Double-Sharpened Decimation Filter Employing a Pre-droop Compensator for Multistandard Wireless Applications

Chanyong Jeong, Young-Jae Min, and Soo-Won Kim

This paper presents a double-sharpened decimation filter based on the application of a Kaiser and Hamming sharpening technique for multistandard wireless systems. The proposed double-sharpened decimation filter uses a pre-droop compensator which improves the passband response of a conventional cascaded integrator-comb filter so that it provides an efficient sharpening performance at half-speed with comparison to conventional sharpened filters. In this paper, 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. These results demonstrate that the proposed double-sharpened decimation filter is suitable for multistandard wireless applications.

Keywords: Cascaded integrator-comb, decimation filter, sharpened filter, sigma-delta.

I. Introduction

Recently, with the expansion of the digital regime in wireless communication systems, digital signal processing has been broadly adopted. Owing to this technical trend, an analog-to-digital converter (ADC), such as a bandpass sigma-delta modulator, is moved near the front-end for more aggressive digitization of signals [1]. As a consequence, a versatile signal processing is allocated in the digital domain which can provide merits, such as a reconfigurable architecture and high performance [2].

Among digital blocks, a digital decimation filter is widely used for channel selection and filtering in wireless systems [3]-[8]. A broadly applicable reduced-rank filtering approach has been presented [3], [4]. Optimization and implementation schemes of the decimation filter architectures have been discussed [5], [6]. In addition, design issues of the decimation filter for sigma-delta ADC have been covered [7], [8].

The different approaches obtain an efficient and flexible decimation filter, as part of multistandard digital receiver. For a realization scheme, the multirate decimation filter employing a cascaded integrator-comb (CIC) filter is a popular choice because of its efficient structure [9], [10]. The CIC-based decimation filter is an advantageous anti-aliasing rate conversion filter, which can be adopted for decimation down to four times the Nyquist rate [11].

For years, various filter schemes have been presented [12]-[17]. There have been two main objectives in the literature, which are related to operating speed based on an efficient filter structure [12], [13] and frequency response [14]. However, the

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Manuscript received May 8, 2010; revised Sept. 15, 2010; accepted Oct. 11, 2010.

This work was supported by the Samsung Electro-Mechanics Co., Ltd., and Korea University.

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doi:10.4218/etrij.11.0110.0272

previous literature concentrated on improvement of the operating speed or the frequency response, but not both together [15], [16]. Recent studies presented a wideband CIC compensator filter for a digital intermediate frequency receiver [17]. However, since the CIC compensator has been included in the main sharpening section, it introduces more complexity.

This paper proposes a system architecture and realization scheme for a double-sharpened multirate digital decimation filter based on a Kaiser and Hamming sharpening technique [18] for multistandard wireless applications, which satisfies the operating speed and frequency objectives.

This paper is organized as follows. Section II discusses the CIC-based sharpened filters which have been previously studied. Section III covers the detailed filter structure and implementation scheme of the proposed double-sharpened decimation filter. Section IV shows the comparison results of the proposed double-sharpened decimation filter with conventional ones. Finally, section V provides a conclusion.

II. CIC-Based Sharpened Filter

1. Sharpened Comb Filter

Figure 1(a) shows the block diagram of a conventional sharpened comb filter [12] which is based on the Kaiser and Hamming sharpening technique. As shown in Fig. 1(a), the sharpened comb filter is organized with cascades of the comb filters, scaling multipliers, and a delay line to equalize the delay through both signal paths in the first section.

The sharpened comb filter improves the passband response and stopband attenuation using multiple copies of the same filter. The resulting transfer function of the sharpened CIC (SCIC) filter is defined as

$$H_{\mathrm{SCIC}}(z) = 3H_{\mathrm{CIC}}(z)^2 - 2H_{\mathrm{CIC}}(z)^3, \tag{1}$$

where the comb filter adopts the CIC structure. Thus, the frequency response of the SCIC filter can be expressed as

$$\left|H_{\mathrm{SCIC}}(e^{j\omega})\right| = \left\| \left[3\left(\frac{\sin(\frac{\omega M}{2})}{M\sin(\frac{\omega}{2})} \right)^{2L} \right] - \left[2\left(\frac{\sin(\frac{\omega M}{2})}{M\sin(\frac{\omega}{2})} \right)^{3L} \right] \right\|. \tag{2}$$

In the case of a multistage decimation filter using the CIC and other filters, the passband droop caused by a conventional CIC filter can be compensated by the following filters. However, the alias rejection cannot be improved.

On the other hand, since the sharpened CIC filter is based on multiple copies of the same CIC filters, it has same alias rejection as the conventional CIC filter, which gives a passband droop compensation and high stopband attenuation. However, there is one drawback that the SCIC filter consumes high power dissipation since the first section of the SCIC filter is still operated at high data rates.

2. Modified Sharpened Filter

Figure 1(b) depicts the block diagram of a modified sharpened comb filter [16]. The modified sharpened comb filter consists of two stages. The first stage is the comb filter section of the decimation factor M_1 and L stages. The second stage is the sharpened filter section, which has a decimation factor M_2 and K stages. Assume that $M=M_1M_2$ and $K=2N$ where M_1, M_2, L, K, and N are integers. Applying this scheme to the comb filter, the transfer function of the modified comb filter is defined as

$$H_M(z) = \left[H_1(z)H_2(z^{M_2})\right]^K, \tag{3}$$

where

$$H_1(z) = \frac{1}{M_1}\left(\frac{1-z^{-M_1}}{1-z^{-1}}\right), \tag{4}$$

$$H_2(z^{M_2}) = \frac{1}{M_2}\left(\frac{1-z^{-M_1M_2}}{1-z^{-M_2}}\right). \tag{5}$$

The corresponding magnitude responses of the modified comb filter can be respectively expressed as,

$$\left|H_1(e^{j\omega})\right| = \left|\frac{1}{M_1}\left(\frac{\sin\frac{\omega M_1}{2}}{\sin\frac{\omega}{2}}\right)\right|, \tag{6}$$

$$\left|H_2(e^{j\omega M_2})\right| = \left|\frac{1}{M_2}\left(\frac{\sin\frac{\omega M_1M_2}{2}}{\sin\frac{\omega M_2}{2}}\right)\right|. \tag{7}$$

As shown in Fig. 1(b), if the modified comb filter is applied to the original sharpened comb filter, the transfer function of the modified SCIC (MSCIC) filter is defined as

$$H_{\mathrm{MSCIC}} = \left[H_1(z)\right]^L \left[H_2(z^{M_2})\right]^{2K} \cdot \left\{3z^{-\frac{M_1(M_2-1)K}{2}} - 2\left[H_2(z^{M_2})\right]^K\right\}, \tag{8}$$

where the comb filter adopts the CIC structure.

The sharpening section in the MSCIC filter operates at a rate which is M_1 times lower than the high input rate in the SCIC filter. Thus, the modified sharpening section is M_1 times shorter

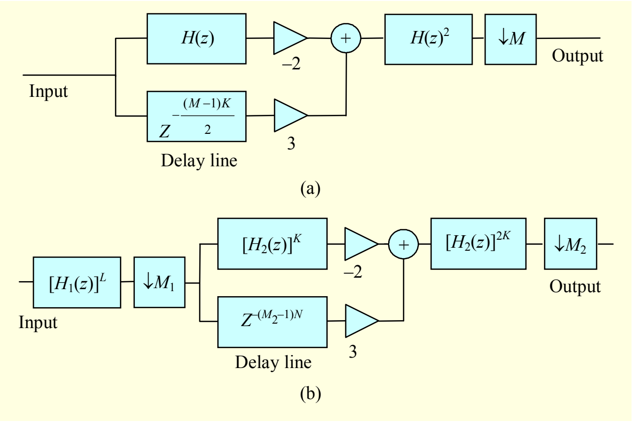

Fig. 1. Block diagrams of sharpened filter: (a) sharpened comb filter [12] and (b) modified sharpened comb filter [16].

than the corresponding SCIC filter [12]. However, the MSCIC has the same or less performance at the passband since there is no additional compensation of the droop caused by the first CIC filter section.

III. Proposed Double-Sharpened Filter

1. Pre-droop Compensator

Figure 2(a) shows the block diagram of the proposed double-sharpened comb filter. In this case, a double-sharpening means a two-step droop compensation, which is based on coarse and fine sharpening. As shown in Fig. 2(a), the proposed double-sharpened comb filter consists of the first comb filter, pre-droop compensator (PDC), and main sharpened comb filter.

Figure 2(b) describes a detailed implementation scheme of the proposed double-sharpened comb filter. The first stage is of the comb decimator with the decimation factor M_1, which can be realized in either a recursive scheme or nonrecursive scheme.

For a recursive scheme, the CIC filter is usually adopted since the CIC filter is an efficient and robust structure for high input rates.

For a nonrecursive scheme, using the cascade equivalence, the down-sampling can be placed before filtering. As a result, the polyphase filters in the first section are moved to a lower rate, which is M_1 times lower than the input rate. In this work, the CIC filter is adopted for the first stage.

In this paper, the following pre-droop compensator plays an important role for compensation of the passband droop introduced by the first comb filter, which is called the coarse sharpening section. As an example of a realization scheme, a simple FIR filter is adopted as a pre-droop compensator, which provides the droop compensation in the first section. There is a tradeoff between performance and complexity.

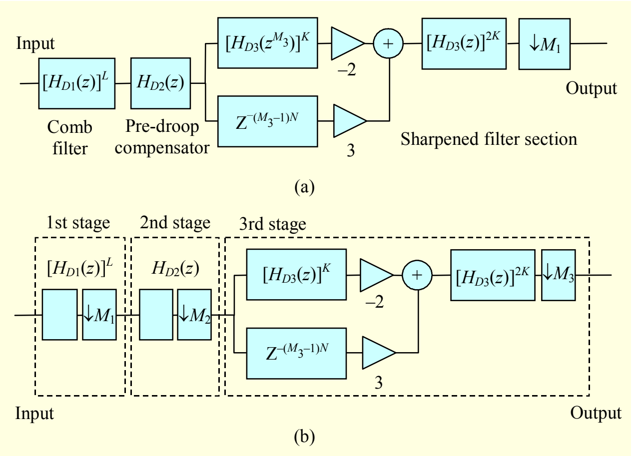

Fig. 2. Block diagrams of proposed double-sharpened comb filter: (a) filter structure and (b) implementation scheme.

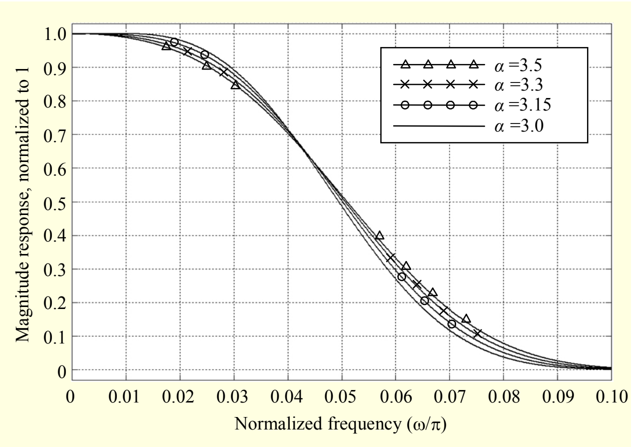

Fig. 3. Overall droop compensation characteristics with respect to passband parameters of pre-droop compensator.

Figure 3 shows the overall droop compensation characteristics with respect to the passband parameters of the pre-droop compensator. In this case, a pre-droop bandwidth is defined and estimated as

$$f_{\mathrm{PDBW}} = \alpha f_{\mathrm{BW}}, \tag{9}$$

where f_{PDBW} is a pre-droop bandwidth, α is a constant, and f_{BW} is a required overall bandwidth in system.

As shown in Fig. 3, in order to efficiently allocate an overall resource, it is an appropriate choice to assign a pre-droop compensation bandwidth that is three times the overall required bandwidth such as α=3.

In addition, other filter schemes, such as a cascade of sine and cosine compensator, can also be adopted [19]. However, owing to the robustness and simplicity, an FIR filter is preferable for PDC. In this paper, since a main sharpening section is allocated in the following stage, it is not necessary to provide extra compensation for the passband droop of the first stage.

2. Double-Sharpened Decimation Filter

For the third stage, the following filter section based on the method of Kaiser and Hamming is operated as the second sharpening block, which is called the fine sharpening section.

As shown in Fig. 2, the proposed double-sharpened filter has the overall decimation factor of M. In this case, assume that $M=M_1M_2M_3$ and $K=4N$, where M_1, M_2, M_3, L, K, and N are integers. Using this scheme to the comb filter, the transfer function of the proposed double-sharpened comb filter is defined as

$$H_D(z)=\left[H_{D1}(z)H_{D2}(z)H_{D3}(z^{M_3})\right]^K, \tag{10}$$

where

$$H_{\mathrm{D1}}(z)=\frac{1}{M_1}\left(\frac{1-z^{-M_1}}{1-z^{-1}}\right), \tag{11}$$

$$H_{\mathrm{D2}}(z)=\frac{1}{M_2}\left(\frac{1-z^{-M_2}}{1-z^{-1}}\right), \tag{12}$$

$$H_{\mathrm{D3}}(z^{M_3})=\frac{1}{M_3}\left(\frac{1-z^{-M_1M_2M_3}}{1-z^{-M_3}}\right). \tag{13}$$

The corresponding magnitude responses of the proposed double-sharpened comb filter can be respectively expressed as

$$\left|H_{\mathrm{D1}}(e^{j\omega})\right|=\left|\frac{1}{M_1}\left(\frac{\sin\frac{\omega M_1}{2}}{\sin\frac{\omega}{2}}\right)\right|, \tag{14}$$

$$\left|H_{\mathrm{D2}}(e^{j\omega})\right|=\left|\frac{1}{M_2}\left(\frac{\sin\frac{\omega M_2}{2}}{\sin\frac{\omega}{2}}\right)\right|, \tag{15}$$

$$\left|H_{\mathrm{D3}}(e^{j\omega M_3})\right|=\left|\frac{1}{M_3}\left(\frac{\sin\frac{\omega M_1M_2M_3}{2}}{\sin\frac{\omega M_3}{2}}\right)\right|. \tag{16}$$

As shown in Fig. 2(b), if the double-sharpened comb filter is applied to a conventional sharpened comb filter [12], the transfer function of the proposed double-sharpened CIC (DSCIC) filter is defined as

$$H_{\mathrm{DSCIC}}=\left[H_{\mathrm{D1}}(z)\right]^L\left[H_{\mathrm{D2}}(z)\right]\left[H_{\mathrm{D3}}(z^{M_3})\right]^{4K}\cdot\left\{3z^{-\frac{M_1M_2(M_3-1)K}{4}}-2\left[H_{\mathrm{D3}}(z^{M_3})^K\right]\right\}, \tag{17}$$

where the comb filter adopts the CIC structure.

Owing to the coarse compensation of the pre-droop compensator, a fine sharpening section at the third stage has a low input rate from the front filter sections so that the proposed double-sharpened comb filter provides an efficient decimation scheme and high performance. As a result, the proposed DSCIC filter provides a solution which overcomes the main drawbacks of the conventional CIC [9] and sharpened filters [12], [16].

Firstly, the proposed DSCIC filter allows the main sharpened comb filter section to operate at a low data rate. In other words, since the main sharpening section operates at a low data rate which is M_1M_2 times lower than the conventional sharpened filter [12], the second sharpening filter section in the proposed DSCIC filter has M_1M_2 times shorter length than the original sharpened filter [12]. Secondly, the frequency response of the proposed DSCIC filter has enough passband performance and alias rejection since it is efficiently compensated by the use of the coarse and fine sharpening sections.

In addition, since a multistage filter structure is one of a proven design scheme in multirate signal processing [11], there is no concern about the group delay which is related to the operating speed and filter structure.

IV. Results

Figure 4 shows the magnitude responses of the proposed DSCIC filter together with that of conventional CIC [9], SCIC [12], and MSCIC [16] filters. The same decimation ratio of M=16 is taken as an example. Moreover, in a wireless system, a reference clock frequency is related to the supported channel bandwidth. If necessary, various sampling frequencies can be regenerated by the clock control block so that there is no problem in adoption of even decimation factors such as M=16. Furthermore, if it is necessary to use an odd decimation factor, such as M=9, a sampling rate converter (SRC) can be adopted. In this case, it is preferable to implement the SRC after the compensated CIC filter stage and multistage decimators so that the operating rate of the SRC can be lowered [20].

As shown in Fig. 4(a), the proposed DSCIC filter gives a better passband performance and alias rejection than other filters. Figure 4(b) shows that the passband droop caused by the first comb filter is compensated so that overall passband performance is improved. The proposed DSCIC filter has sufficient attenuation at null intervals, as shown in Fig. 4(c).

Table 1 shows the performance comparison of the proposed DSCIC filter and conventional sharpened filters [12], [16]. For a simple comparison, the magnitude response on the Y-axis and frequency range on the X-axis are normalized, which are measured at a normalized frequency of 0.0175, as shown in Fig. 4(b).

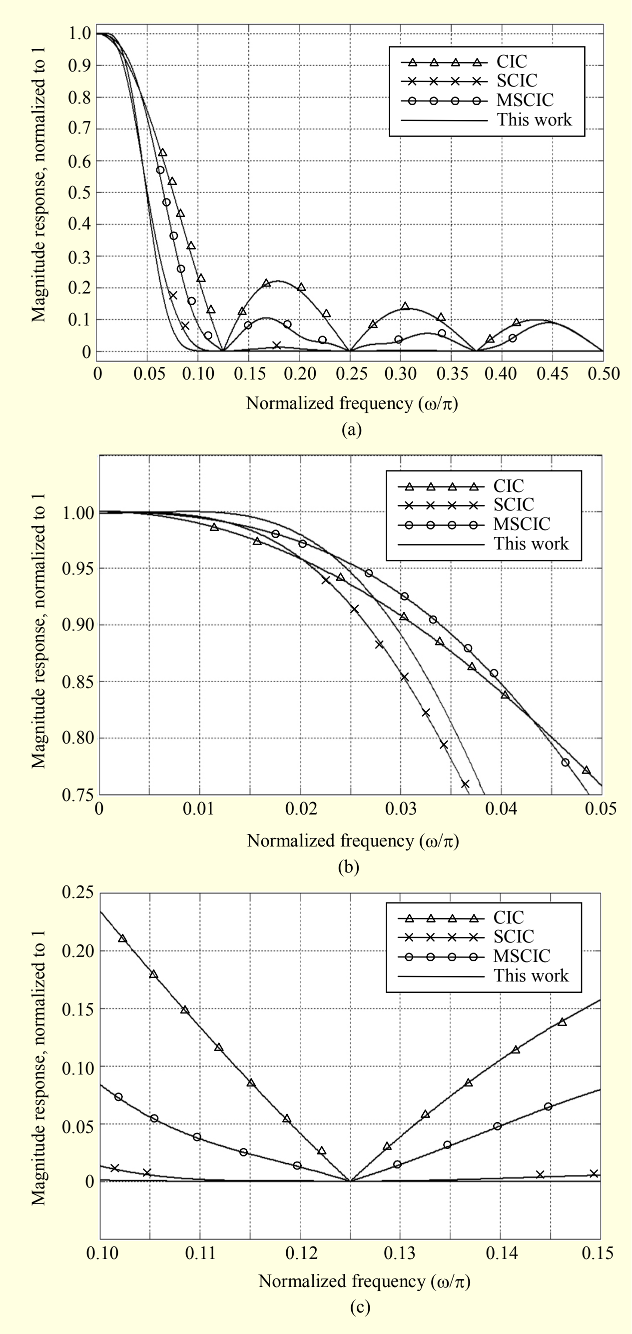

Fig. 4. Magnitude responses: (a) overall response, (b) detailed view of droop characteristic in passband, and (c) performance of alias rejection at first null.

The proposed DSCIC filter improves the passband response of the CIC filter and also provides a better sharpening performance at half-speed in comparison with previous literature [12], [16]. For a simple estimation of the system resource with respect to the clock frequency, a normalized power consumption can be defined and estimated as

$$P = \beta C_L V_{dd}^2 f_{clk}\,, \tag{18}$$

Table 1. Performance comparison of sharpening section.

Parameter	Proposed scheme	[12]	[16]
Passband droop (dB)	–0.10	–0.28	–0.23
Alias rejection (dB)	–145	–138	–70
Decimation factor, M	16	16	16
Operating speed	$f_s/4$	f_s	$f_s/2$
Normalized power consumption	0.25	1	0.5

Table 2. Performance comparison of sharpening section.

Parameter		Proposed scheme				[16]
Channel bandwidth (MHz)		1.25	2.5	5	10	10
Sampling frequency (MHz)		80	80	80	80	80
Number of cascades		3	3	3	3	2
Decimation factor	1st, M_1	16	8	4	2	4
	2nd, M_2	2	2	2	2	2
	3rd, M_3	2	2	2	2	-
Droop (dB)	With comp.	–1.6	–1.4	–1.3	–1.0	–2.6
	Without comp.	–4.1	–3.9	–3.9	–3.9	–3.9

where β is the switching activity parameter, C_L is load capacitance, V_{dd} is operating voltage, and f_{clk} is clock frequency [21].

In [16], the passband droop in the first stage deteriorates with increasing M_1. However, in the proposed DSCIC filter, there is no problem introduced by the first comb filter since the pre-compensator remedies the passband droop response at the band of interest.

Table 2 summarizes the performance of the proposed DSCIC filter, which presents an adequate performance of the passband droop compensation with respect to different channel bandwidths for multistandard wireless systems. As shown in Table 2, 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.

V. Conclusion

This paper discusses the design and implementation scheme of the double-sharpened decimation filter employing a pre-droop compensator for multistandard wireless applications.

According to channel bandwidths and decimation factors, the characteristics of the passband droop are efficiently improved, which can further motivate the flexibility and reconfigurability in multistandard wireless systems. The results show that the proposed double-sharpened decimation filter is suitable for multistandard wireless applications.

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