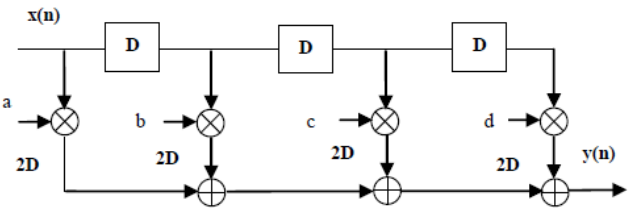

Figure 11: DFG for cutest pipelining retiming for 3rd order non broadcast low pass FIR filter when k=2

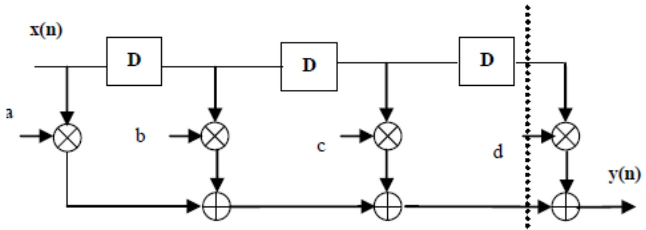

Figure 12:Unretimed DFG for 3rd order non broadcast low pass FIR filter with a feed-forward cutest.

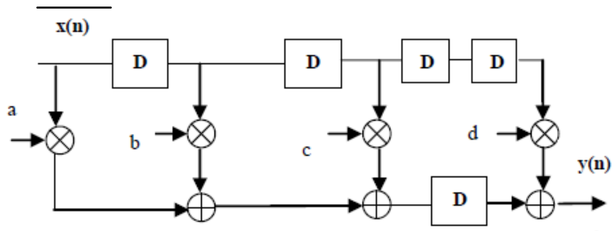

Figure 13:DFG for feed-forward cutset retiming for 3rd order non broadcast low pass FIR filter when k=1

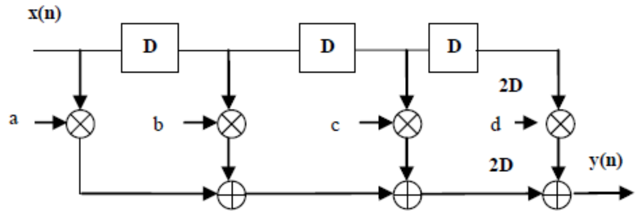

Figure 14:DFG for feed-forward cutset retiming for 3rd order non broadcast low pass FIR filter when k=2

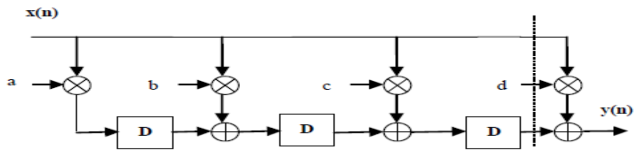

Figure 15:Unretimed DFG for 3rd order broadcast low pass FIR filter with a feed forward cutset.

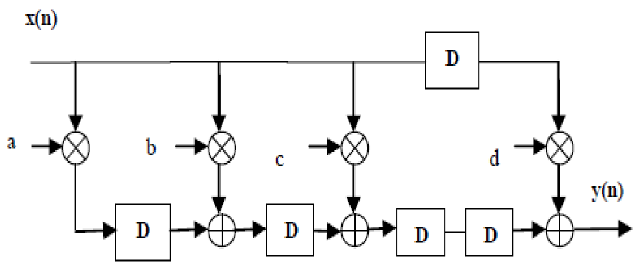

Figure 16:DFG for feed-forward cutset retiming for 3rd order broadcast low pass FIR filter when k=1

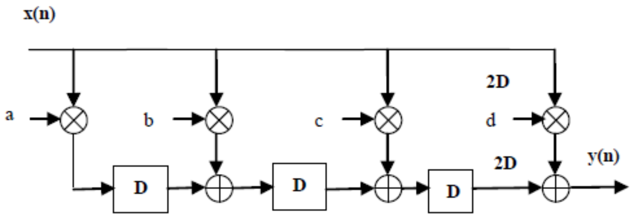

Figure 17:DFG for feed-forward cutest retiming for 3rd order broadcast low pass FIR filter when k=2

VI. EXPERIMENTAL RESULTS AND COMPARISION

We design our algorithm in VHDL and implemented on Xilinx Vivado 2015.2(xc7a35tcpg261-1). Area (LUT), speed and power (watt) are calculated using Xilinx Vivado 2015.2 tool.

Simulation Waveform of third order low pass FIR filter is shown in **Figure 18**. Simulation Waveform for third order retimed FIR Filter for Hamming window when k=1 or k=2 is shown in **Figure 19**. Simulation Waveform for third order retimed FIR Filter for Kaiser window when k=1 or k=2 is shown in **Figure 20**.

Simulation waveform of third order broadcast and non broadcast low pass filter will be same. Simulation waveform of cutest retime and feed forward for third order broadcast and non broadcast low pass filter for Kaiser window when k=1 or k=2 will be same. Simulation waveform of cutest retime and feed forward for third order broadcast and non broadcast low pass filter for Kaiser window when k=1 or k=2 will be same.

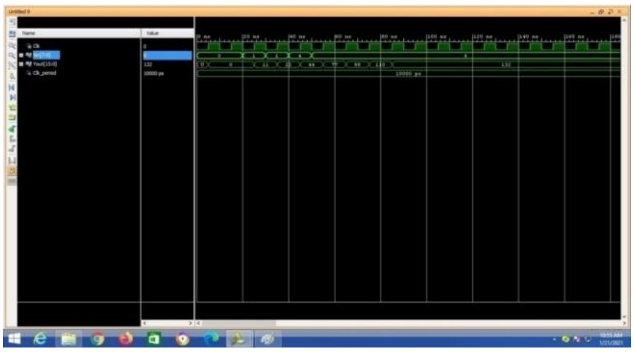

Figure 18: Simulation Waveform of third order low pass FIR filter

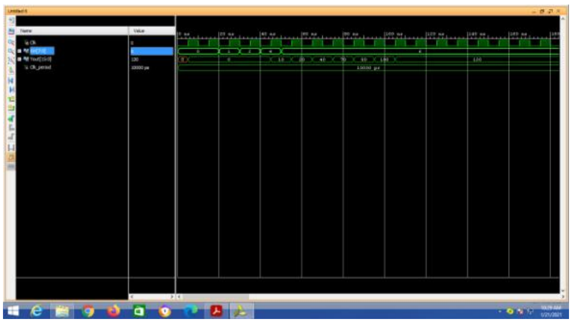

Figure 19: Simulation Waveform for 3rd order retimed FIR Filter for Hamming window when k=1 or k=2

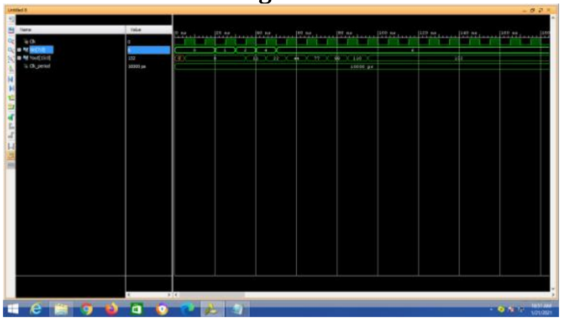

Figure 20: Simulation Waveform for 3rd order retimed FIR Filter for Kaiser Window when k=1 or k=2

The synthesis results and comparison between proposed design and existing 2nd order retimed FIR filter and 3rd order unretimed non-broadcast and broadcast FIR filter in terms of area (number of LUTs), speed(delay in ns) and power(watt) are shown in Table IV. Speed and area of proposed third order low pass FIR filter is improved in comparison with existing designs.

3rd order non-broadcast low pass FIR filter (Hamming) has number of LUT equal to 25,delay equal to 4.921ns and power equal to 10.163W. 3rd order non-broadcast low pass FIR filter (Kaiser) has number of LUT equal to 40, delay equal to 5.134ns and power equal to 12.136W. 3rd order broadcast low pass FIR filter (Hamming) has number of LUT equal to 17, delay equal to 4.946ns and power equal to 10.034W. 3rd order broadcast low pass FIR filter (Kaiser) has number of LUT equal to 25, delay equal to 4.980ns and power equal to 10.022W. Retimed non-broadcast low pass FIR filter(Hamming)when k=1 has number of LUT equal to 29, delay equal to 5.166ns and power equal to 10.033W. Retimed non-broadcast low pass FIR filter (Hamming) when k=2 has number of LUT equal to 30, delay equal to 5.119ns and power equal to 10.361W. Retimed non-broadcast low pass FIR filter(Kaiser) when k= has number of LUT equal to 40, delay equal to 5.122ns and power equal to 12.113W. Retimed non-broadcast low pass FIR filter(Kaiser) when k=2 has number of LUT equal to 40, delay equal to 4.924ns and power equal to 11.994W. Retimed broadcast low pass FIR filter(Hamming) when k=1 has number of LUT equal to 32, delay equal to 5.205ns and power equal to 12.094W. Retimed broadcast low pass FIR filter(Hamming) when k=2 1 has number of LUT equal to 25, delay equal to 5.045ns and power equal to 10.022W. Retimed broadcast low pass FIR filter(Kaiser) when k=1 has number of LUT equal to 32, delay equal to 4.980ns and power equal to 12.094W. Retimed broadcast low pass FIR filter(Kaiser) when k=2 has number of LUT equal to 32, delay equal to 4.980ns and power equal to 12.142W. Feed forward non broadcast low pass FIR filter (Hamming) when k=1 has number of LUT equal to 29, delay equal to 5.116ns and power equal to 10.033W. Feed forward non broadcast low pass FIR filter (Hamming) when k=2 has number of LUT equal to 30, delay equal to 5.119ns and power equal to 10.361W. Feed forward non broadcast low pass FIR filter (Kaiser) when k=1 has number of LUT equal to 40, delay equal to 5.112ns and power equal to 12.113W. Feed forward non broadcast low pass FIR filter (Kaiser) when k=2 has number of LUT equal to 40, delay equal to 4.924ns and power equal to 11.994W. Feed forward broadcast low pass FIR filter (Hamming) when k=1 has number of LUT equal to 26, delay equal to 5.110ns and power equal to 10.426W. Feed forward broadcast low pass FIR filter (Hamming) when k=2 has number of LUT equal to 26,delay equal to 5.061ns and power equal to 10.458W. Feed forward broadcast low pass FIR filter (Kaiser) when k=1 has number of LUT equal to 36, delay equal to 4.940ns and power equal to 12.074W. Feed forward broadcast low pass FIR filter (Kaiser) when k=2 has number of LUT equal to 36, delay equal to 5.609ns and power equal to 12.118W.

Existing 2nd order retimed non-broadcast FIR filter[1] has number of LUT equal to 1281, delay equal to 18.77ns and power equal to 0.0722W. Xilinx ISE 9.2i is used for designing the existing 2nd order retimed non-broadcast FIR filter [1].

Existing 3rd order unretimed non-broadcast FIR filter [10] has number of LUT equal to 308. Existing 3rd order unretimed broadcast FIR filter [10] has number of LUT equal to 251. Xilinx XC3S700A-4fg484 is used for designing.

Speed and area of proposed third order low pass FIR filter is improved in comparison with [1] existing 2nd order retimed non-broadcast FIR filter. But power doesn’t improve. Area of proposed third order low pass FIR filter is improved in comparison with [10]Existing 3rd order unretimed non-broadcast FIR filter and[10]Existing 3rd order unretimed broadcast FIR filter .

Table IV Synthesis results and comparison between proposed design with existing 2nd order retimed FIR filter and 3rd order unretimed FIR filter

Architecture	Area(No. of LUTs)	Speed(delay in ns)	Power(watt)
3rd order non-broadcast low pass filter (Hamming)	25	4.921	10.163
3rd order non-broadcast low pass filter (Kaiser)	40	5.134	12.136
3rd order broadcast low pass filter (Hamming)	17	4.946	10.034
3rd order broadcast low pass filter (Kaiser).	25	4.980	10.022
Retimed non-broadcast filter(Hamming)when k=1	29	5.116	10.033
Retimed non-broadcast filter(Hamming)when k=2	30	5.119	10.361
Retimed non-broadcast filter(Kaiser)when k=1	40	5.122	12.113
Retimed non-broadcast filter(Kaiser)when k=2	40	4.924	11.994
Retimed broadcast filter(Hamming)when k=1	32	5.205	12.094
Retimed broadcast filter(Hamming)when k=2	25	5.045	10.022
Retimed broadcast filter(Kaiser)when k=1	32	4.980	12.094
Retimed broadcast filter(Kaiser)when k=2	32	4.980	12.142
Feed forward non-broadcast filter(Hamming)when k=1	29	5.116	10.033
Feed forward non-broadcast filter(Hamming)when k=2	30	5.119	10.361
Feed forward non-broadcast filter(Kaiser)when k=1	40	5.122	12.113

Feed forward non-broadcast filter(Kaiser)when k=2	**40**	**4.924**	**11.994**
Feed forward broadcast filter(Hamming)when k=1	**26**	**5.110**	**10.426**
Feed forward broadcast filter(Hamming)when k=2	**26**	**5.061**	**10.458**
Feed forward broadcast filter(Kaiser)when k=1	**36**	**4.940**	**12.074**
Feed forward broadcast filter(Kaiser)when k=2	**36**	**5.609**	**12.118**
[1]Existing2nd order retimed non-broadcast FIR filter(Xilinx ISE 9.2i)	**1281**	**18.77**	**0.0722**
[10]Existing 3rd order unretimed non-broadcast FIR filter(XC3S700A-4fg484)	**308**		
[10]Existing 3rd order unretimed broadcast FIR filter(XC3S700A-4fg484)	**251**		

VII. CONCLUSION

Cutset and feed forward pipelining retiming techniques are used to design third order low pass FIR filter. Broadcast and non-broadcast third order low pass digital FIR filter architectures are used to verify the improvement in area and speed with the existing second order retimed and third order broadcast, non broadcast FIR filter. Synthesis and simulation results are discussed in details**.** Speed and area of proposed third order low pass FIR filter is improved in comparison with existing designs. Feed forward non-broadcast FIR filter (Kaiser, when k=2) structure has highest speed in comparison with all the implemented designs.

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