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Sharpening of Maximally Flat Narrowband and Wideband CIC Compensator

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ABSTRACT

This paper presents the design and implementation of sharpening of maximally flat cascaded integrator comb compensation filters. Cascaded integrator-comb (CIC) digital filters are computationally efficient implementations of low pass filters. No multiplication characteristic makes them popular in hardware devices. The modified sharpened cascaded integrator comb compensation filter is used to improve magnitude response and gain. For narrow and wide-band compensation second-order and fourth-order linear phase filters are considered. Power-of-two decimation factors of CIC filter is M and number of adders are depends upon decimation factor. Closed form equations for the computation of the filter coefficients are provided. The new technique delivers gain and stop band attenuation correction comparable to existing techniques.

Introduction

Hogenauer [1] introduced the cascaded integrator-comb filter. It is the simplest multiplierless decimation filter used in communication systems first. But the magnitude response of this filter has high passband droops, which is not desired in many applications. CIC structures consist of a cascade of N integrators running at a high sample rate and N comb filters, which run at the down sampled rate. The attraction of these structures, which can be viewed in [1], lie in their efficient hardware implementation: no multipliers are needed and the storage requirement is minimal. The transfer function of CIC filter is given by

$$\mathbf{H_{CIC}(z)} = \left(\frac{1}{M}\frac{1-Z^{-M}}{1-Z^{-1}}\right)^{N} = \left[\frac{1}{M}\sum_{i=0}^{N-1} Z^{-i}\right]^{N} \qquad (1)$$

Where

M= Decimation factor

N= Number of stages

The decimation ratio is responsible for droops in pass band gain, these droops can be compensated using FIR filter at second stage in the decimation process. Sharpening is a filter design technique that aims at improving passband distortion and stopband attenuation by using multiple realization of a basic filter [1].The sharpening filter proposed in [2] can be used to overcome the disadvantages of CIC filter. New sharpened comb decimator structure consisting of a cascade of a comb-filter based decimator and a sharpened comb decimator. The proposed realization scheme in [3] allows the sharpened section to operate at a lower rate that depends on the decimation factor of the first section operate at a lower rate that depends on the decimation factor of the first section. Using a polyphase decomposition, the sub filters of the first section can also be operated at this lower rate

Using polyphase decomposition, the sub filters of the first section can also be operated at this lower rate. In the late 1970s, Kaiser and Hamming proposed a method for improving filter performance. Sharpening a filter twice can overcome some of the method's limitations. In paper [4] different decimator filter are proposed to reduce passband droop and better stop band alias rejection. Another design of decimation filter called GCFs are suitable for $\sum\Delta$ modulator in terms of better selectivity and quantization noise rejection as compared to conventional comb decimation filter [5]. Another decimation filter without multipliers is proposed in [6] is based on IFIR filter and rounding and sharpening techniques ACF is used. Decimation factor can be presented as the product of two factors. The polyphase decomposition is applied to the rounded interpolator and its polyphase components are moved to the lower rate.

In paper [7] GSM based digital down converter is proposed which uses optimal equiripple technique to reduce resource requirement and polyphase decomposition to improve hardware complexity and also reduces the pass band droop as well as increase the attenuation in folding band of CIC filter. A high speed interpolator using embedded LUT structure for software defined radios increases the speed and also save the resources. In papers [8]- [10] authors proposed the simple compensation filters for both narrow and wide band compensation with low computational complexity.

The pass band droop as well as increase the attenuation in folding bands cab be reduced by the sharpening technique proposed in paper [11]. The compensator based on maximally flat error criterion is suitable for application in narrow-band software radio receivers [12]-[14]. Investigation [13] is also suitable for wide band compensation. In paper [15] a hybrid approach is proposed for GSM digital down converter using multiplierless and multiplier based decimators. The proposed structure reduces the cost, filter order and hardware complexity.

The non-recursive methods proposed in [16] are used to improve the alias rejection in first folding band. Decimator design has been presented for multirate digital signal processing. It is observed from the simulated results that symmetric structure consumes almost 50% less multipliers and MPIS compared to transposed structure. So the symmetric structure based decimator in [17] is suitable to provide cost effective solution. The proposed double-sharpened decimation filter in [18] uses a pre-droop compensator which improves the passband response of a conventional CIC filter so that it provides an efficient sharpening performance at half-speed with comparison to conventional sharpened filters.

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The passband droop characteristics with compensation provides –1.6 dB for 1.25 MHz, –1.4 dB for 2.5 MHz, –1.3 dB for 5 MHz, and –1.0 dB for 10 MHz bandwidths, respectively. Simulation results of [19] shows that the gain responses of the CIC-filter and filter sharpening technique is used to improve the filter performances in terms of a smaller passband error and greater stopband attenuation. In paper [20] author proposed the serial and parallel interpolator which provide speed efficient solution for wireless applications. In papers [21, 22] authors proposed CIC filter architecture to improve frequency response and reduce stop band attenuation.

The main goal of this study is to extend the results given in [13] for narrow-band as well as for wide-band compensation filters. Multiplierless design is proposed and closed form equations are used to compute filter coefficients. The forthcoming section represents the maximally flat compensation filters for narrow-band and wide-band with multiplierless design along with results and discussion followed by conclusion.

Maximally flat compensator design

The design of linear phase FIR compensation filter, with maximally flat magnitude response is expressed as:

$$G(z) = H_{CIC}(z)P(z)^M \qquad (2)$$

Where, H (z) is CIC filter defined in (1) and P(z) is a Type I linear phase filter. The second stage having decimator factor v and pass band edge frequency w_p. At $w_p = \pi/_{Dv}$ the worst case droops occurs. If $v \geq 4$ filter is narrow band, otherwise it is considered wide-band [13]. From (1), the frequency response of the CIC filter is given by:

$$H(e^{jw}) = e^{-j(M-1)N_w/2} H_R(w) \qquad (3)$$

Where, $H_R(w)$ is a real- valued function, given as:

$$H_R(w) = \left(\frac{1}{M}\frac{\sin(Mw/2)}{\sin(w/2)}\right)^N \qquad (4)$$

And P(z) is the Type I linear phase FIR compensation filter and given as:

$$P(z) = \sum_{n=0}^{L} a_n z^{-n} \qquad (5)$$

Where, L is an even integer and is the order of P(z) and n= 0,1.....,L

The error function for designing of compensation filter is defined as [13]:

$$E(w) = P_R(w)H_R(w) - 1 \qquad (6)$$

For maximally flat condition E(0)= 0 and $P_R(0) = 1$

Narrowband (NB) compensator design

The narrow-band compensator filter based on the second-order linear phase filter. The resulting magnitude characteristics exhibits maximally flat characteristics at ω = 0.The transfer function of P(z) at L = 2 is given by:

$$P(z) = a + bz^{-1} + az^{-2} \qquad (7)$$

By using maximally flat conditions given by (6) and by solving (7) we get:

$$a = -\frac{N}{32}\frac{1-M^{-2}}{1-2^{-2}}\ ,\quad b = 1 - 2a \qquad (8)$$

Rewrite the equation for filter coefficient (a) as:

$$a = -2^{-5}N.A \qquad (9)$$

Where, $A = \frac{1-M^{-2}}{1-2^{-2}}$. The value of M for multiplierless design is expressed as the power of two such as M = 2^k, for k> 0 the value of A becomes:

$$A = \frac{1-2^{-2k}}{1-2^{-2}} \qquad (10)$$

The narrow band CIC compensation can be illustrated by taking the following parameters.

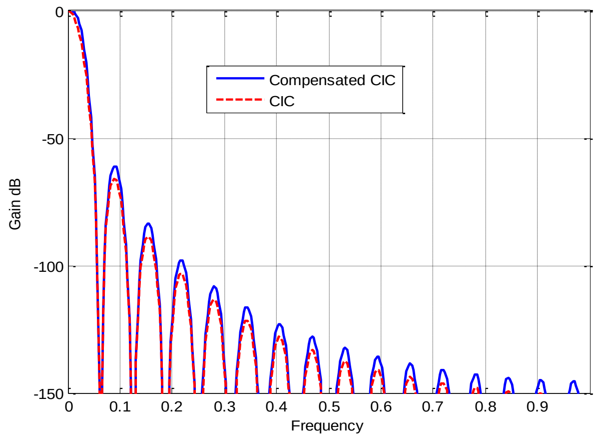

Figure 1. Magnitude response of the narrowband CIC filter

Consider the design parameters; M = 32, N = 5 and v = 4, resulting magnitude response and passband details of both CIC and compensated CIC filters are in Fig. 1 and Fig. 2. The resulting passband frequency wp is 0.0078π rad. The figures show that compensated CIC filter has same attenuation in the alias bands as the CIC filter and having maximally flat passband

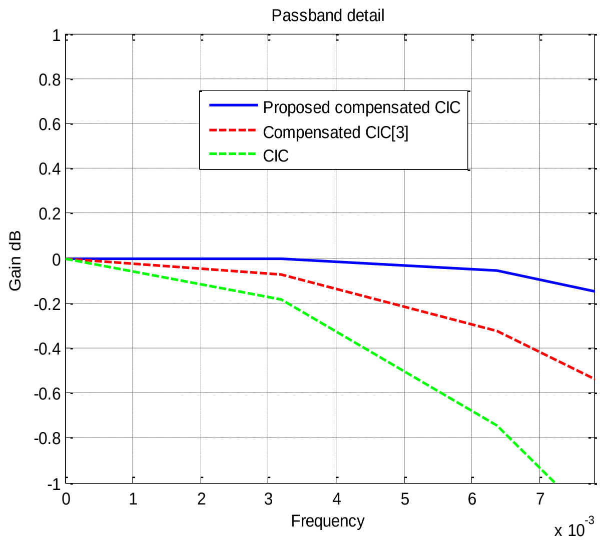

Figure 2. Passband details of CIC compensator filter.

Wideband (WB) compensator

The design of wideband compensator for L=4 using fourth-order type-l linear phase FIR filter having transfer function P (z) is:

$$P(z) = a + bz^{-1} + a_1 z^{-2} + bz^{-3} + az^{-4} \qquad (11)$$

By using maximally flat conditions, we get:

$$a = 2^{-8}N.B(2^{-3}N.B + 1 - 2^{-2}C) \qquad (12)$$

$$b = -2^{-6}N.B(2^{-3}N.B + 3 - 2^{-2}C) \qquad (13)$$

$$a_1 = 1 - 2a - 2b \qquad (14)$$

Where B and C are given as [13]:

$$B = \frac{1-D^{-2}}{1-2^{-2}}\ ,\quad C = \frac{1-(2D)^{-2}}{1-2^{-4}} \qquad (15)$$

For multiplierless design the decimation factor is the power of two in such as $M = 2^{2D-1}$, where D is positive integer. The wideband CIC compensation can be illustrated by taking the design parameters are D= 32, N= 5 and v =2, the resulting passband edge frequency w_p= 0.0156 π rad. The gains of CIC and compensated CIC filters at edge frequency are -5.54 and -0.58 dB as shown on Fig. 3 and Fig.4.

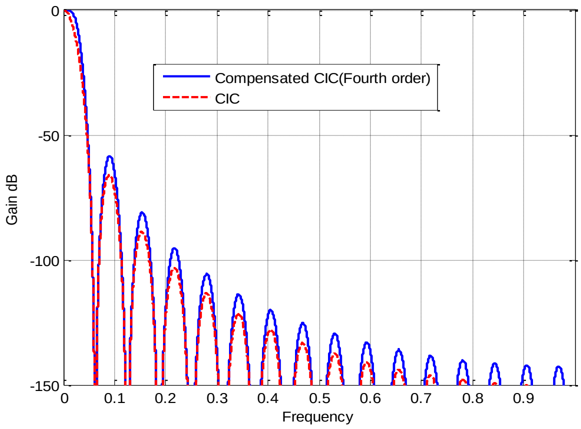

Figure 3. Magnitude response of the WB CIC compensator

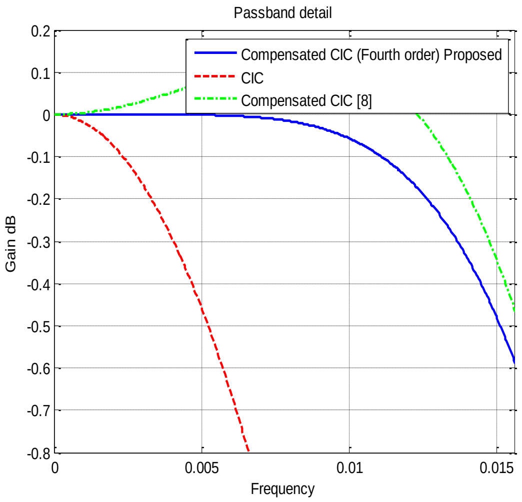

Figure 4. Passband details of WB CIC compensator filter

Proposed Maximally Flat sharpened CIC Compensators

Figure 5 shows the block diagram of the proposed sharpened CIC compensator filter.

As shown in Fig. 5, the proposed sharpened CIC compensator filter consists of sharpened CIC filter, decimation and a compensator. By using the sharpening equations (16), (17) and (18) the narrow-band and wide-band compensators results in the improved gain and magnitude responses as shown in the Fig. 6 and Fig. 7.

$$\mathbf{H_2(z) = \ 2\,H(z) - H^2(z)} \qquad (16)$$

$$\mathbf{H_3(z) = 3H^2(z) - 2H^3(z)} \qquad (17)$$

$$\mathbf{H_4(z) = H^3(z) - 3H^2(z) + \ 3H(z)} \qquad (18)$$

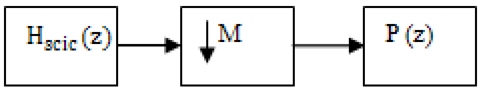

Figure 5. Block diagram of proposed sharpened CIC compensator

Result and discussion

The proposed sharpening of maximally flat compensate CIC filter with the existing methods for both narrow band and wide band compensation. The Figure 6 and Figure 7 shows the magnitude response of the proposed CIC filter is compared with existing CIC[1] and with maximally flat CIC filter, where the gain and stop band attenuation are emphasized. Table 1 shows the summary of basic CIC, maximally flat CIC and proposed CIC structure. For 3rd order of sharpening it gives maximum gain -1.476 dB and minimum stop band attenuation -112.7dB and for wideband compensation 3rd order sharpening gives gain 0.423 dB and -107.5 dB stop band attenuation. It is observed that the proposed sharpening before compensation provide better attenuation and gain by using the seven adders for narrow band compensation and 15 adders for wideband compensation, which are same used in [13].

Table 1. Narrow band CIC compensator details

Filter type	Gain(dB)	Stopband Attenuation (dB)
CIC	-6.882	-66.17
Paper [13]	-3.027	-61.12
2nd order sharpening (S2)	-0.4974	-55.1
3rd order sharpening (S3)	-1.476	-112.7
4th order sharpening (S4)	-0.5537	-51.57

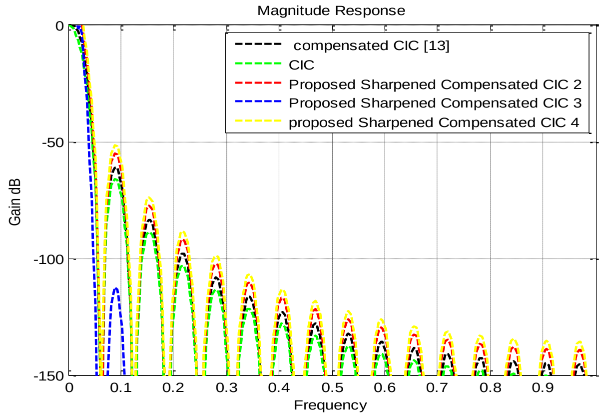

Figure 6. Magnitude responses comparison for NB CIC compensator

Conclusion

This paper discusses the design and implementation scheme of sharpening of maximally flat compensated CIC decimation filter employing a second order compensator for narrow band applications and fourth order compensator used for wide band applications. The results shows that the proposed sharpened decimation filter gives improved the Characteristics of the pass band droops and sideband attenuation.

Table 2. Wideband CIC compensator detail

Filter Type	Gain(dB)	Stop-band Attenuation (dB)
CIC [1]	-3.903	-66.17
Reference [13]	-0.4019	-58.53
Proposed 2nd order sharpening (S2)	0.161	-52.53
Proposed 3rd order sharpening (S3)	0.423	-107.5
Proposed 4th order sharpening (S4)	0.034	-49.15

Table 3 and 4 shows that the initially CIC decimation filter having a large passband droop i.e. 3.0035 dB at 0.04 $\pi \frac{\mathbf{rad}}{\mathbf{sample}}$ without any Compensation method and getting even more worst in high frequencies.

Table 3. Details of pass band droops of narrowband CIC

Norm. Freq.	CIC	CIC[13]	S2	S3	S4
0.0200	-0.7430	-0.0554	0.3363	0.5022	0.5332
0.0250	-1.1632	-0.1305	0.3833	0.5350	0.6456
0.0400	-3.0035	-0.7452	0.3953	0.4574	0.7126
0.0500	-4.7310	-1.6339	0.3095	0.2772	0.5792
0.0600	-6.8821	-3.0269	0.1663	0.0080	0.3532
0.0650	-8.1246	-3.9387	0.0844	-2.9721	0.2348
0.0800	-12.5721	-7.6418	-2.7032	-12.1461	-0.2131
0.0850	-14.3129	-9.2265	-4.0380	-15.1229	-1.3228
0.0900	-16.1941	-11.0006	-5.5024	-18.3502	-2.5014
0.0950	-18.2241	-12.9733	-7.1944	-21.9725	-3.9217

Table 4. Detail of pass band droops of wideband CIC

Norm. Freq.	CIC	CIC[13]	S2	S3	S4
0.0200	-0.7430	-0.0044	0.3389	0.5048	0.5358
0.0400	-3.0035	-0.2070	0.4222	0.4844	0.7395
0.0600	-6.8821	-1.5282	0.2412	0.0829	0.4281
0.0700	-9.4838	-3.0297	0.1034	-4.1773	0.2314
0.0800	-12.5721	-5.2881	-0.3495	-9.7924	0.1070
0.0900	-16.1941	-8.4172	-2.9191	-15.7669	0.0041
0.0950	-18.2241	-10.3391	-4.5602	-19.3383	-1.2875
0.1000	-20.4124	-12.5145	-6.5272	-23.4245	-3.0452

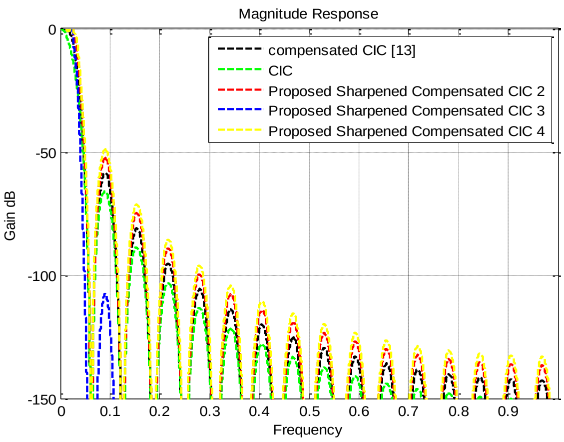

Figure 7. Magnitude responses comparison for WB CIC compensator

2nd, 3rd and 4th ordered Sharpened CIC decimation filter with FIR compensation introduce a significant improvement in its passband characteristic as shown in Figure 2 and figure 4**.**

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