RESEARCH ARTICLE

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ECG Signal Denoising with Field-Programmable Gate Array Implementation of Fast Digital Finite Impulse Response and Infinite Impulse Response Filters

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The suit for digital signal processing (DSP) optimized solutions flourish exceptionally in current years, exclusively in the arena of modern communication and contemporary and signal processing revolution. The finite impulse response (FIR) and infinite impulse response (IIR) filters do an essential role in the blueprint of any complicated signal processing system. This paper exhibits the traditional IIR filters using cascaded integrator-comb (CIC) method and the high-speed IIR filters using look-ahead arithmetic techniques. Also, the standard moving average (MA) FIR filters and the high-speed MA FIR filters using look-ahead arithmetic methods are exemplified in detail. These filters are implemented on Altera EP4CE115F29C7 field-programmable gate array (FPGA) device using Quartus II 13.1 synthesis tool. Finally, artifacts removal from the ECG signal was demonstrated using the conventional MA FIR filters and the high-speed MA FIR filters. Simulation results reveal that, in all perspectives, the high-speed IIR and FIR filters obtain better performance than the conventional ones at the cost logic elements usage.

Keywords: FPGA, High-Speed FIR Filters, High-Speed IIR Filters, Look-Ahead Arithmetic, Quartus II.

1. INTRODUCTION

In a noisy situation, in discrete-time signal processing, the irregular signals should be nullified often by smoothing, which can be attained with the aid of conventional moving average filters. To sketch a specific filter, the knowledge about the input signal frequencies is very significant. In digital data processing, both positive and negative frequencies do exist during the mathematical analysis. But the analytic signals comprise of either the positive or negative frequencies, not both [1, 2]. The primary objective of this study is to make the scholars and young research professionals understand the elucidation of the input signal in terms of a sampling frequency of the discrete-time system. By doing so, people can work on design filters easily for their appropriate fields such as data compression, machine learning, fuzzy logic, neural networks, bio-signal processing, digital communications, signal and image processing, communications, industrial control, speech and audio signal processing applications [3, 4], etc.

The primary or principal blocks of many DSP systems are the digital filters. The finite impulse response (FIR) and the infinite impulse response (IIR) filters are the extensively used digital filters for most signal processing applications. The solitary motive of filter design is to reshape the incoming input data/signal/information so that it can be employed for a particular application [5]. In practical real-time applications, determining the filter coefficients by using pen and paper would be tough, and therefore the computer-aided tools like Matlab, Mathematica, Octave can be used constructively for the same [6].

Convolution and filtering, adaptive filtering, signal detection, correlation, spectral analysis and estimation, and matched filtering are used in general-purpose DSP applications. In audio and speech processing applications, coding and decoding, noise cancellation, speech recognition and synthesis, sound synthesis, encryption and decryption, sound synthesis, echo cancellation, and speaker recognition algorithms are used. Image understanding and recognition, compression and decompression, image transmission and decomposition, and image enhancement are used in image processing applications. Modems, wireless LANs, line equalizers, cellular telephones, data encryption and decryption, modulators/demodulators, spread-spectrum technology, and biomedical signal processing algorithms are used in the field of information technology and systems. In control applications, power system monitors, guidance and navigation, printer control,

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servo control, disk control, robots and vibration control algorithms are used. In the field of instrumentation, steady-state and transient analysis, waveform generation, sonar, radar, and beamforming DSP algorithms are used [7, 8].

Very large scale integration (VLSI) technology plays an imperative role in establishing real-time signal and image processing systems. For example, in the applications such as medical imaging, mobile wireless applications, internet of things (IoT), multimedia communications, speech and audio processing, cognitive and software-defined radio, space imaging applications, remote sensing, data compression and routing, aerial imaging and wearable computers, the VLSI technology and DSP algorithms jointly play an essential role in executing these applications. The need for high-speed DSP systems grows vastly in the arena of real-time systems [9–11].

Typically the FIR filters are inherently stable, but they should have many filter coefficients for the steep filter response specifications. By deploying the various design procedures, we can mitigate this issue. The dominant advantages of the FIR filters are the easier implementation of linear phase or zero phase specifications. But the other class of filters, that is, the IIR filters are potentially unstable and are subjected to quantization errors. The major advantage of the IIR filters is that the better magnitude frequency response can be obtained with very few filter coefficients, and therefore the filtering will be speedier than FIR filters [12, 13].

In this article, the high-speed FIR and IIR filters are deployed on an Altera FPGA device and the performance metric results such as the count/usage of logic elements, system clock speed (performance), and the power dissipation results are analyzed. The materials and methods portion detail implementations on high speed-IIR and FIR filter architectures and the experimental results are shown in the results and discussion section. In the end, the shortcomings and the possible future work are described in the conclusions section.

2. MATERIALS AND METHODS

The look-ahead interleaving in the time domain techniques is used to deploy high-speed IIR filters on an Altera FPGA device. Also, the cascaded-integrator-comb (CIC) with look-ahead schemes are combined to implement the high-speed MA FIR filters.

2.1. The Look-Ahead Scheme on IIR Filters

The main task of a filter must be to remove the noise from a signal. The integrator is often used to nullify the effects of unwanted high-frequency noise in an environment which contains a wide-band random zero-mean noise.

2.1.1. The Conventional First-Order IIR Filter

Figure 1 portrays the lossy integrator (a first-order IIR filter) and is expressed as [3],

$$y(n+1) = \frac{2}{5}y(n) + x(n) \quad (1)$$

Here, $y(n) = (2/5)y(n-1) + x(n-1)$ and its discrete-time filter function is obtained as,

$$H(z) = \frac{z^{-1}}{1-(2/5)z^{-1}} \quad (2)$$

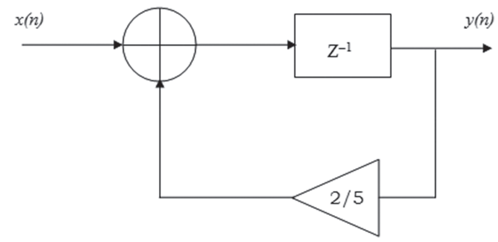

Fig. 1. The conventional first-order IIR filter.

Figure 2 depicts the Matlab script deployment of a response for an input, $x(n) = 100\delta(n)$ [3]. Figure 3 shows the behavioral results using VHDL on Quartus II software tool [17, 18].

2.1.2. Level One Look-Ahead Method

The architecture of the first-order IIR filter is slightly altered with the aid of the look-ahead method. Assume the first-order IIR filter be [2, 7],

$$y_{n+1} = ay_n + bx_n$$

This is again developed using the look-ahead technique as,

$$\begin{aligned} y_{n+2} &= ay_{n+1} + bx_{n+1} \\ &= a\{ay_n + bx_n\} + bx_{n+1} \\ &= a^2y_n + abx_n + bx_{n+1} \end{aligned}$$

Hence, the output $y(n)$ is obtained as,

$$y_n = a^2y_n - 2 + abx_n - 2 + bx_{n-1} \quad (3)$$

Therefore, first-order IIR filter, discussed earlier (Eq. (1)) is examined an example, for exhibiting the look-ahead interleaving in the time-domain method. Equation (1) is,

$$y_{n+1} = \frac{2}{5}y_n + x_n$$

where $a = 2/5$ and $b = 1$. Hence, the Eq. (3) can be revisited as,

$$y_n = \frac{4}{25}y_{n-2} + \frac{2}{5}x_{n-2} + x_{n-1} \quad (4)$$

In general, the IIR filter section is split up with two sections, namely an FIR portion (feed-forward) and an IIR portion (feed-back). The performance can be improved with the help of look-ahead interleaving method.

2.1.3. A Level Two Deployment of the Look-Ahead Method

The increment of levels with the method look-ahead will improve the performance further. Here, it is acquired again with level two and $y(n+3)$ can be obtained as [3],

$$\begin{aligned} y_{n+3} &= ay_{n+2} + bx_{n+2} \\ &= (a^3y_n + a^2bx_n) + abx_{n+1} + bx_{n+2} \end{aligned} \quad (5)$$

Therefore, the final output can be viewed as,

$$y_n = a^3y_{n-3} + a^2bx_{n-3} + abx_{n-2} + bx_{n-1} \quad (6)$$

```
>> filter( [0  1], [1  -2/ 5], [100  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0] )

ans =

Columns 1 through 12

0  100.0000   40.0000   16.0000    6.4000    2.5600    1.0240    0.4096    0.1638    0.0655
0.0262    0.0105    0.0042    0.0017    0.0007    0.0003

Columns 13 through 23

0.0001    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
```

Fig. 2. The output of a first-order IIR filter using Matlab.

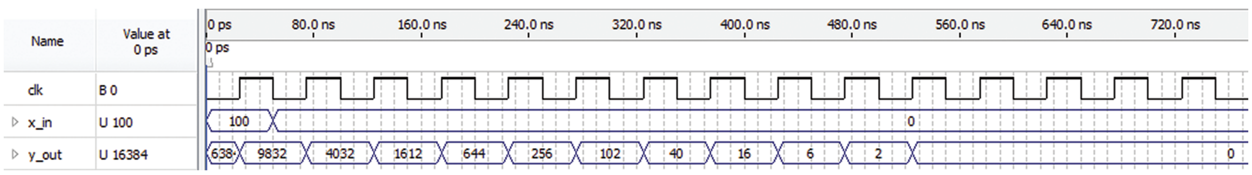

Fig. 3. Behavioral verification of a first-order IIR filter.

2.2. Adopting CIC and Look-Ahead Methods on FIR Filters

The integrator and comb sections can be connected in a series manner to construct MA FIR filter. Hence the resulting structure is called as cascaded-integrator-comb (CIC).

2.2.1. An 4-Tap MA FIR Filter with CIC

A 4-tap moving average FIR filter has a transfer function as [12–14],

$$H(z) = \frac{1}{4}(1+z^{-1}+z^{-2}+z^{-3}) = \frac{1-z^{-4}}{1-z^{-1}} \tag{7}$$

2.2.2. Look-Ahead Adopted to a 4-Tap MA FIR Filter

To raise the performance, the integrator section is exploited along with the look-ahead interleaving in the time domain method. This is exemplified as [3],

$$\begin{aligned} y_n &= x_n + y_{n-1} \\ y_{n+1} &= x_{n+1} + y_n \\ y_{n+2} &= x_{n+2} + y_{n+1} \\ y_{n+2} &= x_{n+2} + x_{n+1} + y_n \\ y_n &= x_n + x_{n-1} + y_{n-2} \end{aligned} \tag{8}$$

2.3. Application Example—ECG Signal Processing

In the biomedical domain, ECG filtering is a great challenge since the actual signal will be around 0.5 mV in offset

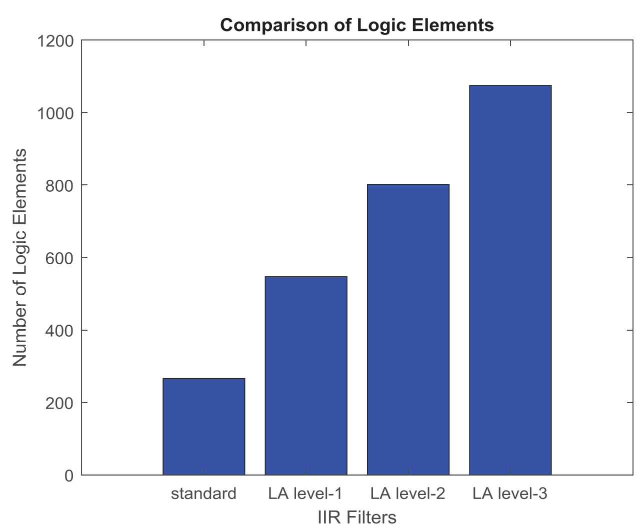

Fig. 4. Usage of logic elements.

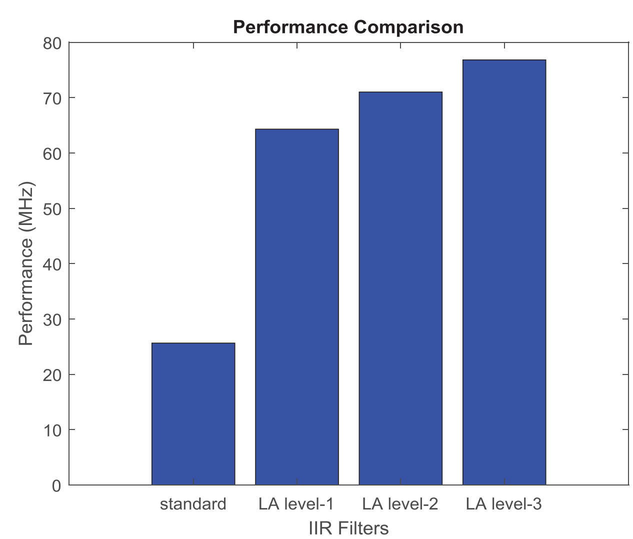

Fig. 5. Comparison of performance results.

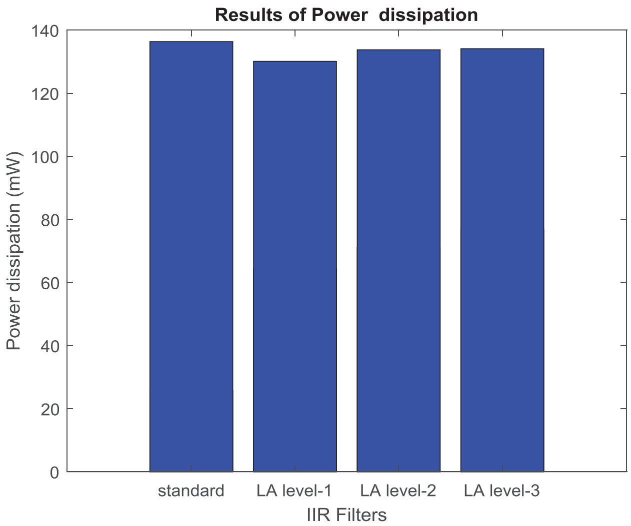

Fig. 6. Simulation results of power dissipation.

surroundings. Other factors such as power supply noise (interference), radio frequency (RF) radiation from surgery equipment, and implanted devices like pacemakers can degrade the accuracy of the captured ECG signal. The preeminent sources of noise in ECG recording are as follows:

- Power line interference (50 Hz or 60 Hz)
- Baseline wander (low frequency noise)
- Muscle noise (EMG)
- Electrode motion artifact
- Other interference from other devices or equipment.

Out of all the above, the filtering of muscle noise would be difficult since both ECG and EMG signals fall in the same region. In such circumstances, muscle noise can be corrected using some specialized software.

Table I. Performance results.

Design for the denoising ECG signal	Performance (MHz)
8-tap MA FIR using conventional	113
8-tap MA FIR using CIC	162
8-tap MA FIR using CIC with look-ahead level one	165
8-tap MA FIR using CIC with look-ahead level two	168
8-tap MA FIR using CIC with look-ahead level three	173

3. RESULTS AND DISCUSSION

3.1. Simulation Results of Fast IIR Filters

The traditional first-order and second-order IIR filters, the high-speed IIR filters using the look-ahead method, and the high-speed MA FIR filters using CIC with look-ahead designs are deployed on an Altera FPGA EP4CE115F29C7 device. Figure 4 shows the usage of Logic Elements (LEs), that is the device utilization report, which reveals that more utility by IIR filter using look-ahead level 3 as expected. Also, it is evident from the results that the IIR filter (level 3) provides better performance (76.84 MHz) than others (see Fig. 5). The traditional IIR filter dissipates lower power (136.37 mW) than others (see Fig. 6).

3.2. Filtering Noisy ECG Signals Using MA FIR Filters

The ECG signal processing, especially denoising ECG signal has been taken as an application example to compare the performances of the existing and proposed MA FIR filters in this study. The test data records to verify the designs were collected from the MIT-BIH Arrhythmia database from the "www.physionet.org" website. The ECG signal was sampled at

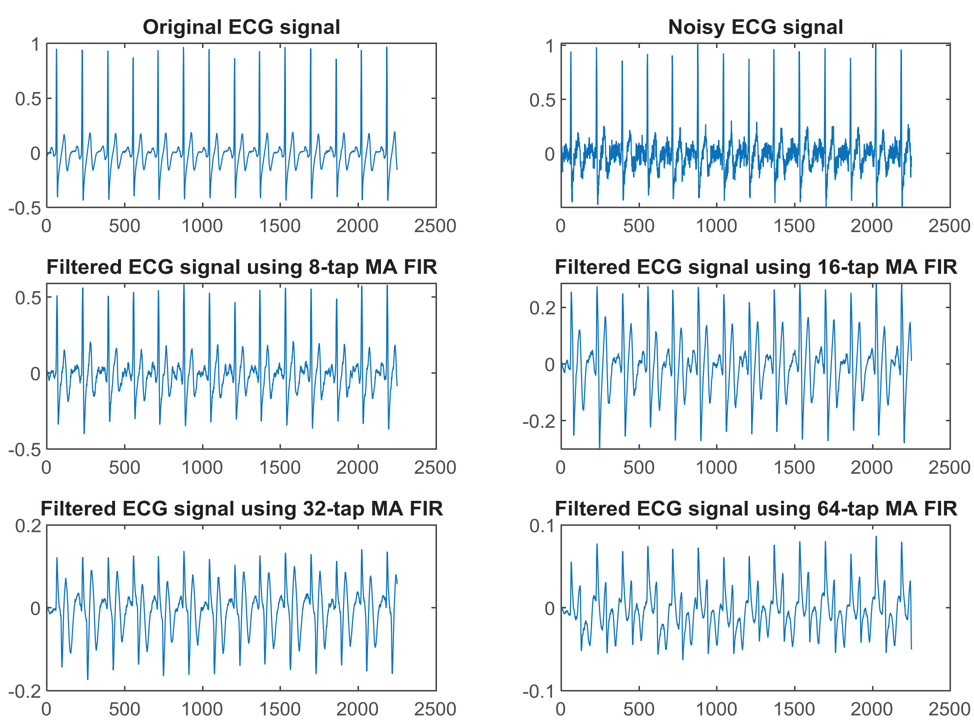

Fig. 7. Noise removal from ECG using MA FIR filters.

250 Hz and is a 9-second recording with a total length of 2250 samples. To demonstrate the impact of MA FIR filters, the original ECG signal is corrupted by Gaussian white noise (GWN). The original ECG signal, the noisy ECG signal, and the filtered ECG signal using 8-, 16-, 32-, and 64-tap MA FIR filters are shown in Figure 7. The corresponding performance results are shown in Table I.

4. CONCLUSION

It is evident from the experimental results that the high-speed MA FIR and IIR filters obtain better performance results than the conventional filters. This study work can be further continued with the cost-effective hardware design architectures to the variant concepts of DSP like half-band filters, Hilbert-transform filters, multi-rate filter banks, etc.

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