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Employing Interpolated Wavelets for Hard and Soft Digital Processing of Scintillation Detector Signals

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Abstract. In this article, hard and soft digital cores have been developed for refining, shaping, counting and multi-channel analysing (MCA) of scintillation detector signals. These cores are implemented to apply the forward wavelet transform for signal decomposition and the back interpolation technique for the reconstruction phase. We aim to de-noise, compress and reconstruct these signals by which the processing speed and storage will be optimized. Moreover, the presented technique deliver all important features of the scintillation signals such as; counting, shaping, pulse height. Also, it performs multichannel analysing from the single channel analyzing results. The new contribution of our framework arises from employing the interpolation techniques to reconstruct the signal where the mother wavelet and details are neglected. Moreover, soft techniques have been applied to evaluate the performance of the nonlinear mother wavelets and interpolation methods. The hardware design is implemented using hardware description language (HDL) and is implemented practically on the FPGA. The performance of the design has been tested in simulation mode on Model Sim benchmark and in real time mode on XC2S 50 Spartan-II FPGA. The soft processing included in this article employs a special purpose digital filter to refine the nuclear pulses and to extract their important features.

1. Introduction

The scintillation detector is one of the most important detectors used in nuclear and particle physics experiments as well as in nuclear medicine. These detectors are used in several radiation detection systems such as detection of mixed ionizing fluxes near nuclear objects, radionuclide control of samples and radiation pollution and in determination of the type and energy of high-energy particles and products of their reactions with targets. Scintillation signals are digitized, consequently quantization noise is added, the loss in signal quality is due to additional noise and shaping or pickup on signal line. Optimum filtering and more complex algorithms are implemented relying on the VHDL core. These algorisms are implemented on field programmable gate arrays (FPGAs). The overall scintillation system presented in this study is shown in figure (1).

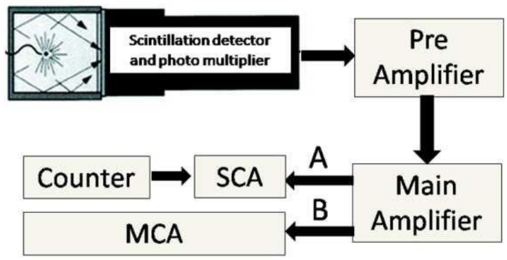

Figure (1). The overall scintillation system.

Throughout this framework the wavelets has been used as base for the pre-processing phase. The wavelet transform has recently emerged as a powerful tool for many applications such as data compression, de-noising, feature detection, and biomedical signal processing. Wavelets have been used in ultrasonic detection [1], in biomedical signals [2], in digital communications channels [3], and in medical images [4]. B. Mahmoud *et al* [5] described an acquisition and treatment system designed for semi-analog Gamma-camera. It consisted of a nuclear medical image acquisition, treatment and scintigraphic image construction in real time.

R. Engels *et al*. [6] developed a data acquisition board, it was a one slot board which received all the temporary information of the detector signals and allowed for complete pulse shape discrimination. A digital acquisition and elaboration system were developed and assembled for the direct sampling of fast pulses from nuclear detectors such as scintillators and diamond detectors [7]. G. Pasqualia *et al*. [8] implemented a DSP equipped fast digitizer. They used a digital signal processor (DSP) online analysis of detector signals. Algorithms have been written and tested on detectors of different types (scintillators, solid-state, gas-filled), implementing pulse shape discrimination, constant fraction timing, semi-Gaussian shaping, and gated integration. S. Zuberi [8] described a series of experiments and technical developments concerning the digital signal processing (DSP) of scintillator pulses in nuclear physics applications. J. Carletta *et al*. [9] designed a field programmable gate array (FPGA)-based digital hardware platform that implements wavelet transform algorithms for real-time signal de-noising of optical imaging signals.

Our proposed digital processor for scintillation detector signals is described as follows, see figure (2);

- De-noising and compression of scintillation signals relying on wavelet transform
- Employing hard and soft interpolations to reconstruct signal patterns
- Shaping signals with respect to threshold level
- Pulse counting
- Multichannel analyzing

The acquired scintillation signals are negative with floating decimal values. To overcome these problems we upscale all signals by large number and raise signals by adding a dc value. Also, we check the synchronization between PC and the FPGA kit to ensure the stability of our integrated system. Our digital processing core has been developed using HDL and it is implemented on an FPGA for denoising, compression, reconstruction based on linear interpolation, shaping and counting of scintillation signals. Moreover the developed technique converts the single channel analyser to multi channel analyser. The proposed solution is illustrated in figure (2).

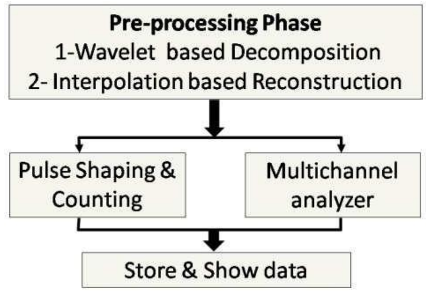

Figure (2). The applied Technique.

The rest of this paper is organized as follows; Section 2 is an overview on scintillation detectors. Section 3 reviews the fundamentals of the pre-processing technique presented in this study where the wavelets decomposition and the interpolation based reconstruction are presented. The FPGA implementation for computing the Haar Wavelets Transform (HWT) and the linear interpolation are presented in section 4. Section 5 presents signal shaping and counting obtained from an online analysis algorithm. In section 6 the concept of the transfer from single channel analyzing to the multi-channel analyzing is presented. Section 7 introduces the soft processing. Finally, Section 8 summarizes the conclusion.

2. Scintillation Detector

A brief overview of the most important parts of the physics behind gamma detection, scintillators and pulse shape analysis (PSA) are needed to fully grasp the content of this research work. A scintillator is a material that emits light, scintillates, when absorbing radiation. When a particle passes through the material it collides with atomic electrons, exciting them to higher energy levels. After a very short period of time the electrons fall back to their natural levels, causing emission of light. There are six different types of scintillators they are; organic crystals, organic liquids, plastics, inorganic crystal, gases and glasses. Pulses of light emitted by the scintillating material can be detected by a sensitive light detector, such as the photomultiplier tube (PMT) or photo diodes. The photocathode of the PMT, which is situated on the backside of the entrance window, converts the light (photons) into so-called photoelectrons. On the other hand in a photodiode, the scintillation photons produce electron-hole pairs that are collected at respectively the anode and the cathode of the diode. Most frequently, reverse biased PIN photodiodes are used having a low capacitance and leakage current. Hence an alternative way to detect the scintillation light from a crystal is the use of a silicon photodiode. The low level noise limitation of photodiode can be overcome by using Avalanche Photodiodes. Avalanche photodiodes (APDs) are photo detectors that can be regarded as the semiconductor analog to photomultipliers [10]. By applying a high reverse bias voltage (typically 100-200 V in silicon), APDs show an internal current gain effect due to impact ionization (avalanche effect).

In scintillators, the efficiency of converting the high-energy radiation into light is typically about 10%, hence the scintillator material must be transparent to the radiation it produces[11]. To accomplish this, the wide-gap material is activated with impurities which represent recombination sites for electrons and holes. Thus produced light has much lower energy than the band gap of the host crystal. Anyhow, PMTs have several merits they are; they are standard devices, large signals can be detected and fast rise times to signals is feasible. Conversely, the quantum efficiency of silicon photodiodes is typically 70 % but its’ surface area are limited and noise threshold is low.

3. The Pre-Processing Phase

The pre-processing phase is divided into two steps the first one is the wavelets and the second one is the interpolation.

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3.1.1 Principles of the wavelet based decomposition

Wavelet transforms are associated with multiresolution into different scales, see figure (3).

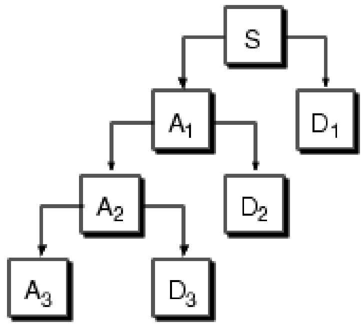


Figure (3). Signal Decomposition.

$$
\begin{aligned}
s &= A_1 + D_1 \\
&= A_2 + D_2 + D_1 \\
&= A_3 + D_3 + D_2 + D_1
\end{aligned} \tag{1}
$$

Wavelet transforms do not have a single set of basis functions like the Fourier transform, which utilizes just the sine and cosine functions. Instead, wavelet transforms have a set of possible basis functions. Thus wavelet analysis provides immediate access to information that can be obscured by other time-frequency methods such as Fourier analysis. Dilations and translations of the Mother function, or analyzing wavelet $\varphi(x)$; define an orthogonal basis, our wavelet basis:

$$\varphi_{(s,l)}(x) = 2^{-\frac{s}{2}} \varphi(2^{-s}x - l) \tag{2}$$

The variables *s* and *l* are integers that scale and dilate the mother function φ to generate wavelets. Hence, the mother functions are rescaled, or dilated by powers of two, and translated by integers. What makes wavelet bases especially interesting is the self-similarity caused by the scales and dilations. To span our data domain at different resolutions, the analyzing wavelet is used in a scaling equation:

$$w(x) = \sum_{k=-1}^{N-2} (-1)^k c_{k-1}\, \varphi(2x - k) \tag{3}$$

Where $w(x)$ is the scaling function for the mother function ; and c_k are the wavelet coefficients. The wavelet coefficients must satisfy linear and quadratic constraints of the form

$$\sum_{k=0}^{N-1} c_k = 2, \quad \sum_{k=0}^{N-1} c_k c_{k-2l} = 2\delta_{l,0} \tag{4}$$

Where (δ) is the delta function and (l) is the location index. One of the most useful features of wavelets is the ease with which a scientist can choose the defining coefficients for a given wavelet system to be adapted for a given problem. Where the coefficients $\{c_0\ c_n\}$ are filter coefficients. The filters are placed in a transformation matrix, which is applied to a raw data vector. The coefficients are ordered using two dominant patterns, one that works as a smoothing filter (like a moving average), and one pattern that works to bring out the data's detail information. In this paper the signals is filtered in a hierarchical algorithm called a pyramidal algorithm. This algorithm was applied to the original signals, then it is smoothed and decimated by half using down sampler. Just as in the first stage, we repeat to find second wavelet transform. This completes the iteration of the Haar analysis bank, which is graphically represented in figure (3). The mother wavelets (Haar, Daubechies, Coiflet, and Meyer) have been tested to select the best one of them according to the similarity measures as shown in table (1.a). The peak signal to noise ration (PSNR), mean square error (MSE), Eucleadian distance (ED) and the cross correlation (CC) prove that Coiflet is the best mother wavelet. To select the best decomposition level, practical tests have been carried out to find the best one of them. Table (1.b) shows that the third decomposition level is the best one according to the results of the similarity measures

Table (1).a) The statistics of the similarity measure of the different mother wavelets.

Mother Wavelet	CC	ED	MSE	PSNR
Haar	0.9866	12.7990	0.1643	31.926
Daubechies	0.9890	11.8139	0.1418	32.5656
Coiflet	0.9900	11.3834	0.1324	32.8635
Meyer	0.0148	106.878	11.4230	13.5046

Table (1).b) The statistics of the similarity measure of the different decomposition levels.

Level	CC	ED	MSE	PSNR
One	0.9681	20.4778	0.1493	27.8567
Two	0.9830	14.7395	0.1575	30.7084
Three	0.9866	12.7290	0.1443	31.9258
Four	0.7021	18.9554	3.2561	27.0625

3.1.2 The Interpolation based Reconstruction

In the mathematical subfield of numerical analysis, interpolation is a method of constructing new data points within the range of a discrete set of known data points. Interpolation is often recommended for signal de-noising, and would not be much more difficult to implement. We also intend to consider methods that threshold based on estimates of the noise, generated in real time alongside the data. Signals recovered using both hard and soft interpolation; in hard interpolation only linear interpolation is implemented on FPGA. In soft interpolation, several Matlab functions are described, which implement various interpolation algorithms such as nearest neighbor interpolation, linear interpolation, cubic hermite interpolation and cubic spline interpolation. The statistics presented in table (2) prove that the best method was the cubic spline.

Table (2). The statistics of the similarity measure of the different interpolation techniques

Method	CC	ED	MSE	PSNR
Linear	0.9782	16.4669	0.2731	29.7192
Cubic Spline	0.9866	12.7990	0.1643	31.9258
Nearst	0.9307	28.8462	0.8380	27.8501
Cubic Hermit	0.9818	14.8984	0.2226	30.6066

We propose reconstruction method using only approximation coefficient by applying the interpolation technique. Hence, a simple function is applied to calculate new data points. The some of the signal features may be lost but this algorithm is the right manner to remove noise from signals also these signals were stored in economical way by which only approximation coefficients were stored. There are many interpolation methods, in this work we implement linear interpolation on FPGA and the cubic spline in soft techniques.

4. FPGA-based Implementation

In this section, we design and implement the signal pre-processing algorithm on the FPGA

4.1 Design simulation

The proposed architecture is designed using HDL and simulated on Mentor Graphics (Model Sim) to validate its functionality on FPGA. The simulation results are shown in figure (4). The main parameters of this simulation are the master clock "**clk**", the enable signal called "**b**" and ram which use to save intermediate signals "**RAM**", the address of ram is given by signal "**add**". The simulation results and the schematics show the hard wavelets decomposition and the hard interpolation technique.

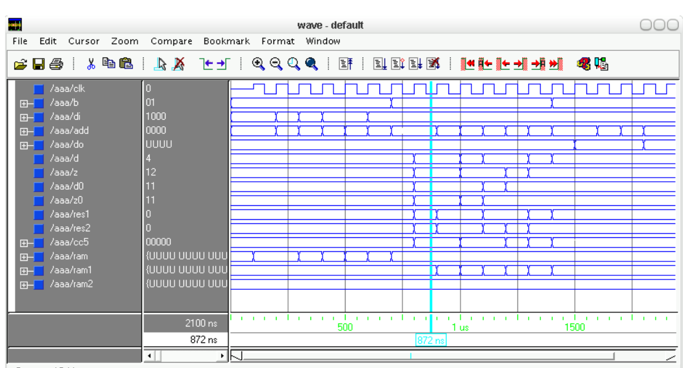
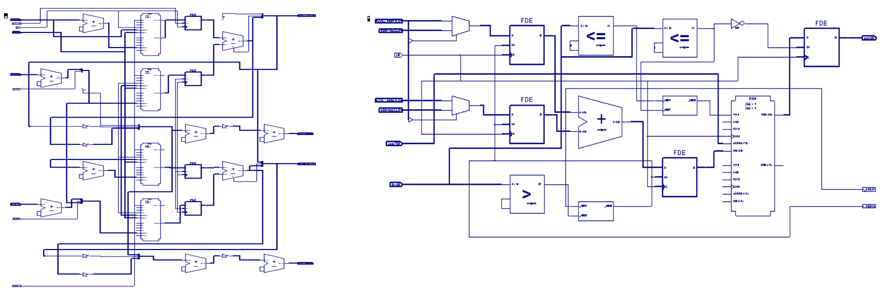


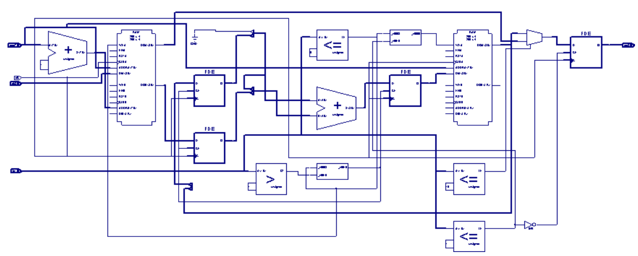
Figure (4). Simulation using Model Sim program.

4.2 Wavelet based Hard Denoising of Scintillation Detector Signals

The hard denoising has been designed and implemented on the FPGA in two phases; the first phase is the down sampling shown in figure (4.a); while the second phase is the interpolation shown in figure (4.b). The device utilization summary, micro statistics and timing summary of the down sampling phase are shown in tables (3-5) while the device utilization summary, micro statistics and timing summary of the interpolation phase are shown in tables (6-8). The original scintillation detector signal, the down sampled one and the reconstructed signal are presented in figure (6). The results shown in figure (6) shows that the compression reaches 50% without scarifying the original signal. The hardware description of the system with the computer interface is shown in figures (7, 8).



a) Wavelet decomposition phase



b) Interpolation based reconstruction

Figure (5 a,b). Schematic of the interpolated based Wavelets for scintillation signal denoising.

Table (3).Device utilization summary.

Number of Slices	**374**	**48%**
Number of Slice Flip Flops	32	2%
Number of 4 input LUTs	647	42%
Number of bonded IOBs	18	18%
Number of GCLKs	1	25%

Table (4). macro statistics.

LUT Ram 256x4-bit	**5**
Adders/Subtractors	11
Registers	8
Comparators	3
Multiplexers	2

Table (5). Timing Summary.

Minimum period	**6.536ns**
Minimum input arrival time before clock	26.204ns
Maximum output required time after clock	6.788ns

Table (6). Device utilization summary.

Number of Slices	**176**	**22%**
Number of Slice Flip Flops	16	1%
Number of 4 input LUTs	277	18%
Number of GCLKs	18	185
Number of GCLKs	1	25%

Table (7). macro statistics.

LUT Ram 256x4-bit	**2**
Adders/Subtractors	2
Registers	4
Comparators	4
Multiplexers	1

Table (8). Timing Summary.

Minimum period	**7.022ns**
Minimum input arrival time before clock	23.366ns
Maximum output required time after clock	6.788ns

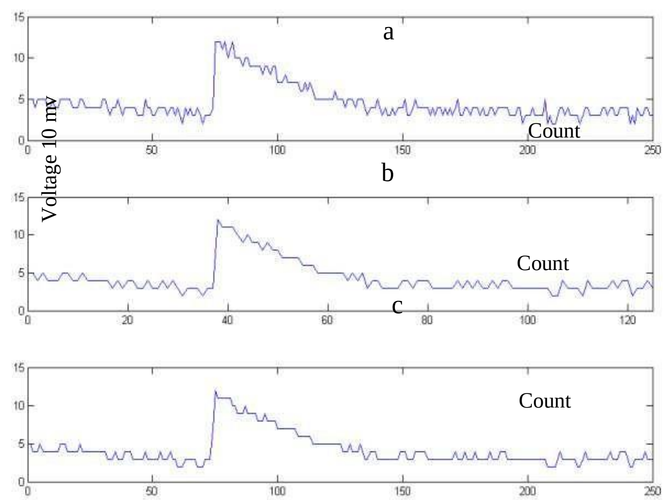


Figure (6). De-noising using wavelet transform and interpolation (a) original signal (b) transformed signal (c) reconstructed signal.

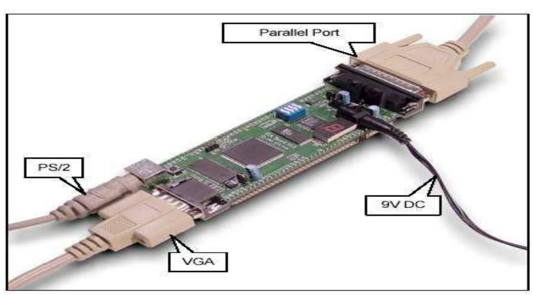


Figure (7). XSA -50 board.

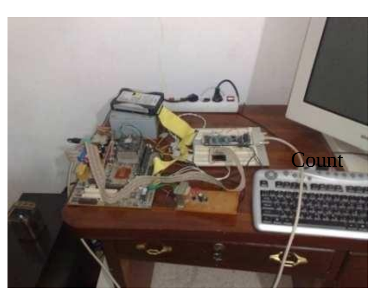


Figure (8). The hardware setup of the system.

5. Signal Shaping and Counting

The previous denoising filtering is an essential step in pulse shaping and counting. Figures (9, 10) show the effect of denoising on pulse shaping and counting. The noise has harmful effect on the digital signal processing. Figure (8) shows the imprecise counting occurred due to presence of noise while the removal of noise led to very precise results as shown in figure (10). Successful results for counting and shaping of series of pulses are presented in figure (11) where (a) is a series of pulses, (b) is the shaping while (c) is the count of nuclear pulses.

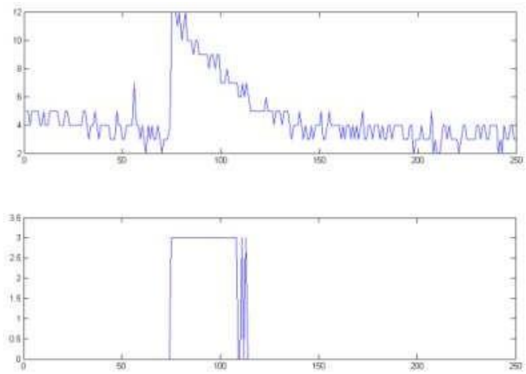


Figure (9).explain the incorrect discrimination.

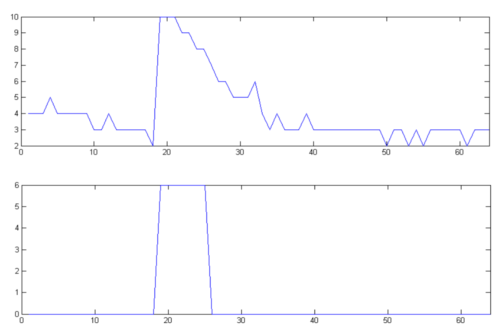


Figure (10). correct pulse shaping.

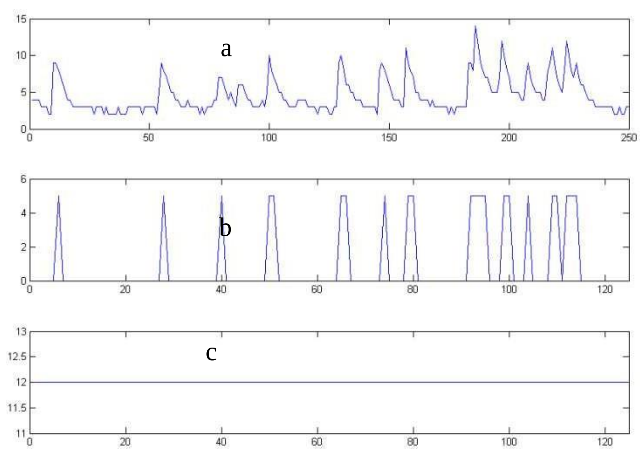


Figure (11).Counting and shaping of scintillation detector signal (a) denoising (b) pulse shaping (c) pulse count.

6. Multi Channel Analyzer

In MCA the pulse height of each input analog signal is digitized as shown in figures (12, 13). The MCA tabulates the voltage pulses on the basis of the output of the ADC by assigning an energy range to each of the detection channel. If a voltage pulse falls within the range represented by one of the channel, a memory location corresponding to that channel has the number of counts in it incremented by one. By performing this operation for all detector events in a given interval the MCA generates a spectrum of the distribution of energy for a measured events (energy histogram) with the y axis representing counts and the x axis representing channel value (relative energy).

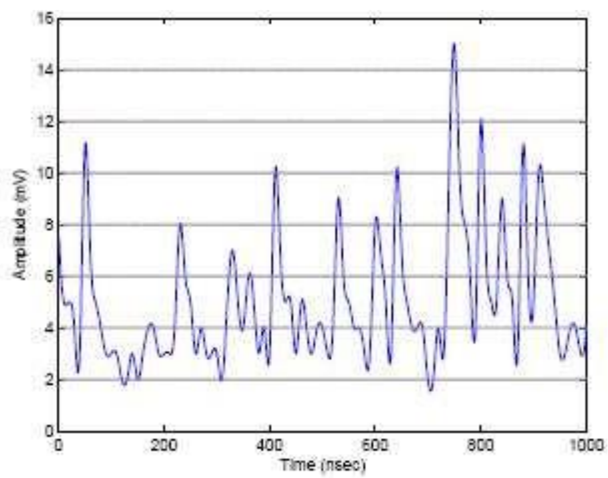


Figure (12). the scintillation signal.

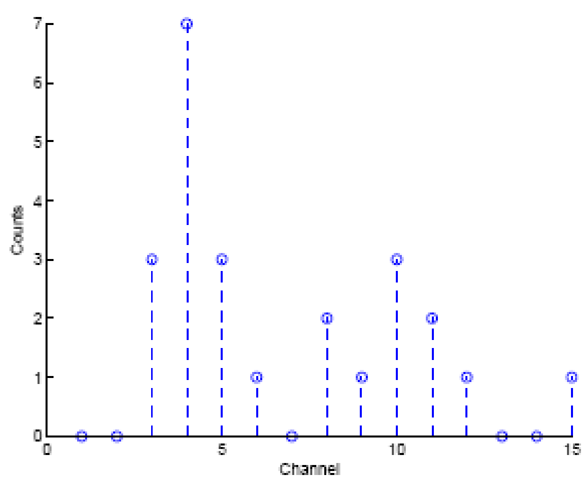


Figure (13). the output of the multichannel analyzer.

Channel Calibration

Energy channel values are converted into kilo electron volts with a channel-to-kilo electron volt conversion factor which is determined from a comparison of photo peak energies and channel location close to the energy of interest.

7. Soft Processing of Scintillation Detector Signals

Throughout this study two modules have been developed; the first one is the hard processing implemented on the FPGA for the real time application and the soft processing for the off line data manipulation. The soft pre-processing includes applying the non-linear wavelets for decomposition and non-linear interpolation techniques presented in section 3. The comparison between the proposed pre-processing technique presented in this paper and the pre-processing techniques based on the accumulation algorithm presented in [11] and the pre-processing based on median filter proves that the proposed technique is superior to them as shown in table (9).

Table (9). Comparison Statistics of the Preprocessing Techniques .

Method	CC	ED	MSE	PSNR
Accumulation Tech	0.9680	21.3433	0.4555	27.4972
Median filter	0.9831	14.7856	0.2186	30.6856
Proposed Solution.	0.9866	12.7990	0.1643	31.9258

8. Conclusion

This research work presented a qualitative pre-processing, pulse shaping, pulse counting and multichannel analyzing based on hard and soft techniques. One of the most important advantages of this system is the high compression rate using the interpolated wavelets where the mother wavelet and the details have been neglected. FPGAs are visible computational platform for processing of scintillation detector signals with high speed while the high precision has been achieved from the soft processing as well in off-line applications. The wavelet transform and interpolation based reconstruction operation are simultaneously implemented in one processor. The applied techniques achieved high precision denoising, compression, reconstruction, shaping and counting of the signals under study up to (12.5%) without scarifying the original signal. The presented study shows the superiority of the proposed technique compared with the others. The main target of that was the optimization of the overall system by which the storage capacity, precision and speed have been significantly improved.

9. References

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