A novel method for design and implementation of systolic associative cascaded variable leaky least mean square adaptive filter for denoising of ECG signals

Chitra Manickam
Kongu Engineering College
Murugesan Govindasamy
Kongu Engineering College
Suresh Muthusamy (infostosuresh@gmail.com)
Kongu Engineering College
Muneeshwari Paramasivam
Saveetha Engineering College

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Abstract

The most essential diagnostic test for heart disease detection is the electrocardiogram (ECG). It has a low frequency and a small amplitude, making it vulnerable to a variety of stimuli, including high/low-frequency noises. As a result, the diagnostic quality suffers. ECG signal analysis deals with the major problem of removing the noise from ECG signal. Implementation of adaptive filter removes noise from the signal in a better way. Adaptive filters in signal processing plays a major role in biomedical applications for denoising different types of noises such as Power Line Interference (PLI) noise which is generated by the power line electromagnetic field and it exhibits its peak from 50Hz to 60Hz, Baseline Wander (BW) noise which occurs due to the variation of electrode skin impedance, Motion Artifacts (MA) which is generated by the electrode motions away from the contact zone on the skins and Muscle Noise, this is due to the Electromyographic signals (EMG), originating from the skeletal muscle contractions. In order to eliminate the above-mentioned noises, the most common adaptive filters such as Least Mean Square (LMS) and Recursive Least Squares (RLS) are used. In existing method, they used Cascaded Least Mean Square adaptive filters to reduce noises at a much higher rate than the Least Mean Square Adaptive filter and to achieve the higher Signal to Noise Ratio (SNR). The Cascaded RLS filter can be used to obtain faster range of convergence than the Cascaded LMS. But the problem is that while using RLS filters the computational complexity will increase and as well as the delay will also increase. So, in order to counteract these problems, Cascaded Leaky Least Mean Square filter is designed not only to increase the rate of convergence and SNR and stability but also to reduce the computational complexity. The filter is designed with adaptive variable step size which calculates the step size according to the input signal of the filter, this is used to increase the stability of the filter. The systolic architecture and associativity of the VLLMS filter is implemented to reduce the number of adders and multipliers along the critical path of the filter. This systolic architecture increases the SNR of the filter and systolic combined with associativity reduces the delay and area of the filter. The work comprises of designing the 4 tap, 8 tap and 16 tap cascaded systolic associative variable leaky least mean square adaptive filters using Simulink and the SNR comparisons have been made between normal LMS cascaded filter and cascaded VLLMS filter. The area and delay between normal filter and systolic associative filter are compared by converting the Simulink design into Verilog and by implementing in Xilinx.

I. Introduction

In today's world, noise cancellation is quite important. For instance, when we talk to someone, not only do we send our speech signal, but also send some noises along with it. Noises such as fan noise, crowd noise, automobile noise, and others, when coupled with the original speech signal, cause data loss. Adaptive filters are employed to address these issues. Fixed digital filters are only suited for stationary signals; for non-stationary signals, the filter coefficient should change in response to the signal's changing characteristics at any given time. For noise cancellation, adaptive filters have a wide range of techniques such as LMS, RLS, and NLMS. The cascaded LMS filters are used to increase the SNR than the normal LMS adaptive filter. The stability of the LMS filter will be reduced when the input signal has fewer gradient values for processing and when there are unbounded signal properties. The stability and the rate of convergence can be increased by incorporating RLS algorithm in cascaded adaptive filter. But, the RLS adaptive filter will result in higher computational and structural complexity and the area and delay of the filter will be increased. To overcome these cons the Leaky LMS algorithm is used. The leakage factor in the LMS algorithm solves the problem of drifting in the LMS algorithm by bounding the parameter estimate and it also increases the tracking capability of the algorithm and stability of the filter. Although the Leaky LMS used to increase the stability it has lower rate of convergence. To overcome that the variable step size algorithm is incorporated with the LLMS adaptive filter. The variable adaptive step size is calculated automatically from the input signal of the filter. The step size changes in accordance with varying coefficients of the adaptive filter. Hence the Variable Leaky Least Mean Square (VLLMS) filter is designed to achieve higher stability and better convergence rate. The proposed work also consists of systolic architecture which is incorporated with the VLLMS filter. This systolic architecture increases the Signal to Noise Ratio (SNR) of the filter but the area is increased because of the number of delays and adders. To conquer this problem the associativity principle is used which is used to reduce the delay and the number of adders in the critical path of the filter. The input signal and the reference noises are taken from the MIT database. Here this project not only uses the ECG signal from the dataset but also the ECG signal taken from us using the mi-beat kit. At the end, the Systolic Associative Cascaded VLLMS (SACVLLMS) filter is designed for 4 tap, 8 tap and 16 tap which end up as proposed work. The SNR values are compared between the Systolic Cascaded Variable Leaky Least Mean Square (SCVLLMS) filter and the normal cascaded VLLMS filter. The area and delay of the filter is compared between SACLLMS filter and normal filter using XILINX.

Ii. Existing Method

The LMS method is a popular adaptive filtering technique. To find the best wiener solution, it employs a gradient vector of filter tap weights. Because of its computational ease, it is well recognized and frequently utilized. Because of its simplicity, the LMS algorithm has served as a valuable reference point for other algorithms. The filter weights of the filter are adjusted in each iteration of the LMS algorithm according to the formula stated in (1),

$$w(n+1) = w(n)+\mu*e(n)*x(n) \quad (1)$$

Where μ denotes the step size and n denotes the time step that regulates the convergence speed and ability. The filter's performance is determined by the selection of a suitable value. The output of the filter y(n) is defined as,

$$y(n) = w(n)*x(n) \quad (2)$$

Where w(n) is the correction factor and x(n) are the input signal. The correction factor is depending upon the adaptive algorithms which is used to update the weight of the adaptive filters. The difference between desired signal and obtained signal is given in (3), e(n) = d(n)-w(n)x(n) (3)

Where e(n) is the error signal which is used in upgrading the coefficients of the weight of the filter. The least square estimation of the filter will be high if the mean square error is minimized. The LMS algorithm's prominence in adaptive filtering is mostly due to its computational simplicity, which makes it easier to implement than any other regularly used adaptive algorithms. The LMS adaptive filter is good for cancelling out noises from ECG signals. But, in some cases when the intensity of the noise is higher the LMS algorithm fails to cancel out the noise completely and results in lower SNR and lower stability. To deal with this the LMS filters can be cascaded as shown in Fig. 1 to cancel out the noises completely and to achieve higher SNR value. Figure 1 represents the block diagram of cascaded LMS adaptive filter. The LMS filter is cascaded in a way that the error signal e(n) of the first LMS filter is given as the desired signal of the second LMS filter. The difference between the input signal x(n) and the output signal y(n) of the first LMS filter x(n)-y(n) is fed into another filter as the input signal x(n).

Iii. Proposed Method

A. *Variable Cascaded Least Mean Square Filter*

The variable leaky least mean square adaptive filter is cascaded to achieve higher SNR value, higher stability and faster convergence rate. Unbounded parameter estimations might come from insufficient excitation in the input sequence. Because of the unbounded prediction error, this behavior might produce difficulties owing to overflow and poor filter performance. As a result, including the leakage component in the LMS filter helps to stabilize the system. Another benefit of the leaky factor is that it prevents stalling, which occurs when the gradient estimate is too tiny to alter the adaptive filter coefficients. The leaky was also implemented to prevent the bursting effect in echo cancellation, as well as channel normalization and echo cancellation. Stability, tracking capabilities, and convergence are all important considerations when designing adaptive filters. The leaky least mean square (LLMS) technique can increase both stability and tracking. The performance of LLMS is improved by introducing the leakage factor in the weight update equation of conventional LMS algorithms. The weight update equation of the LLMS is given by,

w(n + 1) = (1- μn γn) w(n) + μn e(n) x(n) (4)

Where, x(n) is the input signal of the filter, e(n) is the error signal, w(n) is the tap weight vector of the filter, μ is the step size of the filter and γ is the leakage factor of the filter. Step size μn is varied for better convergence of the VLLMS algorithm in the presence of noise and γn is the leak factor which is a time-varying parameter. The factor (1−$\mu\gamma$) is called leakage coefficient that satisfies the follow condition,

0 ≤ γ < 1/μ (5)

B. *Variable Step Size Calculation*

The selection of step size is a key difficulty with the LMS algorithm. Fast adaptation is facilitated by a large step size, but this comes at the cost of a significant excess Mean Square Error. Stability will be lost if the step size is too great. However, even when the extra MSE is little, a tiny step-size causes stagnant convergence. The top constraint for step size required to keep the LMS algorithm stable is,

$0 < \mu_n < 2/ \lambda_{max}$ (6)

Where μ is the step-size and λ_{max} is the largest eigen value of the auto correlation matrix of the input signal x(n). The Fig. 2 represents the flow chart for calculating the variable step size.

C. *Systolic Architecture and Associativity Principle of FIR filter*

The filter in which impulse response is of finite duration is defined as Finite Impulse Response. FIR filters can be designed with different methods. The objective of FIR filter is to produce ideal results. The transfer function of FIR filter is when the order of the filter increases the complexity and amount needed for processing the input is also increased. The function of a FIR filter is to accept the input signal and blocking specific frequency and passing the real signal minus those components to the output side. Where FIR is a digital filter the filter operates on the digital input and provides the digital output. The architecture is a Systolic architecture with associativity method FIR filter design. A number of Processing Elements (PE) that calculate and transport data are included in the systolic design. It's also known as a Systolic array, and it sends data into and out of the network on a regular basis. The critical path of Systolic 4-tap FIR filter is given below,

Tc = Tmult + Tadd

Where, Tc represents the critical path of the filter, Tmult represents the delay of multiplier and Tadd represents the delay of the adder. While designing the Filter structure with systolic architecture technique the area and register utilization is increased when the architecture is implemented, so in order to minimize the utilization of registers the associativity technique is included where it reduces the height reduction of the architecture which in terms reduces the area and delay of the circuit by reducing the critical path of the circuit in terms of adder and multiplier blocks. Hence by incorporating both the systolic architecture with the associativity with the cascaded VLLMS adaptive filter, the number of adders and multipliers will get decreased in the critical path and therefore the area and delay of the filter will get reduced comparing to the normal cascaded VLLMS filter. The Fig. 3 represents the structure of the FIR filter incorporated with systolic architecture and associativity.

Iv. Results And Discussion

A. *Structure of Conventional Cascaded VLLMS filter*

Figure 4 represents the structure of 4 tap cascaded variable leaky least mean square filter. The Interpreted function block is used to call a specific function in a specific MATLAB file which is present in the current location. The input signal or reference signal is fed into the FIR filter part and the weight updating part. The constant block is a varying one with the input signal properties. The Leaky factor is calculated and it is fed into the weight updating part of the filter by using MATLAB interpreted function block. The error signal e(n) is then given as a feedback for updating the coefficients of the filter in order to eliminate the noises from the ECG signal. The four-tap adaptive filter consists of three delays in the FIR filter part and it has four computation in the weight updating part.

B. *Structure of Systolic Cascaded VLLMS filter*

Figure 5 represents the systolic architecture of the VLLMS filter. The modification is done in the FIR filter part of the adaptive filter. Here the delays are added before every multiplier block and before every adder and then the summation of those is given in order to compute the error signal.

C. *Structure of Associative Cascaded VLLMS filter*

Figure 6 represents the structure of VLLMS adaptive filter with associativity. The systolic structure results in utilization of a greater number of registers and LUT's. Hence this will lead to increase in area and delay and to reduce those we incorporate the associativity which then used to reduce the delay and area of the filter and reduce the critical path in order of utilization of a smaller number of multipliers and adders.

D. *Structure of Systolic Associative Cascaded VLLMS filter*

E. *Output of Systolic Associative Cascaded VLLMS filter*

Figure 8 represents the output of the filter. The first grid denotes the clear ECG signal which is the input signal. The second grid denotes the reference signal which is PLI noise and third one is the desired signal and the final plot is the output of the filter.

F. *Comparison of SNR values among the different type and tap lengths of the filter*

Figure 9 represents the comparison between different tap length of the filter and different type of the filter such as normal and cascaded. When a highly corrupted noise incorporate with the ECG signal the normal adaptive filter can only reduce the noise to a particular extent and it results in decrease in effeciency and signal quality. So in order to came over this, the filter is cascaded and it results in higher SNR values. In the Fig. 9 we can notice that SNR value is gradually increases from normal VLLMS filter to cascaded VLLMS filter. The various ECG datasets have been taken from MITBH for analysis. The average SNR is increased by almost 4–5% by cascading the filters comparing to normal VLLMS filter.

G. *Comparison of area and delay among various cascaded VLLMS filters*

All types of filter are designed and then it is implemented in Virtux FPGA inorder to compare the delay and area. It has been came to know that both the delay and area were reduced in systolic associative cascaded VLLMS filter while comparing to the normal conventional VLLMS adaptive filter.

TABLE I. Comparison of area and delay among different transformation techniques

Transformation techniques	4 Tap		8 Tap		16 Tap	
	Delay (ns)	LUT	Delay (ns)	LUT	Delay (ns)	LUT
Conventional	19.1	5783	23.5	19275	29.2	44283
Systolic	16.0	5883	18.4	19281	18.5	44294
Associative	17.2	4989	22.1	18501	23.0	42291
Systolic Associative	**15.2**	**5626**	**19.9**	**18492**	**22.8**	**42277**

V. Conclusion And Futurework

When compared to the traditional cascaded design, the latency is minimized by using the systolic architecture. However, by utilizing systolic, the number of delay blocks is increased, resulting in the need of bigger number of registers and LUTs, resulting in an increase in the filter's size. As a consequence, the associativity principle is employed to minimize delay by shortening the critical path of the cascaded VLLMS adaptive filter, resulting in the need of fewer multipliers and adders. The leaky factor is used to increase the stability of the LMS filter. All of the transformation techniques were planned and implemented, and the adders and multipliers in the filter may be tweaked or replaced with alternative adders, such as the Brent Kung Adder or the Kogge Stone Adder, for improved performance in the future.

Declarations

Author contributions

All authors are equally contributed for the preparation of this manuscript.

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Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current work.

Conflict of interest

The authors whose names are listed immediately certify that they have NO affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Ethics approval

Agreed.

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Figures

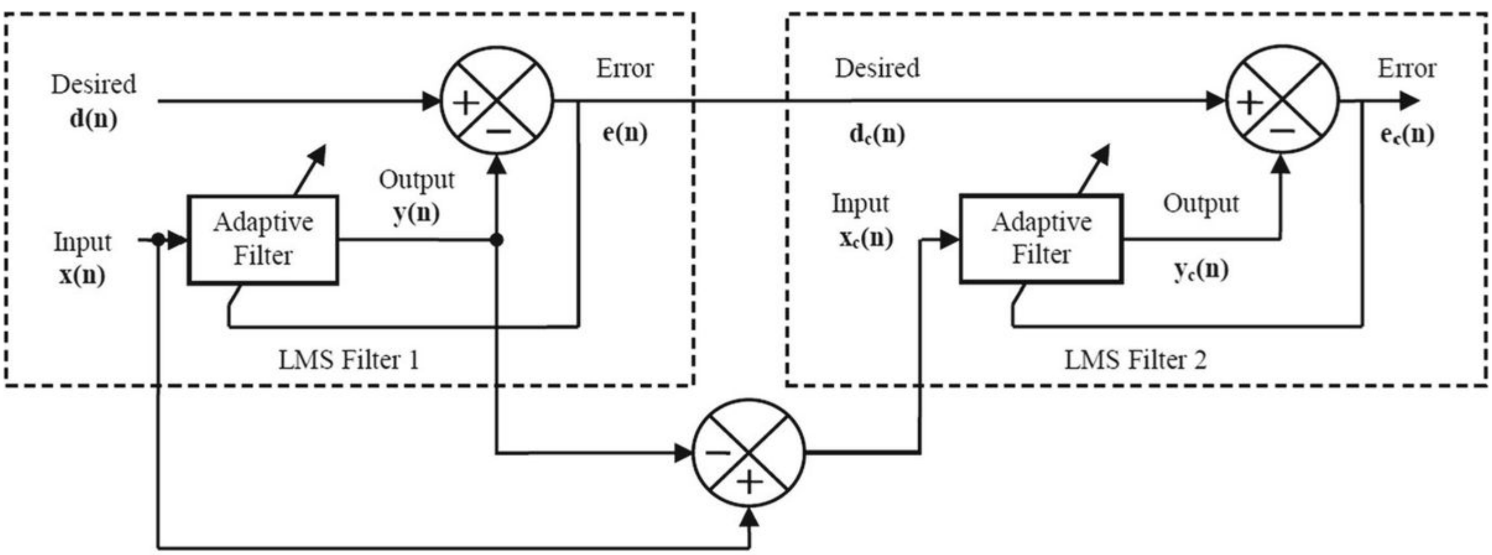

Figure 1

Cascaded LMS adaptive filter

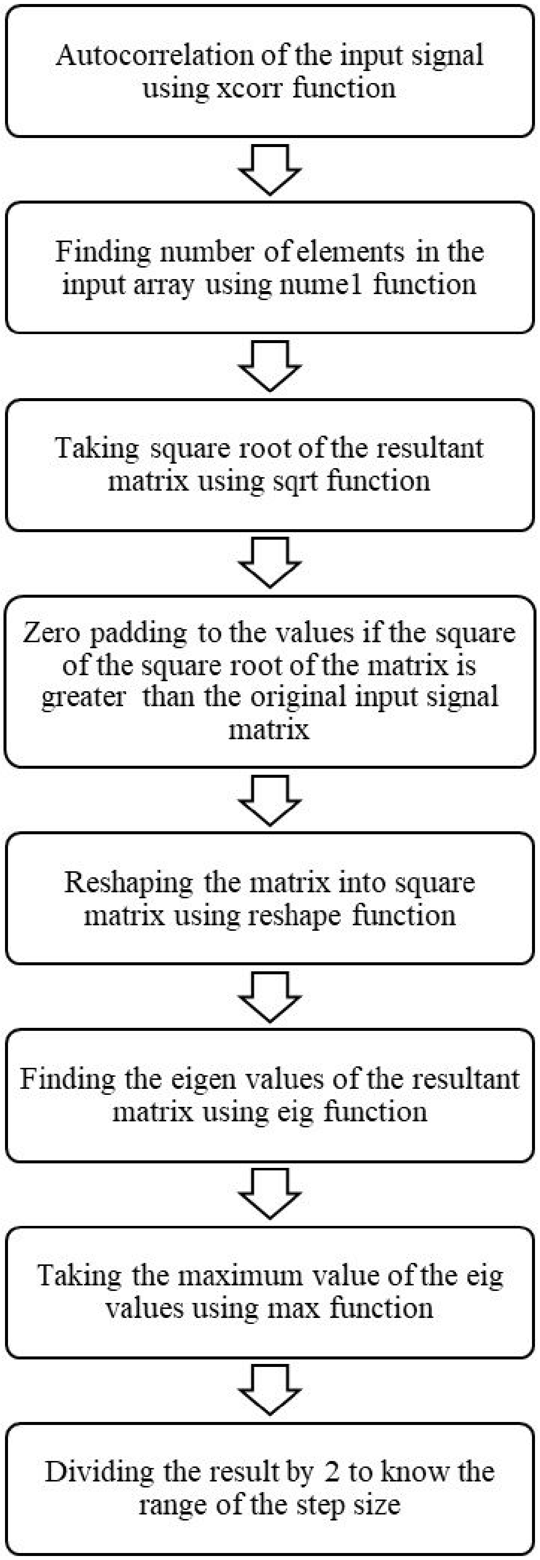

Figure 2

Flow chart for variable step size calculation

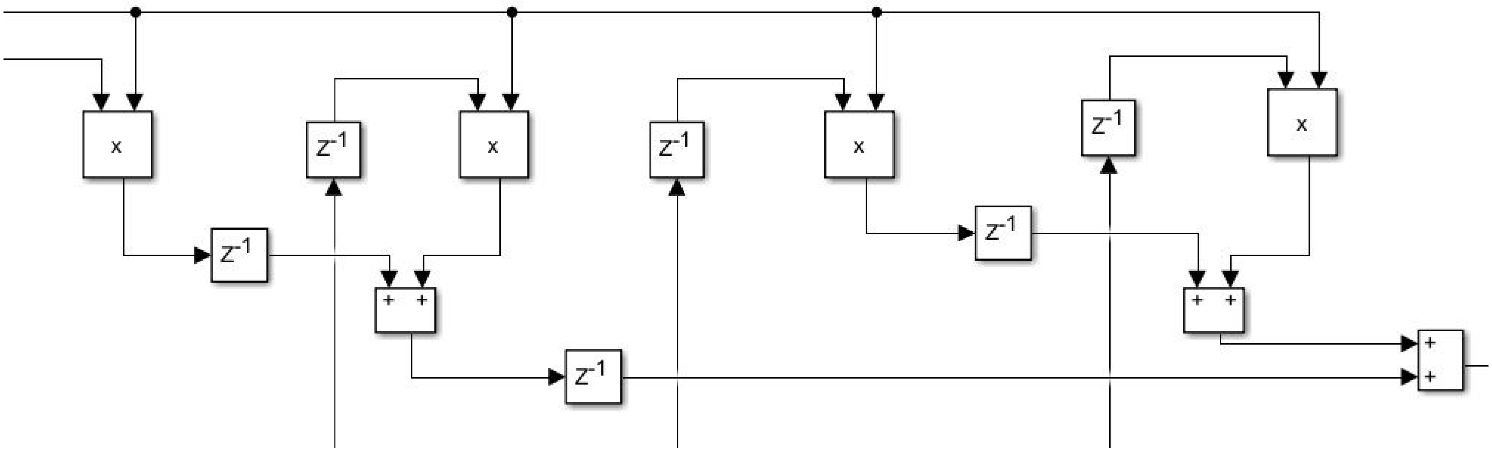

Figure 3

Systolic Associative structure of FIR filter

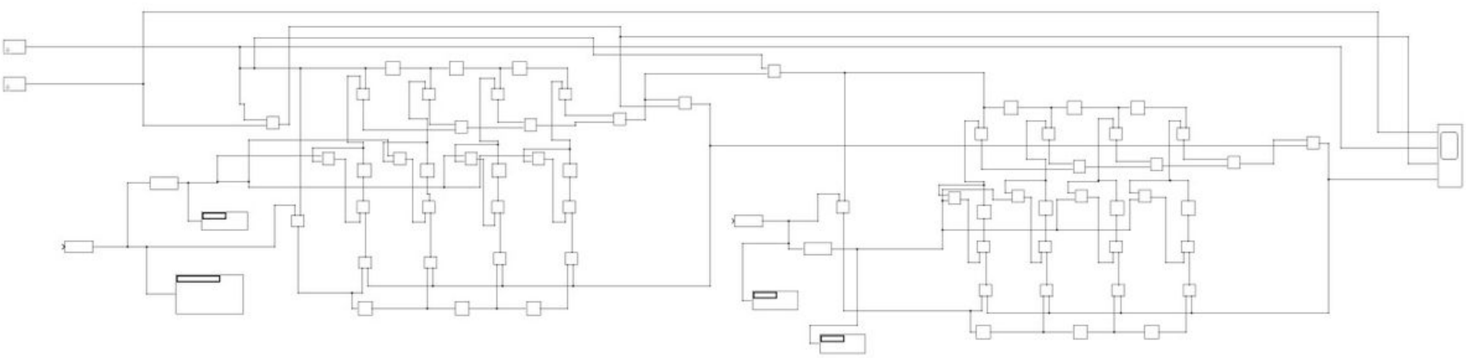

Figure 4

Structure of Conventional Cascaded VLLMS filter

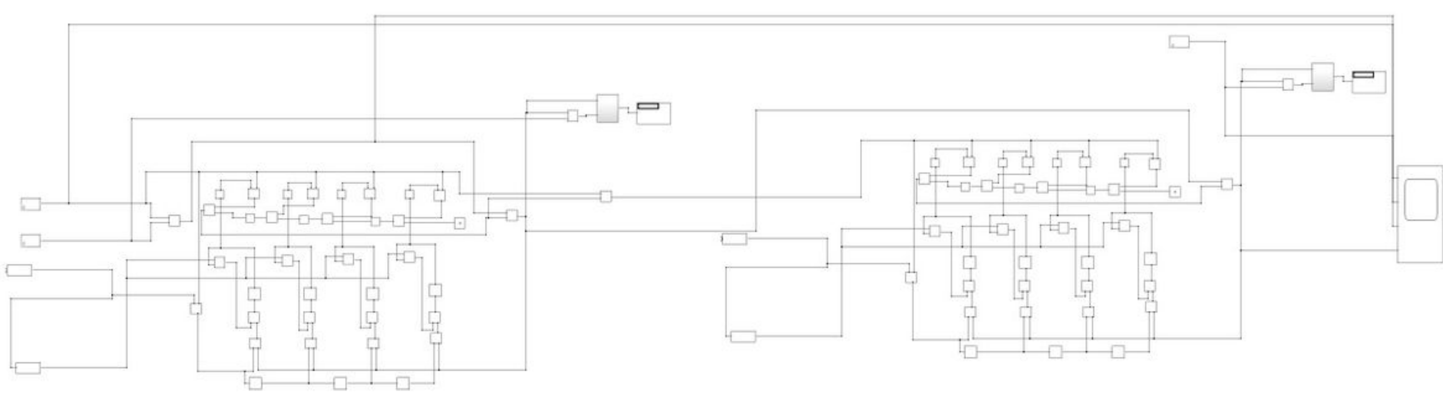

Figure 5

Structure of Systolic Cascaded VLLMS filter

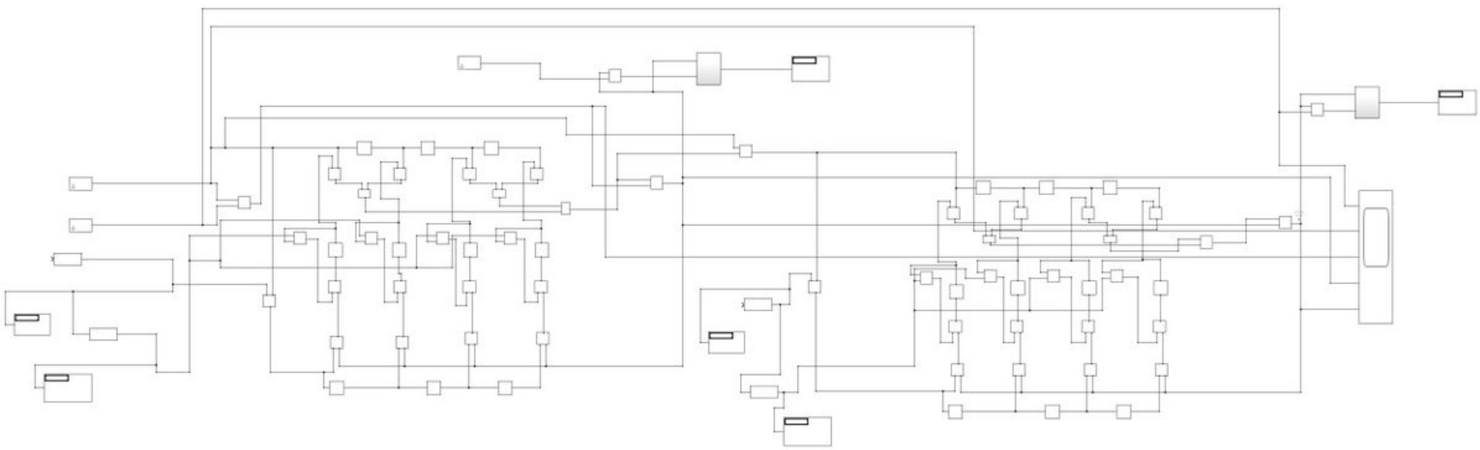

Figure 6

Structure of Associative Cascaded VLLMS filter

Figure 7

Structure of Systolic Associative Cascaded VLLMS filter

Figure 8

Output of Systolic Associative Cascaded VLLMS filter

Figure 9

Chart representation of SNR values among the different type of filters