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Implementation of CIC Filter for Multirate Transmission Systems

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ABSTRACT

In this paper a Cascaded Integrated Comb (CIC) filter, an optimized class of linear filters such as FIR is implemented for Digital Down Conversion (DDC) for efficient transmission multi-rate system. CIC filters are often used for the purpose of reducing sampling rate (decimation) and increasing sampling rate (interpolation). This work is to show the efficiency of CIC filters over FIR filters in fixed point applications. Single stage CIC filter and multistage CIC filters are realized. Here CIC filter design models are developed using Simulink software. Also the multi-rate filters are further improved by cascading various CIC filter stages.

***Keywords*--** cascaded Integrated comb, interpolation, decimation

I. INTRODUCTION

In signal processing, most frequently used procedure is to adjust sample rate frequency with respect to signal of interest. Systems dealing with different kind of sampling rates are termed as multi-rate system. As the need of data conversion is increasing day by day, extraction of narrow band from the wide band sources, and designing narrow band filters with wideband signals are becoming more decisive. The use of non-recursive filter structures has been increasing in the recent years for various applications. This is due to the low power consumption and increase in the circuit speed, especially when the decimation factor and the filter order are high. The frequency response of CIC (Cascaded-integrator comb) decimation filter with various techniques has been reported in the past few decades by many researchers [1-12]. In 1981, Eugene Hogenauer [12] proposed a class of digital filter for interpolation and decimation that requires no multipliers and use limited storage hereby leading to more economical hardware implementations. They are designated as cascaded integrator -comb (CIC) filter, because structure consists of an equal number of integrator section operating at the high sampling rate and a comb section operating at the low sampling rate. A low power fifth order decimation comb filter with programmable decimation ratio (16 and 8) and sampling rate (128 MHz and 44.8 GHz) for GSM and DECT application have been proposed by Y.Gao et al [3]. The low power consumption is achieved by following approaches. First the non-recursive architecture for comb filter is employed, second unnecessary computations eliminated with polyphase implementation of each stage and third each polyphase components implemented with data broadcast structure. H. Aboushady et al. [4] presented a multistage polyphase structure with maximum decimation factor in the first stage has been used. The proper choice of this first stage decimation factor can significantly improve the power consumption, area and maximum sampling frequency. F. Kaiser and R.W. Hamming[8] describes the filter sharpening technique based on the idea of amplitude change function (ACF) which is restricted to symmetric non-recursive (FIR) filters with piecewise constant pass band and stop band. A. Kwentus [5] designed and implemented a programmable CIC multi-rate decimation filter structure with filter sharpening techniques to improve the filters pass band response. This allows the first stage CIC decimation filter to be followed by a fixed-coefficient second-stage filter rather than a programmable filter thereby achieving a significant hardware reduction over existing approaches. A very efficient multistage decimation filter for a sigma-delta A/D converter has been proposed by L.L. Presti [6]. In this structure, the first-stage of the filter is obtained by properly rotating the zero-pole distribution of a comb filter in z-plane and then it can be implemented by using a recursive structure. Several schemes have been proposed by G. J. Dolecek and S.K. Mitra [7], [9-11] to design CIC filters with improved magnitude response. The authors proposed a different structure that consists of a comb section and a sharpening comb section with the latter section operating at a lower rate than the high input rate for the realization of comb-decimation filter with a sharpened magnitude response. Applying sharpening to the decimation filter in the last stage provides very good results, saving in number of operations comparing to the case of sharpening of complete filter. The main idea of this paper is to integrate the advantages of the structures presented in order to obtain the structure that can operate at a lower sampling rate while achieving better performances than the original comb filter based structure.

II. CASCADED INTEGRATOR – COMB FILTER

The CIC filter is formed by cascade of digital accumulator (integrator) subsequently chased by a cascade of digital differentiators (combs) in equal number. A digital switch or decimator is serviced to lower the sampling frequency of the comb signals with respect to the system sampling frequency, which is placed in between the integrators and the combs. This cascaded filter architecture is more powerful. Consider for decimation , one can get down computational complexity of narrowband low pass filter as compared with using a single stage low pass FIR, along which the filter operate at reduced clock rates, with low power and high speed applications. The reason of CIC filter more popular is because of its architecture that uses only adders, subtractors and registers. The CIC arithmetic requires no multiplication. After performing A/D conversion, the signal of interest could be recovered in a small frequency band compared to original frequency band transmitted, if it's so then it's necessary to filter it with a lowpass or bandpass filter to decrease the sampling rate. A narrowband filter followed by a down sampler as termed as decimator. The sampling rate can be decreased up to the "Nyquist rate" which says sampling rate is twice the highest frequency that means sampling rate is higher than the bandwidth of the signal, so as to avoid aliasing. In a band pass signal, the required frequency band for signal of interest should be within the integer band. The CIC filter is a class of hardware efficient linear phase FIR digital filter consists of an equal number of stages of ideal integrator and comb filter pairs. The highly symmetric structure of this filter allows efficient implementation in hardware. However the disadvantage of a CIC filter is that is passband is not flat, which is undesirable in many applications. This problem can be overcome through the use of compensation filter. CIC filter achieve sampling rate decrease (decimation) without using multiplication. The CIC filter first performs the averaging operation then follows it with the decimation. The transfer function of the CIC filter in z-domain is given as

$$H(Z) = \left[\frac{1}{N}\frac{1-z^{-N}}{1-z^{-1}}\right]^K \quad (1)$$

where M is the decimation factor, and K is the number of the stages. The transfer function in (1) will be also referred to as the comb filter. The integrator section works at the higher input data rate thereby resulting in higher chip area and higher power dissipation for this section. In order to resolve this problem the non-recursive structure of Eq. (1) can be used [12], [13].

In order to improve the low pass characteristics, multiple stages of the single CIC can be cascaded as Figure (1) illustrates. Each of the CIC components can be relocated with each other.

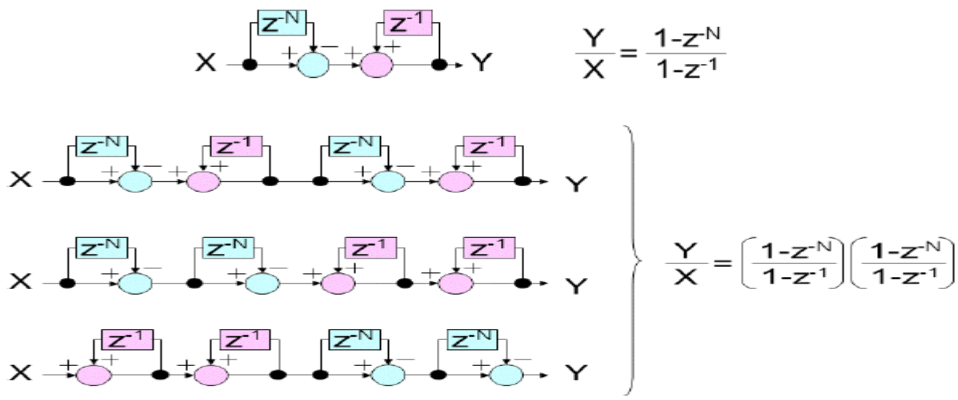


Figure 1 Cascaded CIC filter

$$H(z) = \left[\frac{1}{M}\right]^K \left[1 + z^{-1} + z^{-2} + \ldots + z^{-(M-1)}\right]^K \quad (2)$$

Implementing $H(z)$ of Eq. (2) in a polyphase form, the filtering at the high input rate can be moved to the lower rate. In this chapter we do not discuss the CIC implementation issues.

2.1 Magnitude characteristic:

The magnitude characteristic of the comb decimator must satisfy two requirements:

- To have a low droop in the frequency band defined by the passband frequency ωp in order to preserve the signal after decimation.
- To have a high attenuations in so called folding bands, i. e. the bands around of the zeros of the comb filter,

$$\left[\frac{2\pi i}{M}-\omega_p;\frac{2\pi i}{M}+\omega_p\right],\ \text{for}\quad i=\begin{cases}1,...,M/2 & \text{for}\quad M\ even\\ 1,...,(M-1)/2 & \text{for}\quad M\ odd\end{cases} \tag{3}$$

We define the passband frequency as the frequency where the worst case of passband drop occurs, (Kwentus, Willson, 1997).

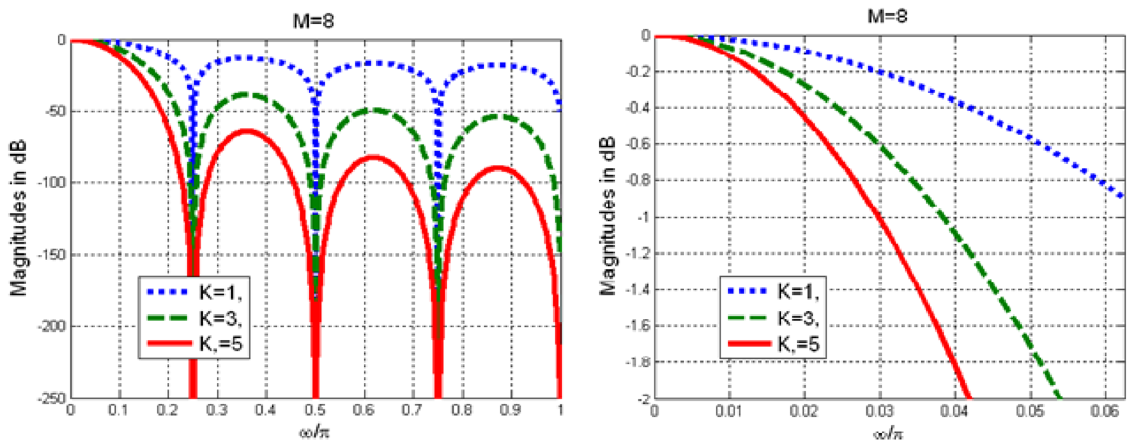
$$\omega_p=\frac{\pi}{MR}, \tag{4}$$

where R is the decimation stage that follows the CIC decimation stage, and that is usually much less than M.

The magnitude response of the comb filter exhibits a linear-phase, lowpass characteristic which can be expressed as

$$\left|H_{comb}(e^{j\omega})\right|=\left|\frac{1}{M}\frac{\sin(\omega M/2)}{\sin(\omega/2)}\right|^K \tag{5}$$

Figure 2.(a) shows the magnitude characteristics in dB for M=8 and the values of K=1, 3, and 5.



a. Overall magnitude responses. **b. Passband zooms.**

Fig. 2. Magnitude responses of comb filters.

Note that the attenuations in the folding bands are increased by increasing the numbers of stages. However, an increasing in the number of stages results in the increasing of the passband droop as shown in Fig. 2.b. In the continuation we will consider different methods to improve the comb magnitude characteristics keeping its simplicity.

The frequency responses of the comb, integrator and CIC are described in Figure 3, where the number of comb delay stages $N$is 4. The gain of this CIC becomes 4 (=N)at DC so that the output should be scaled to 1/Nat the end. The first null point resides at fs/Nso that the number of delay N establishes the passband width. The total response of the LPF actually looks something like a SINC (sin$X$/X) curve. It is not flat, so a wide band signal waveform would be distorted to some extent.

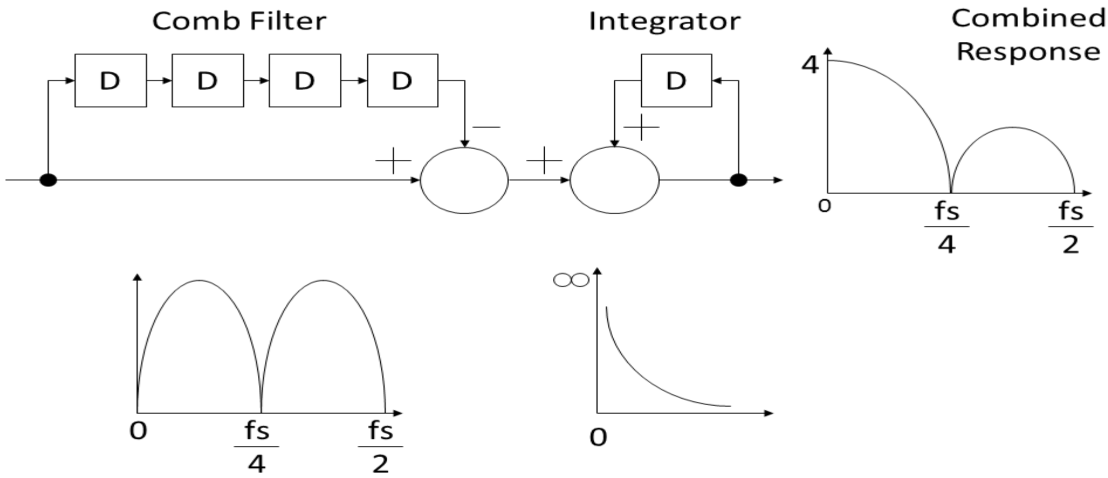


Figure 3 Comb Filter and its Responces

In this work the designing CIC decimation filter is performed. The block diagram of the CIC decimation filter is shown in the figure below.

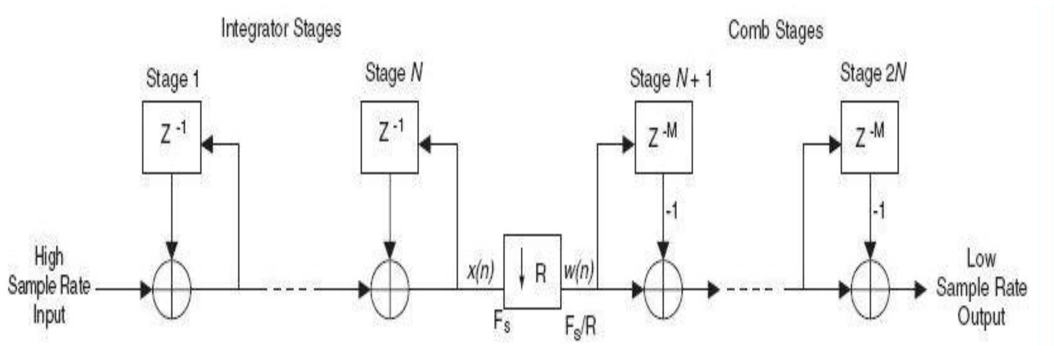


Figure 4: CIC decimation filter block diagram

Above Figure (4) shows the CIC decimation filter block diagram. Here in the figure we are designing CIC decimation filter with the help of Simulink software in MATLAB. Selecting the parameters for the designing CIC filter is explained below.

2.2 Implementation of CIC Filters:

Simulink is used to design the systems by using only block diagram representation. By giving the parameters we can design the system without writing the code. The diagrammatic representation of CIC Filters is shown in the fig. below.

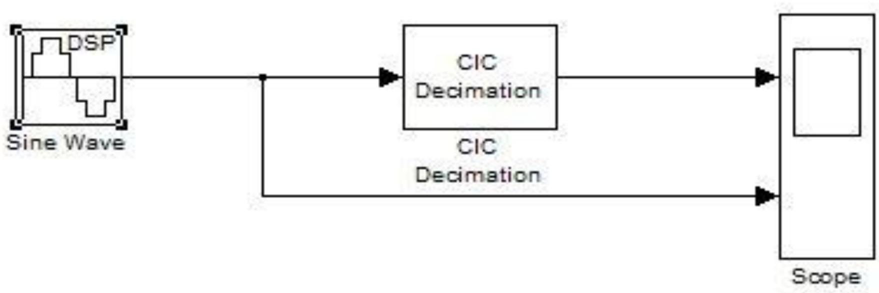


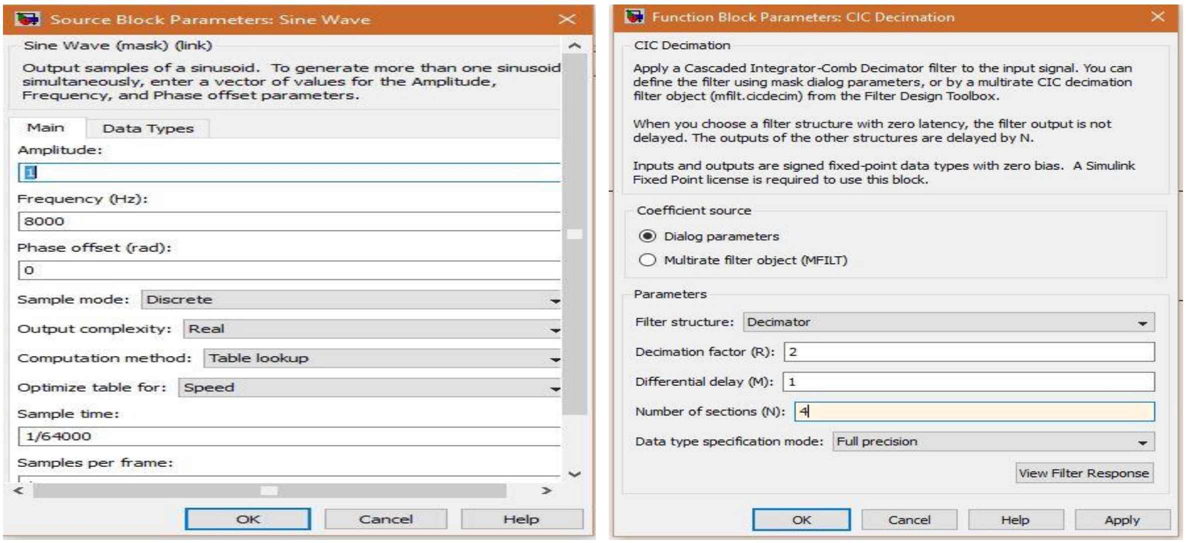
Figure 5 CIC filter circuit diagram using simulink

We can select the components of the system in simulink library browser, where we have to select CIC decimation form 'CIC library' and discrete sine wave from the 'signal processing block set'. To see the output of our system, scope has to be selected from the 'sinks' block.

Here we are sampling the signal with the frequency of 64 KHz. For example we have 8 KHz sine wave. We have decimate it at the rate of two. It means in the input side we have 8 samples (i.e. 64/8=8), at the output side we should have only 4 samples when we decimate the signal at the rate of two. The input sine wave parameters are shown in the Figure 6(a).

After giving the parameters for sine wave we have to give the parameters for CIC decimation block. The parameters should be selected according to our desired output. We have to keep decimation factor as required i.e. in this project we are keeping decimation factor as two. This is shown in the Figure 6(b).
Fig (a) source block parameters
Fig (b) CIC function block parameters

Figure 6: The CIC decimation block parameters are shown in the figure below



As shown in the above figure we have given the parameters for both input signal and CIC decimation filter. The filter response is shown in the Figure 7 below.

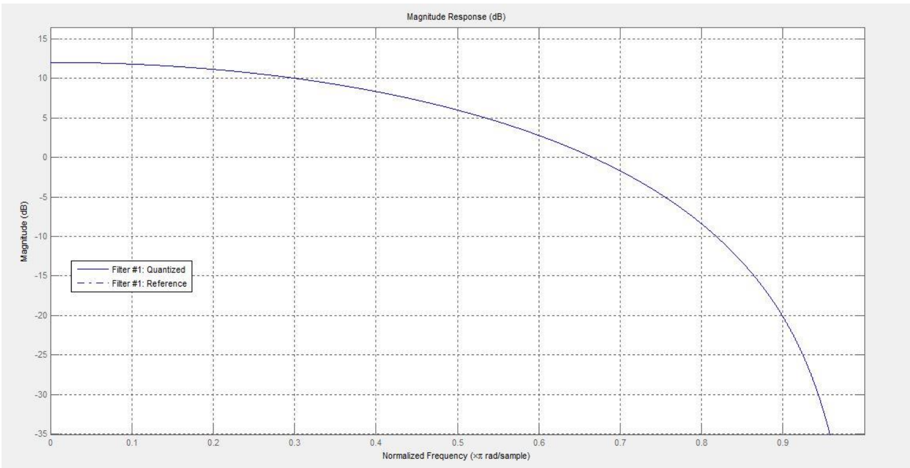


Fig 7 CIC decimation filter response.

Here we are getting a gain of about 12db. This is the main disadvantage of CIC filters. As a result in the output there is change in the amplitude i.e. the amplitude of the output signal is increased. So in order to compensate this, we will use compensation filter which will be explained later. After giving the required parameters to the signal and CIC filter the output of the filter will be observed in the 'scope'. Here in Scope we have two channels one for input channel and one for output. The output of the filter is shown in the below Figure 8.

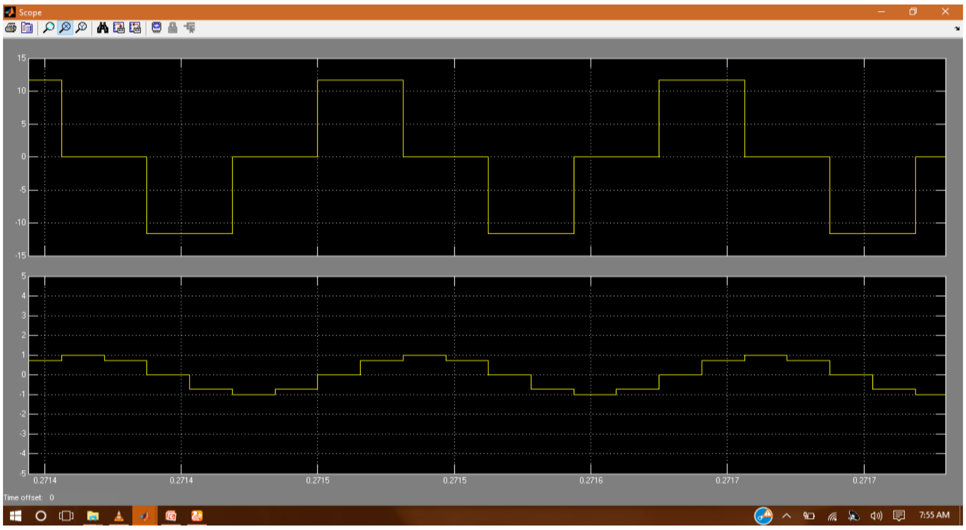


Figure 8 Output response of CIC filter

Here the below channel shows the input signal and the upper channel shows the output signal of the CIC filter. In the input channel we have 8 samples where as in the output channel we have only 4 channels. So we can say that it is decimated. But where as the amplitude of the signal got increased because the gain of the CIC filter is very high. This can be reduced with the help of Compensation filter.

III. COMPENSATION FILTER

As discussed earlier the disadvantage of using CIC filter is it has more gain in the frequency response. It means the CIC filter frequency response does not have a wide, flat pass band. To overcome the magnitude droop, a FIR filter that has a magnitude response that is the inverse of the CIC filter can be applied to achieve frequency response correction. Such filters are called "compensation filters." compensation filter always operates at the lower rate in a rate conversion design. One benefit of running the compensation filter at the low rate is to achieve a more efficient hardware solution, that is, more time sharing in the compensation FIR filter.

3.1 Mathematical model:

We describe here the compensation filter (Jovanovic Dolecek & Mitra, 2008) [7] because this filter satisfies all the properties mentioned previously. Consider a filter with the Magnitude response

$$\left|G(e^{j\omega})\right| = \left|1 + 2^{-b}\sin^2(\omega M / 2)\right| \tag{6}$$

where b is a integer parameter the corresponding transfer function can be expressed as

$$G(z^M) = -2^{-(b+2)}\left[1 - (2^{b+2} + 2)z^{-M} + z^{-2M}\right] \tag{7}$$

Denoting

$$A = -2^{-(b+2)}; B = -(2^{b+2} + 2) \tag{8}$$

we arrive at

$$G(z^M) = A\left[1 - Bz^{-M} + z^{-2M}\right] \tag{9}$$

The compensator filter has the scaling factor A and a single coefficient B which requires only one adder. Additionally, the compensator can be implemented at a lower rate after the downsampling by M by making use of the multirate identity (Jovanovic Dolecek, 2002), becoming a second order filter

$$G(z) = A\left[1 - Bz^{-1} + z^{-2}\right] \tag{10}$$

In that way the filter does not depend on the decimation factor M but only on the number of the stages K which defines the parameter b in equation (7). The system after compensation filter used is shown in the Figure (9) below.

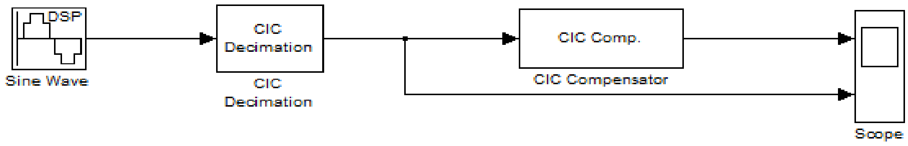


Figure 9: CIC filter using compensation filter

Compensation filter parameters should be selected such that the gain of the decimation filter is to be reduced in a considerable manner. It means we have gain of the decimation filter about 22dB. So in order to compensate this we have to design the compensation filter in the right way. The first thing we have to consider while designing the decimation filter is no. of sections in the compensation filter should be equal to the no. of sections of the decimation filter. It means that no. of sections that we have taken in the compensation filter sections should be equal to the no. of sections that we have taken in the decimation filter section.

In our filter we have taken the no. of sections in the decimation filter is 4. So we have to take no. of sections in the compensation filter also as 4. As we have already decimated the signal by 2, we have to take the filter type in the compensation filter is single rate. The parameters of the compensation filter are shown below.

As shown in the figure8 no. of CIC sections are 4 because no. of sections that we have taken in the decimation filter are 4, so no. of sections in the Compensation filter are also 4. We have selected the filter type is single rate because we have already did the decimation process in the decimation filter. So if we select decimator in this compensation filter again then we will get the decimated signal again in the output of compensation filter. Compensation filter is used just for compensation purpose but not for decimation purpose. So we will select filter type as single rate. The filter specifications parameters selection is shown in Figure (10).

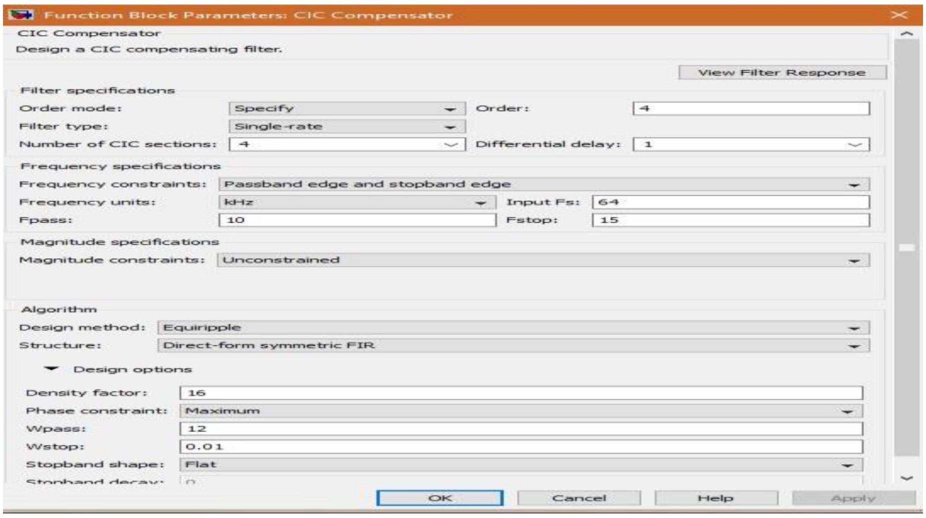


Figure 10 parameters for selecting the compensation filter

After using the compensation filter the output amplitude of the signal is reduced to great extent. The output of the signal without using compensation filter is 12v whereas after using compensation filter is 1.5v as shown in the simulation results. The frequency response of the compensation filter is shown Figure 11.

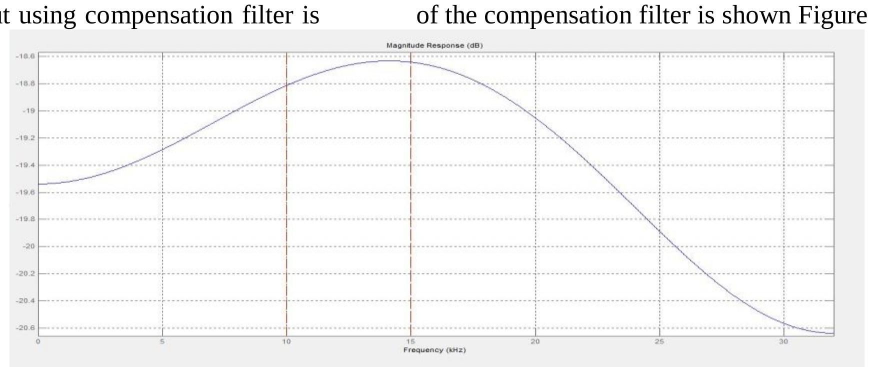


Figure 11 Response of CIC compensation filter

IV. SIMULATION RESULTS

If an 8 KHz signal is applied then the output contains about 12V.The output of the filter with and without using the compensation filter is shown in the below Figure (12). So after using compensation filter, the amplitude got reduced to 1.4V from 12V

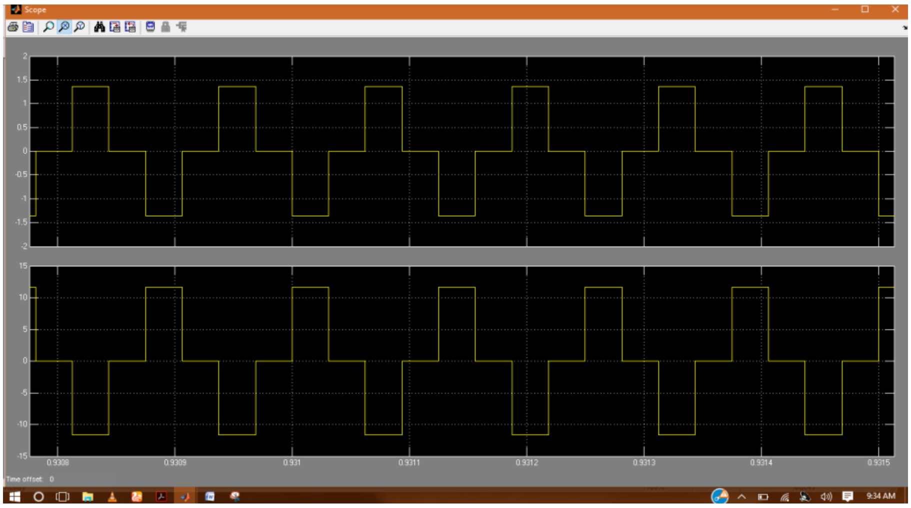


Figure 12: Output responses of CIC filter for 8 KHz signal.

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V. CONCLUSION

A Cascaded Integrated Comb (CIC) filter has been designed for efficient transmission multirate systems. This paper presented different methods that have been proposed to improve the magnitude characteristics of the CIC decimator. The CIC filter has given better result than the traditional FIR filter. Particularly, the methods are divided into 3 groups based on the improvement in the passband, stopband or in both i.e. passband and stopband. The CIC filter is also implemented using compensation filter, after using this magnitude is drastically decreases which is shown in the simulation results. All the codes are done in MATLAB.

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