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Exhaustive Approach for Multistage Filter Design to Minimize Complexity of FIR Filter for WCDMA Applications

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***Abstract*: In this paper we introduce a new multistage filter design to implement a decimation filter for WCDMA applications. Here we use a low pass filter to design our decimation structure. Among all the window techniques the worthy window for any application is the Kaiser window and in filtering methods linear phase equiripple FIR filter dominates the remaining filters. So, in this paper we choose Kaiser Window and equiripple technique for the design of decimation filter. For these two filters performance analysis is done in terms of pass band ripples, length of filter, number of multipliers, number of adders, number of states, multiplications per input sample, Additions per inpsut sample are compared with respect to single stage filter design. For single stage filter design the order of the filter is very high so, our attempt is to try various exhaustive combinations of multistage design and prove which design is the worthy multi stage approach among all the combinations by considering the parameters like filter order, complexity and multiplication rate at the output.**

***Index Terms*: Multistage filter design, WCDMA, Kaiser window, equiripple FIR filter**

I. INTRODUCTION

The main aim of multistage design is to enhance the performance of FIR decimation filter to reduce the complexity of the decimation filter and reduce the order and there by multiplication rate at the output of each stage [1-2]. A triple mode WCDMA, CDMA 2000 and GSM using programmable FIR filter was designed [3]. Initially 3G was operating at 384 kbps later it was updated to a speed of 2 Mbps for voice, image and video transmission In analog and digital communications the main motto of decimation is for data conversion and filtering, with help of FIR filter desired magnitude response is achieved but large amount of external hardware is required because we need to store large amount of coefficients. In the year 1974 an optimal linear phase digital filter was developed using Rabiner for interpolation and decimation filter was found and they derived an approximate equation for estimating the filter order given in equation (1).

$$N = \frac{-10\log_{10}(\delta_1\delta_2)-15}{14\Delta F}+1 \qquad (1)$$

Where, $\Delta F = \dfrac{F_s - F_p}{F_{sampling}}$

In our paper this equation plays a major role for assuming the filter order when first stage decimation factor is 2. Multirate means "many sampling rates at different instances of a system". Any system in digital signal processing uses multiple sampling rates within the system. Multi rate DSP means art of changing sampling rate of the signal [5] until it reaches the reception end. We go for Multirate system because when there is a situation that when we need to pass the data between two systems which use incompatible sampling rates then it is difficult to meet the standards. Multirate DSP increases the efficiency of processing a signal. Fig.1 indicates a linear phase FIR filter with a decimation factor of M where the decimation factor is kept at the output of the filter design so frequency at the output is divided by a factor of M.

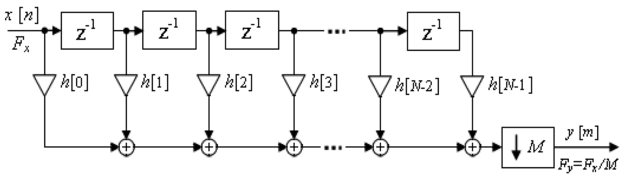

Fig. 1 Linear phase FIR filter with a decimation factor of M

So, multiplication rate at the output is $\dfrac{N * F_x}{M}$

In, time domain it can be represented as,

$$v[n] = \sum_{k=0}^{N-1} h[k]\, x[n-k] \qquad (2)$$

After down sampling by a factor of M, v[n] is rewritten as,

$$y[m] = v[nM] \qquad (3)$$

For calculating y[m] we require every Mth sample of v[n]. Therefore, the calculation of decimated signal y[m] can be done by computing every Mth sample of the convolution sum written as,

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$$y[m]=\sum_{k=0}^{N-1}h[k]\,x[nM-k] \qquad (4)$$

II. WCDMA

WCDMA can accept bit rates up to 2Mbps. WCDMA has inbuilt property of variable bit rate to offer bandwidth on demand [6]. The major property of WCDMA is that we can multiplex speech, video, data on a single link. WCDMA technology has compatibility to handle variable delay requirements. WCDMA is the coexistence of 2G and 3G with intersystem handovers for enhanced data coverage. The WCDMA technology is backward compatible. Another good property of WCDMA is it has high spectrum efficiency WCDMA also supports asymmetric property which is best suitable for web browsing. WCDMA is coexistence of FDD and TDD modes [7]. FDD refers to frequency division duplexing and TDD refers to time division duplexing. There are two pairs of bands used for FDD mode they are 1920-1980 MHz and 2110-2170 MHz, the other mode is TDD its frequency mode of operation is in two pairs they are 1900-1920 MHz and 2010-2025 Mhz. Another name for WCDMA is it is a packet successor of 2G global system for mobile communications (GSM) standard. In the beginning stages it was first adopted by IMT-2000 direct spread. It is practically used in capacity demanding applications like video, internet digital radio communications etc.

A. FIR Filter Design

For designing a FIR filter we use convolution property, in simple words it is stated as cross correlation between input signal and time reversed copy of impulse response. For designing a filter there are various methods they are:

1) Window design method
2) Weighted least squares design
3) Parks McClellan design
4) Equiripple technique

Parks McClellan method is also called as equiripple, optimal or minimax method. For designing this method remez exchange algorithm which is commonly used for finding optimal set of coefficients. In this method the user gives his specifications in terms of magnitude and phase response, a weighing function for errors from this user defined response and order N. This remez algorithm finds N+ 1 coefficients that minimizes the maximum deviation from ideal response characteristics [8]. Equiripple filter can also be defined by FFT as well. Firstly, compute DFT of original filter by using FFT. In the Fourier domain correct the response according to desired specifications and compute inverse FFT [9].

B. Kaiser Window

Jim Kaiser derived an approximated window technique by using Bessel function

$$w(n)=\frac{I_O\left(\alpha\sqrt{1-\left(\frac{2n}{N-1}-1\right)^2}\right)}{I_O(\alpha)} \quad 0\le N\le N-1 \qquad (4)$$

0 elsewhere

where, N=filter length

I_0= zeroth order modified Bessel of first kind

α =non-negative.

These parameters determine shape of the window and there is a tradeoff between main lobe width and side lobe level.

III. DECIMATOR

In crude form, the process of down sampling followed by filtering is called decimation. Decimation is the ratio of sampling rate at the output to sampling rate at the input [10].

M=output sampling rate/input sampling rate

Practically decimator is used in digital down conversion (DDC), software defined radios (SDR) and communication systems like 3G,4G. The main purpose of decimator is to shift the spectrum the desired range of interest. In our application decimation filter is chosen to be a FIR type because efficiency can be improved at receiver end i.e. at the output [11]. When we receive the data, we down sample it and pass through the filter. FIR filter is designed to keep it linear in phase i.e. achieved by adding few delays to the input signal. So, with this concept we can prove that FIR filter is used for multi rate applications [12].

Design Procedure for WCDMA

Table I shows the design specifications of decimation filter structures for WCDMA applications.

Table. I

Sampling frequency	64.44MHz
Pass band frequency	2MHz
Stop band frequency	2.5MHz
Pass band ripple	0.5dB
Stop band ripple	55dB

Normalized frequency

$$W_p=\frac{2\pi f_{pass}}{f_s}=2\pi\frac{2\times 2\times 10^6}{64.44\times 10^6}=0.062\pi \qquad (5)$$

$$W_s=\frac{2\pi f_{stop}}{f_s}=2\pi\frac{2.5\times 10^6}{64.44\times 10^6}=0.776\pi \qquad (6)$$

By using the above specifications, we reduce the complexity of design by introducing the concept of multistage filter design. In the multistage design we go for exhaustive combinations of single stage, two stages, three stages and four stage filter design and compare all the combinations with respect to single stage design.

A. Single Stage Realization

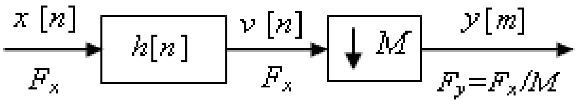

Fig. 2 Single stage realization of a decimation filter

In this realization the multiplication rate is $Rm\_dec\_H = N * F_y = N * F_x / M$

Where N = Order of the filter.

B. Two Stage Realization

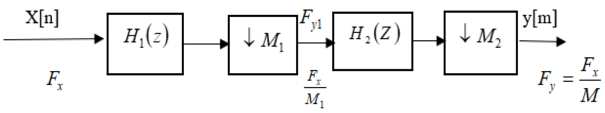

Fig. 3 Two stage realization of a decimation filter

The possible combinations for various values of M_1 and M_2 are

1) $M_1 = 4, M_2 = 4$
2) $M_1 = 8, M_2 = 2$
3) $M \; = 2, M_2 = 8$

The two-stage realization at multiplication rate at the output variation at each stage is shown in Figure. 3

Efficiency of $H_1(z)$

$$Rm\_dec\_H_1 = N_1 * F_{y1} = N_1 * F_x / M_1 = N_1 * F_{y1}$$

$$Rm\_dec\_H_2 = N_2 * F_{y2}$$

Now the total multiplication rate is

$$Rm\_dec = R_{m\_dec\_H1} + R_{m\_dec\_H2}$$
$$= N_1 * F_{y1} + N_2 * F_{y2}$$

where,

N_1= Order of first stage
N_2= Order of second stage

C. Three Stage Realization

Three stage realization is as shown in figure 4. For three stage realization the possible combinations of M_1 , M_2 and M_3 are, 1) $M_1 = 2, M_2 = 2, M_3 = 4$

2) $M_1 = 2, M_2 = 4, \; M_3 = 2$

3) $M_1 = 4, M_2 = 2, \; M_3 = 2$

Multiplication rate at the output of first stage is given by,

$$Rm\_dec\_H_1 = N_1 * F_{y1} = N1 * F_x / M_1 = N_1 * F_{y1}$$

Multiplication rate at the output of second stage is given by,

$$Rm\_dec\_H_2 = N_2 * F_{y2} = N2 * F_x/M_1 * M_2 = N_2 * F_{y2}$$

Multiplication rate at the output of third stage is given by,

$$Rm\_dec\_H_3 = N_3 * F_{y3} = N3 * F_x / M_1 * M_2 * M_3 = N_3 * F_{y3}$$

Now, the total multiplication rate at the end is given by,

$$Rm\_dec = R_{m\_dec\_H1} + R_{m\_dec\_H2} + R_{m\_dec\_H3}$$
$$= N_1 * F_{y1} + N_2 * F_{y2} + N_3 * F_{y3}$$

Where,

N_1 = Order of first stage
N_2 = Order of second stage
N_3 = Order of third stage

C. Four Stage Realization

For four stages realization there is only one possible combination that is

$$M_1 = 2, M_2 = 2, \; M_3 = 2, M_4 = 2$$

Multiplication rate after the first stage is,

$$Rm\_dec\_H_1 = N_1 * F_{y1} = N1 * F_x / M_1 = N_1 * F_{y1}$$

Multiplication rate at the output of second stage is,

$$Rm\_dec\_H_2 = N_2 * F_{y2} = N_2 * F_x / M_1 * M_2$$
$$= N_2 * F_{y2}$$

Multiplication rate at the output of third stage is,

$$Rm\_dec\_H_3 = N_3 * F_{y3} = N_3 * F_x/M_1 * M_2 * M_3$$
$$= N_3 * F_{y3}$$

Multiplication rate at the output of fourth stage is,

$$Rm\_dec\_H_4 = N_4 * F_{y4} = N_4 * F_x / M_1 * M_2 * M_3 * M_4$$
$$= N_4 * F_{y4}$$

At the end, the total multiplication rate at the final stage is given by,

$$Rm\_dec = N_1 * F_{y1} + N_2 * F_{y2} + N_3 * F_{y3} + N_4 * F_{y4}$$

Where

N_1 = Order of first stage
N_2 = Order of second stage
N_3 = Order of third stage
N_4 = Order of fourth stage

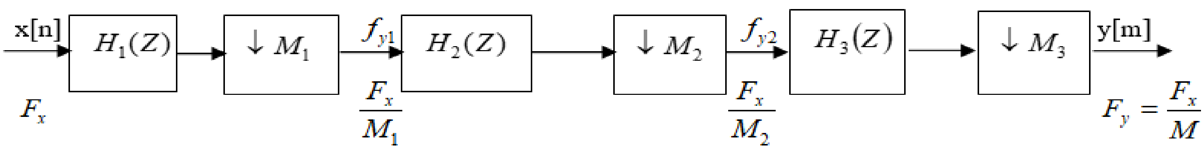

Fig. 4 Three stage realization of a decimation filter

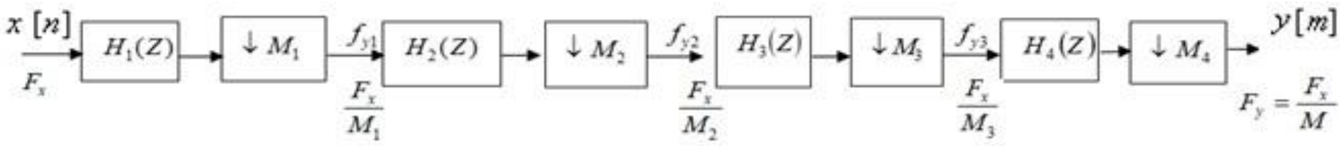

Fig. 5 Four stage realization of a decimation filter

IV. RESULTS AND DISCUSSION

An exhaustive combination of various multi stage filter design must be discussed in the results section and now here we must compare all these results with respect to single stage design. In this the first combination is a single stage design and its hardware requirements and multiplication rate are discussed in Table II, the two stage design the possible combinations are M_1=4, M_2=4 and M_1=8, M_2=2 and last combination is M_1=2, M_2=8 its parameters are discussed in Table III, in the three stage design the possible combinations are M_1=2, M_2=2, M_3=4 second combination is M_1=2, M_2=4,M_3=2 and the third combination is M_1=4, M_2=2, M_3=2 and its results are discussed in table IV.

Finally, four stage realization in terms of powers of 2 is finally discussed in Table V but practically with FDA tool in MATLAB we cannot design the four-stage design as the filter order is below the order of 3 for the equiripple filter so we cannot use this tool. so, we go for approximation equation of Rabiner which was discussed in the year 1974 for multistage filter design. This equation also comes into picture when decimation filter in the first stage is 2 example M_1=2, M_2=8, and another example of M_1=2, M_2=4, M_3=2

1) Single Stage Realization

Normalized pass band and stop band frequencies are $W_p = 0.062\pi$ and $W_s = \frac{2\pi * 5 * 10^6}{64.44 * 10^6} = 0.0776\pi$

Table II describes number of multipliers, number of adders, number of states, Multiplications per input sample, additions per input sample, Multiplication rate at the output required for single stage realization.

Table. II

Specifications	Number of Multipliers	Number of Adders	Number of States	Multiplications per Input Sample	Additions per Input Sample	Multiplication rate at the Output
Kaiser	424	423	423	424	423	1703632500
Equiripple	267	266	266	267	256	1071315000

2) Two Stage Realization

The possible combinations are, M_1=4, M_2=4; M_1=8, M_2=2 and M_1=$_2$, M_2=8. All the two stage combinations are discussed below in detail the order, the normalized pass band and stop band frequencies of each stage are discussed in detail.

M_1=4, M_2=4

For the first stage where $M_1 = 4$ the normalized pass band and stop band frequencies are $W_p = 0.062\pi$ and $W_s = 0.4224\pi$ for the second stage $M_2 = 4$ the pass band and stop band frequencies are $W_P = 0.2484\pi$ and $W_s = 0.3104\pi$.

For linear phase FIR equiripple FIR filter the order of first stage $N_1 = 10$ and order of second stage $N_2 = 74$ in total the order is 84, for Kaiser window $N_1 = 18, N_2 = 106$. In total the order is 124. So, by analyzing its order and other parameters the order of Kaiser has decreased from 424 to 124 and for equiripple order has decreased from 266 to 86. So, complexity and multiplication rate will also decrease proportionately.

M_1=8, M_2=2

For the first stage where $M_1 = 8$ the normalized pass band and stop band frequencies are $W_p = 0.062\pi$ and $W_s = 0.1724\pi$ for the second stage $M_2 = 2$ the pass band

and stop band frequencies are $W_P = 0.4968\pi$ and $W_s = 0.6208\pi$ respectively. For linear phase equiripple FIR

filter the order of first stage $N_1 = 36$ and order of second stage $N_2 = 36$ in total the order is 72, for Kaiser window $N_1 = 53, N_2 = 53$. In total the order is 106.

M_1=2, M_2=8

For the first stage where $M_1 = 2$ the normalized pass band and stop band frequencies for the first stage are $W_p = 0.062\pi$ and $W_s = 0.9224\pi$ for the second stage $M_2 = 8$ the pass band and stop band frequencies are $W_P = 0.1242\pi$ and $W_s = 0.1552\pi$ respectively. For linear phase FIR equiripple filter the order of first stage $N_1 = 7$ and order of second stage $N_2 = 147$ in total the order is 154, for Kaiser window $N_1 = 8, N_2 = 212$. In total the order is 220. So, all the combinations of two stage realization are including the amount of hardware required, multiplication rate at the output are specified in Table III.

3) Three Stage Realization

The possible combinations are M_1=2, M_2=2, M_3=4; M_1=2, M_2=4, M_3=2 and M1= 4, M_2=2, M_3=2. All the three stage combinations are discussed below in detail the order, the normalized pass band and stop band frequencies of each stage are discussed in detail.

M_1=2, M_2=2, M_3=4

For the first stage where $M_1 = 2$ the normalized pass band and stop band frequencies for the first stage are $W_p = 0.062\pi$ and $W_s = 0.9375\pi$ for the second stage $M_2 = 2$ the pass band and stop band frequencies are $W_P = 0.12416\pi$ and $W_s = 0.87554\pi$ for the second stage $M_3 = 4$ the pass band and stop band frequencies are $W_P = 0.248929\pi$ and $W_s = 0.31036\pi$ respectively.

For linear phase FIR equiripple filter the order of first stage $N_1 = 7$,order of second stage $N_2 = 3$ and order of third stage $N_3 = 78$ in total the order is 88, for Kaiser window $N_1 = 8, N_2 = 9, N_3 = 106$. In total the order is 123.

M_1=2, M_2=4, M_3=2

For the first stage where $M_1 = 2$ the normalized pass band and stop band frequencies for the first stage are $W_p = 0.062\pi$ and $W_s = 0.9375\pi$ for the second stage $M_2 = 4$ the pass band and stop band frequencies are $W_P = 0.12416\pi$ and $W_s = 0.3750\pi$ for the second stage $M_3 = 4$ the pass band and stop band frequencies are $W_P = 0.4965\pi$ and $W_s = 0.6207\pi$ respectively.

For linear phase FIR equiripple filter the order of first stage $N_1 = 7$,order of second stage $N_2 = 18$ and order of third stage $N_3 = 39$ in total the order is 64, for Kaiser window $N_1 = 8, N_2 = 27, N_3 = 53$. In total the order is 88.

Table. III

Specifications	M_1=4 & M_2=4		M_1=8 & M_2=2		M_1=2 & M_2=8	
	Kaiser	Equiripple	Kaiser	Equiripple	Kaiser	Equiripple
Number of Multipliers	126	86	108	74	222	156
Number of Adders	124	84	106	72	220	154
Number of States	124	84	106	72	220	154
Multiplications per Input Sample	126	86	108	74	222	155
Additions per Input Sample	124	84	106	72	220	154
Multiplication Rate at the Output of First Stage	289980000	16110000	426915000	289980000	257760000	225540000
Multiplication Rate at the Output of Second Stage	426915000	298035000	213457500	144990000	853830000	592042500
Total Multiplication Rate	716895000	459135000	640372500	304970000	1111590000	817852500

Table. IV

Specifications	M_1=2 , M_2=2 & M_3=4		M_1=2 , M_2=4 & M_3=2		M_1=4 , M_2=2 & M_3=2	
	Kaiser	Equiripple	Kaiser	Equiripple	Kaiser	Equiripple
Number of Multipliers	126	91	91	66	86	59
Number of Adders	123	88	88	63	83	56
Number of States	124	88	88	63	83	56
Multiplications per Input Sample	125	91	91	66	86	59
Additions per Input Sample	124	88	88	63	83	56

Multiplication Rate at the Output of First Stage	257760000	225540000	257760000	225540000	289980000	177210000
Multiplication Rate at the Output of Second Stage	144990000	48330000	217485000	144990000	96660000	48330000
Multiplication Rate at the Output of Third Stage	426915000	314145000	213457500	157072500	213457500	157072500
Total Multiplication Rate	829665000	588015000	688702500	397602500	600097500	382612500

M_1=4, M_2=2, M_3=2

For the first stage where $M_1 = 4$ the normalized pass band and stop band frequencies for the first stage are $W_p = 0.062\pi$ and $W_s = 0.9375\pi$ for the second stage $M_2 = 4$ the pass band and stop band frequencies are $W_P = 0.12416\pi$ and $W_s = 0.3750\pi$ for the second stage $M_3 = 4$ the pass band and stop band frequencies are $W_P = 0.4965\pi$ and $W_s = 0.6207\pi$ respectively. For linear phase FIR equirippe filter the order of first stage $N_1 = 11$,order of second stage $N_2 = 6$ and order of third stage $N_3 = 39$ in total the order is 56, for Kaiser window $N_1 = 18$,N_2 = 12, $N_3 = 53$. In total the order is 83. Table IV indicates the Hardware requirements details.

4) Four Stage Realization

For the first stage where $M_1 = 2$ the normalized pass band and stop band frequencies are $W_p = 0.062\pi$ and $W_s = 0.9375\pi$ for the second stage $M_2 = 2$ the pass band and stop band frequencies are $W_P = 0.12416\pi$ and $W_s = 0.87554\pi$ for the third stage $M_3 = 2$ the pass band and stop band frequencies are $W_P = 0.0.24829\pi$ and $W_s = 0.75\pi$ respectively. For the fourth stage $M_4 = 2$ the pass band and stop band frequencies are $W_P = 0.4965\pi$ and $W_s = 0.62073\pi$ respectively. The four-stage realization is worst case for the design and this only possible if we use the approximate formula of Rabiner. Table V shows the hardware requirements and multiplication rate in detail.

IV. CONCLUSIONS

From the above discussions the of multistage design worthy multistage design is three stage design with M_1=4, M_2=2, M_3=2 because before multistage design was introduced, in the single stage the order of equiripple and Kaiser were 266 and 423 respectively. now, after utilizing multistage design it got decreased to 56 and 83 for equiripple method and Kaiser respectively and multiplication rate at the output has also decreased drastically. When we compare this filter i.e. M_1=4, M_2=2, M_3=2 with other combinations, this multi stage design results the minimum length with a smaller number of taps. The next worthy filter design is four stage design for this the order is 62 and 82 for equiripple and Kaiser respectively but when we use directly the FDA tool in MATLAB, we cannot find the filter order directly so we use approximation equation of Rabiner and design it which our filter design very efficient.

Table V

Specifications	M_1=2, M_2=2, M_3=2 & M_4=2	
	Kaiser	Equiripple
Number of Multipliers	86	61
Number of Adders	82	57
Number of States	82	57
Multiplications per Input Sample	86	61
Additions per Input Sample	82	57
Multiplication Rate at the Output of First Stage	257760000	225540000
Multiplication Rate at the Output of Second Stage	144900000	48330000
Multiplication Rate at the Output of Third Stage	96660000	56385000
Multiplication Rate at the Output of Forth Stage	213457500	157072500
Total Multiplication Rate	7172777500	487327500

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