*Sindh Univ. Res. Jour. (Sci. Ser.) Vol.50 (001) 33-40 (2018)*

http://doi.org/10.26692/sujo/2018.01.0006

**SINDH UNIVERSITY RESEARCH JOURNAL (SCIENCE SERIES)**

# Realization of a Finite Impulse Response Pulse Shaping Filter for Ultra-Wide Band Electronic Communication System

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Received 13[th] May 2016 and Revised 29[th] December 2017

**Abstract:** This paper has addressed the problem to design the Finite Impulse Response (FIR) filter for a pulse shaper used in electronics communication systems for a frequency band of 3.1 to 10.6 GHz, which is unlicensed indoor UWB. Therefore unlikely from the previous approaches, an LSE combined pulse which is a procedural grouping of the initial fifteen higher time offshoots of a Gaussian pulse has been used to obtain desired pulse shape. The impulse outcome of the system doing pulse shaping has been cross validated against FCC indoor channel emission mask and the results are well satisfactory for UWB propagation standards proposed by FCC. The impulse response being highly non-linear poses problems for the implementation. We have solved this problem by using Recursive Least Square (RLS) technique to develop an FIR structure for the pulse shaper of this LSE combined pulse. The attraction of the solution is that the resultant filter structure is simple and cost effective.

**Keywords:** Finite Impulse Response Filters, FIR, Impulse response, pulse shaper, UWB transceiver system, UWB indoor channel emission mask, FCC, LSE, RLS.

## 1. INTRODUCTION

The UWB is deemed as an exhilarating and a penetrating technological breakthrough of the recent era which is changing the wireless industry today as there has been a discernible swell in the demand for wireless wideband communication which is, predominantly, attributable to the existing requirement to support more users and to provide more information with higher data rates. Owing to the recent emphasis on low power, low interference the employment of UWB has become a prominent alternative for existing and future wireless applications.

Pulsed UWB is reckoned as a promising area of present-day research that has its descent from the Marconi spark gap radio.

Ultra wide band is a wireless technology that is employed to transmit hefty digital data over a broader spectrum of frequency bands with extremely low power for shorter distances. Ultra wideband (UWB) communication systems can be, by and large, categorized as communication systems with surplus bandwidth ranging from 3.1 to 10.6 GHz.

UWB communication system can be sketched in **(Fig. 1).**

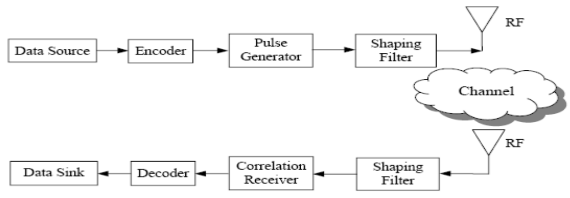


**Fig. 1: A general UWB communication system**

Requirements of obtaining a UWB communication system rely critically on the pulse shaper.

This paper has presented a prime pulse shaper using Gaussian pulse and digital filter design methods, namely the recursive FIR filter using as the learning method.

## 2. PULSE SHAPING

Pulse shaping is used to transform an input signal into a desired and different shaped output signal. They can be viewed as linear time invariant filters. In a communication system pulse shapers are widely used to shape the communicated signal as required by the communication pathway. Characteristically they do this by restraining the operative bandwidth of the communication. This also controls the inter symbol interference produced by the channel. In radio frequency communication pulse shaping is an important contemplation for fitting the signalin the communication band.

As indicated earlier, pulse shaping helps in controlling inter symbol interference. Inter symbol interference effects are prominent when the signal to be transmitted has higher bandwidth then the channel bandwidth. Pulse shapers help to confront this problem by the fact that transmitted signal's spectrum is determined by the band response of the pulse shaping filter. Usually Dirac delta pulses are used to represent the transmitted symbols. These individual impulses are then passed through the pulse shaping filter, shaping acceptable to be passed through the channel. The spectrum of the transmission is thus dependent on the impulse response of this pulse shaping filter.

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The basic criteria for pulse shaping filter is that it should not set up inter symbol interference. For that purpose the filter must satisfy certain criteria. Nyquist ISI criteria as cited in (Proakis, 2003) and (Baas, 2004) is a normally used method. Nyquist ISI narrates the spectrum of the transmitter to inter symbol interference phenomenon. Examples of pulse shaping filters include, raised cosine filters, sinc filters and Gaussian filters. Nyquist ISI criteria elucidates the conditions which when fulfilled by a communication channel affords a method for making band limited functions to astound the effects of inter symbol interference. This criteria states that if channel impulse response in time domain, t, is h(t) with a frequency domain translation H(f), then the condition for an ISI-free response states that frequency replicas of H(f) must sum up to a constant value. In time domain it means that sampling instants possess only one non-zero sample.

Thus by meeting this criteria, if we have the channel's impulse response to be zero at multiples of the symbol period then the next symbol coming at the multiples of the previous symbol will not be interfering with the former and thus we have no inter symbol interference.

## 3. PULSE SHAPING FOR UWB SIGNALS

As indicated earlier an important **concern** in the UWB and in any other communication system is the pulse shapers. The impulse outputfrom pulse shaper is standardized mainly by the spectrum of the energy, percentage bandwidth and -10 dB transmission spectrum(Khuda *et.al.*, 2016). Other important considerations for UWB pulses include non-damped nature and zero dc offset. Damped waveforms have low bandwidth and therefore cannot be used in UWB systems. The presence of a dc component can cause problems in the radiated signal.

Emission constraints enforce restrictions over power spectral density, PSD, of the transmitted signals. Their values are commonly provided in dBm at a given frequency band. According to the limits set by FCC cited in (Sheng, 2003) (Molisch, 2005) and (Ketan, 2003) for indoor UWB channels, the allowed emission mask for indoor UWB generated pulseis -41.3dBm less.

In the formulation of Energy Spectral Density (ESD), let $f_l$ defined the lower frequency limit and $f_h$ defined the the higher frequency limit, then the mid frequency $f_c$of the band is defined as,

$$f_c = \frac{f_h + f_l}{2} \quad (1)$$

Using this, the fractional spectrum is obtained as percentage of energy spectrum and central frequency as,

$$\text{fractional spectrum} = \frac{f_h - f_l}{\frac{f_h + f_l}{2}} \times 100 \quad (2)$$

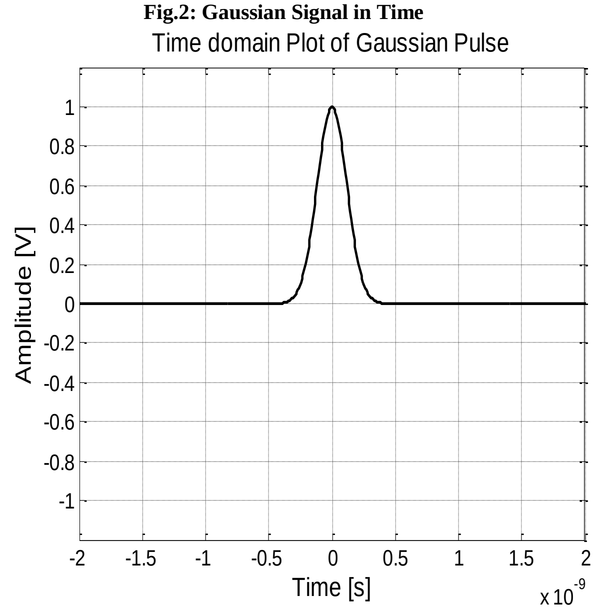
According to(Zhu, 2005) and(Giannakis, 2003) if the fractional bandwidth, as defined by Equation (2), is greater than 20%-25% with $f_l$ and $f_h$ are set to be at -10 dB emission points in the interval of 3.1-10.6 GHz, then that signal is considered UWB(Khuda, 2016).

Other waveforms that can serve as pulse shaper designsfor a UWB are indicated in(Sinyavin and Immoreev, 2002). In almost all of the previous researches Gaussian isdistinctive UWB waveform in wavering applications (Wentzloff, 2010),(Xia, 2010),(Khuda, 2016) and (Khuda, 2017).Gaussian pulse $g(t)$ can be written mathematically as,

$$g(t) = \pm \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\left(\frac{t^2}{2\sigma^2}\right)} = \pm \frac{\sqrt{2}}{\alpha} e^{-\frac{2\pi t^2}{\alpha^2}} \quad (3)$$

where$\alpha^2 = 4\pi\sigma^2$ is taken as the parameter that defines the shape of the Gaussian and $\sigma^2$gives the error component in the form of wave dispersion. The Gaussian waveform and its energyis simulated in **(Fig. 2)**and **(Fig. 3)** as shown in(Khuda *et.al*, 2016).

**Fig.2: Gaussian Signal in Time**



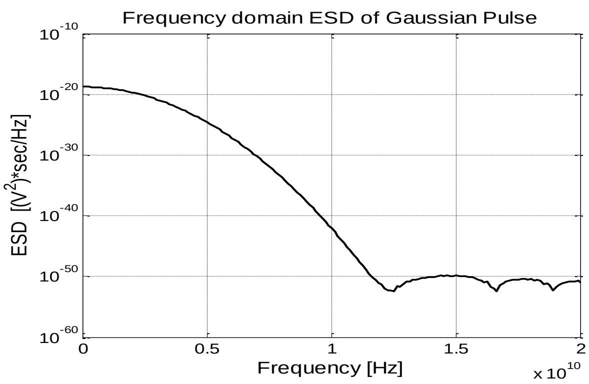



**Fig.3: Gaussian Signal Spectrum in as Energy Density**

Gaussian derivatives are characterized to have zero dc offsets. High pass filtering of the Gaussian pulse is mathematically equivalent to the derivative of it and they are usually used in the design of pulse shaper. Because of the ease in generation, the commonly used pulse shapes in UWB systems are 2nd, 5th and 7thderivative Gaussian pulses. UWB pulse shaping can be obtained mainly by changing the width of Gaussian pulse, differentiating Gaussian pulses higher order derivatives and combination of Gaussian derivatives serving as base functions.

### *A. Pulse-Width Variation*

As indicated in Equation (3), a Gaussian pulse includes a parameter called the shaped factor, α. By varying α, different shapes of Gaussian pulse with different PSD values can be obtained. We carried out the simulations with different shape factor$\alpha$. As stated in (Benedetto, 2008)decreasing the value of$\alpha$, shortened the Gaussian width and enlarged the spectrum of the transmitted waveform. Results of the simulations are reproduced here in **(Fig. 4 and 5)**.Decreasing shape factor$\alpha$does increase the bandwidth but limitations impose by hardware do not allow for decreasing the shape factor$\alpha$ to least extent and obtain the optimum bandwidth and PSD simultaneously.

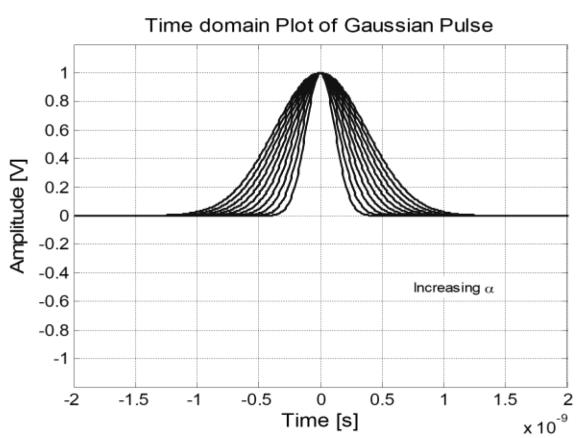



**Fig.4: Time domain plot of the Gaussian Pulses with different values of shape factor α.**

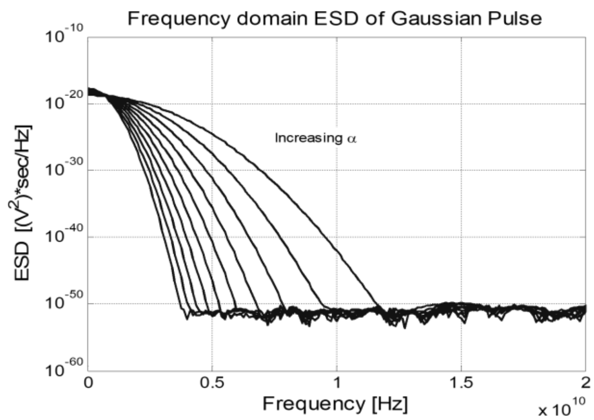



**Fig.5: Frequency domain plot of the ESD of Gaussian Pulses with different values of shape factor α.**

### *B. Pulse Differentiation*

As mentioned earlier, Gaussian derivatives have zero dc offsets; a property which is very much required for UWB pulses. We carried out the simulations for different orders of differentiation and it was observed that ESD changed with it. These simulations are shown in **(Fig. 6, Fig. 7).** It is observable from these simulations that highest frequency and spectrum of the Gaussian increased with increasing differentiation order.

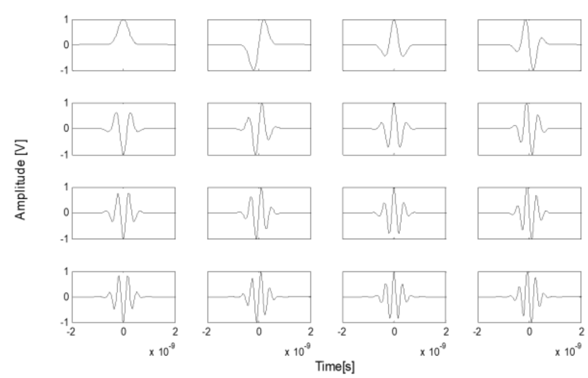



**Fig.6: Time Domain plot of Zero to Fifteen Derivatives of Gaussian Pulses from Left to Right.**

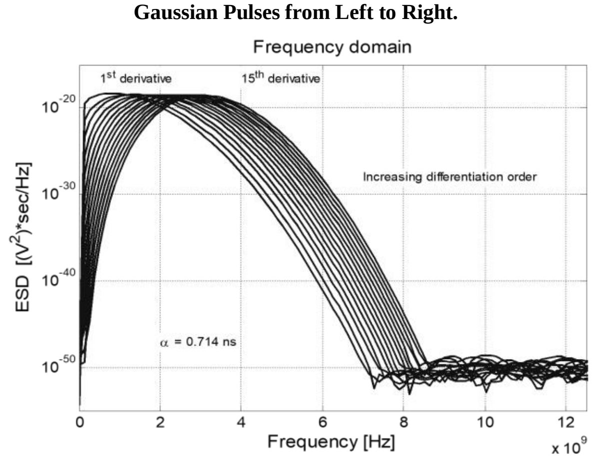



**Fig.7: Frequency Domain plot of ESD of Zero to Fifteen Derivatives of Gaussian Pulses from Left to Right.**

## *C. Combination of Gaussian Derivatives*

Combining Gaussian and its time derivatives is the approach followed in (Khuda *.et.al*, 2016). Altogether 15 higher order derivatives of Gaussian pulse were pooled to meet the FCC emission mask constraints. The simulation results are shown in **(Fig.8 and Fig. 9).**

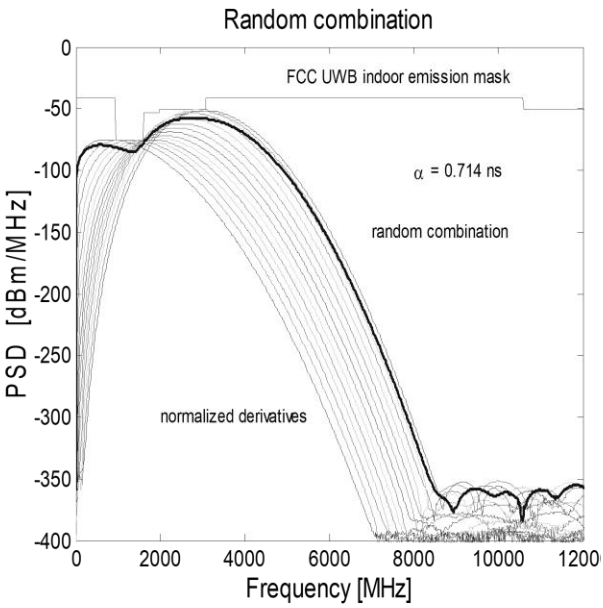



**Fig.8: PSD for Derivatives of Gaussian Signal**

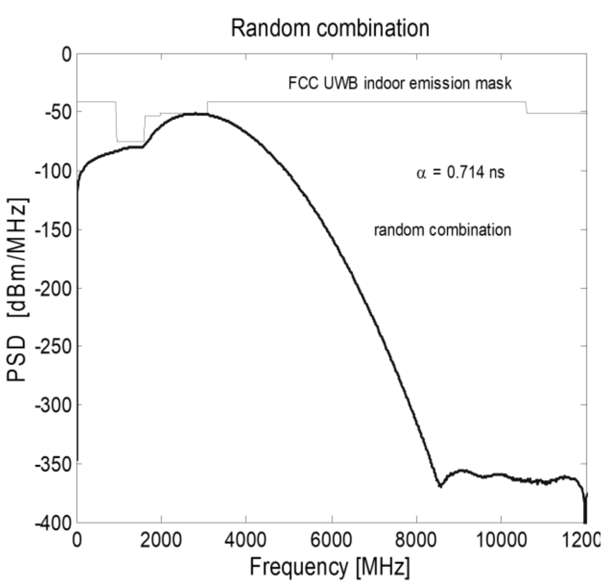



**Fig.9: PSD of the Summed Waveform with FCC Constraints**

However as studied, the value of α=1.5ns for first derivative and α=0.314ns for higher derivatives improved the performance as compared to the former combination. Simulation results are shown in **(Fig. 10 and Fig. 11).**

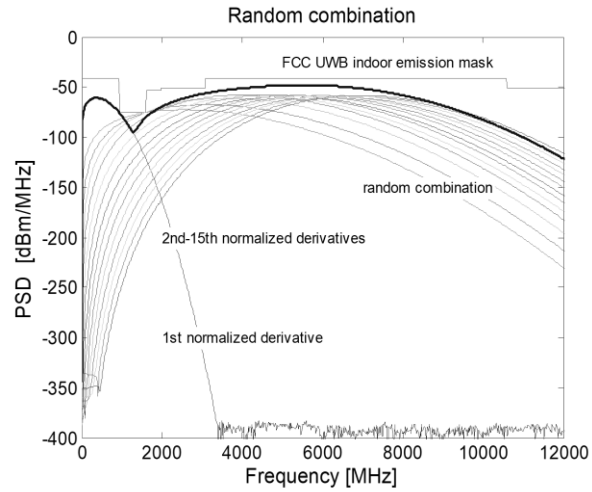



**Fig.10: Frequency Domain Plot of Derivatives of Gaussian Pulse (PSD).**

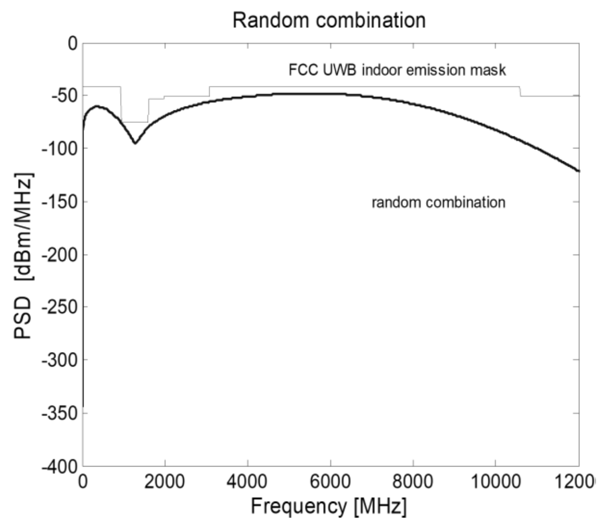



**Fig. 11.Frequency Domain Plot of Summed Waveform(PSD) with α=1.5 ns for 1st Gaussian Derivative and α=0.314 ns for 2nd to 15th Gaussian Derivatives. along with the FCC Constraints.**

Since random selection is one of the possible strategies for the set of coefficients in the linear combination, therefore the optimization problem can be improved by using a more systematic way of selecting coefficients of the linear combination with the help of applying standard procedures for error minimization such as Least Square Error (LSE) in which the following error function was minimized

$$e = \int_{-\infty}^{\infty} |P_M(f) - F(f)|^2 \, df \qquad (6)$$

where$P_M(f)$ is the ideal emission mask and $F(f)$ is the PSD of the rectilinear permutation. We carried a similar set of simulations here. The simulations are replicated here as shown in **(Fig.12).**Shows the time domain new UWB pulse obtained from the LSE combination and **(Fig. 13).**shows its PSD against the FCC UWB emission mask.

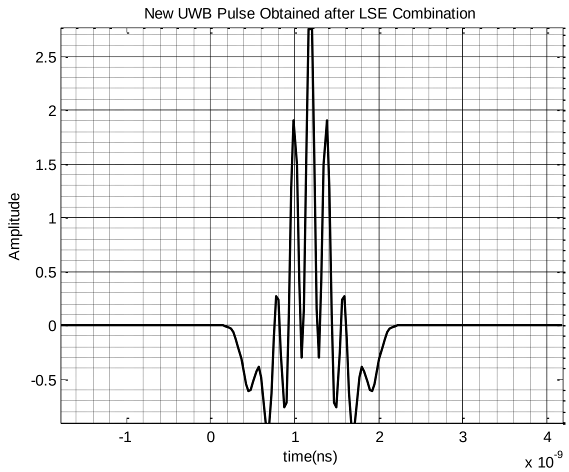



**Fig. 12: New UWB Pulse obtained by LSE combination of coefficients.**

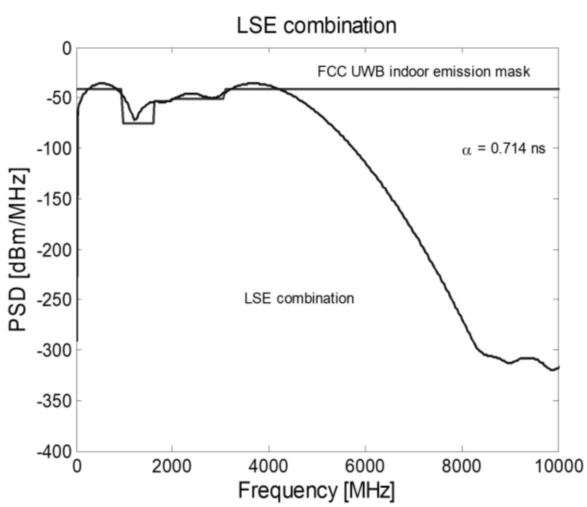



**Fig.13: Comparison of FCC UWB Indoor Emission Mask and PSD of Combined Pulses Optimized by LSE.**

## 4. EXISTING PULSE SHAPER DESIGNS FOR GAUSSIAN PULSE-LIMITATIONS AND CONSTRAINTS

There are two foremost design methodologies in tweaking spectrum characteristics of radiated UWB signal to suffice the FCC constraints. First method is modeling the Gaussian signal with a baseband analog/digital. Other method is modifying parameters of waveforms to make them comply with the standards. Since our research is confined to Gaussian pulses only, therefore in this section we have briefly reviewed the work that has been conducted for the Gaussian pulse.

In the past decade mainly four different pulse shaping filters design methods have been proposed. In (**Table I)** a brief comparison of different pulse shaper designs is made from our study.

**Table I. Comparison of Pulse Shaper Designs**

| Design Reference | Technique |
|---|---|
| **(Giannakis G. B., 2003)** | **The method to model *p(t)* is defined as** $$p(t)=\sum_{n=0}^{M-1} w(n)g(t-nt_o)$$ **Here *g(t)* is the Gaussian monocycle. The Fourier transform of *p(t)* can be adjusted by the values of the weights w(n). They designed the required FIR filter using classical Chebyshev approximation problem.** |
| **(Giannakis G. B., 2006)** | **The proposed a convex optimization based waveform design method. The purpose of their was to find *p(t)* that maximizes normalized effective signal power or NESP under the spectral mask constraint of FCC. Their designed was as** $$p(t)=\sum_{i=0}^{L-1} g_i q(t-iT_q)$$ **Where $T_q$is the sampling interval, *q(t)* is Gaussian monocycle and the set $g_{i}{}_{i=0}^{L-1}$ had the *L* no of coefficients of the pulse required.** |
| **(Molisch, 2003)** | **Formulated a solution by resembling the single-sided min-max problem with a least squares approach. Linear phased FIR filter was used to shape the spectrum of *p(t)* so could be adjusted in the mask. The output signals from the shaper were as** $$s(t)=\sum_{i=0}^{M} s_i p(t-\tau_i)$$ **Where $s_i$ is the filter coefficients and *M* is the number of filter coefficients.** |
| **(A. Annamalai Jr, 2003)** | **It is an extension of [25] using minimum mean square error approach.** |

## 5. RESEARCH METHODOLOGY

Using the results from the previous Section III and knowledge of pulse shapers from Section IV we can formulate pulse shaper for the desired UWB pulse. It is obvious that from Section III that UWB pulse obtained from random combination of the coefficients and with least square error (LSE) between power spectral density for combined signal and FCC constraints, is a better candidate as compared to other UWB pulses. From now on, in the rest of the paper we have termed this pulse as ***LSE combined pulse***.

Our research methodology consists of the following steps

1) Obtain time domain LSE combined pulse using zero order Gaussian signal, x(n)
2) Determine filter coefficients to reproduce LSE combined pulse
3) Use the filter coefficients to design the FIR filter, y(n)
4) Verify the FIR filter output against the desired signal
5) Conclude the results

The research instrument we have used is Matlab® **(Fig. 14).** shows the block diagram of this process.

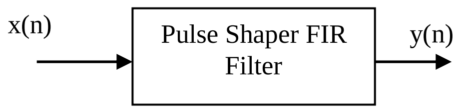



**Fig. 14.Compact block diagram of research methodology**

## 6. DESIGNED FIR FILTER

For our pulse shaper functionality we targeted of developing an FIR filter for the impulse response of our LSE combined pulse. Input signal x(n) is the zero order Gaussian pulse and output y(n) of the designed FIR filter is the new UWB pulse obtained from LSE combination of coefficients. *Figure 12*shows highly non-linear characteristics of our *LSE combined pulse.* Therefore extending the pulse shaper from non-linear case, in the design of desired FIR filter our problem has now converged to an adaptive system identification problem for this non-linearly characterized LSE combined pulse. We have used recursive least square (RLS) estimation to find out the desired filter coefficients for the non-linear LSE combined pulse.

Our work showcases system identification using an RLS filter because of highly non-linear characteristics of desired LSE combined pulse. The workflow is depicted in **(Fig. 15).**

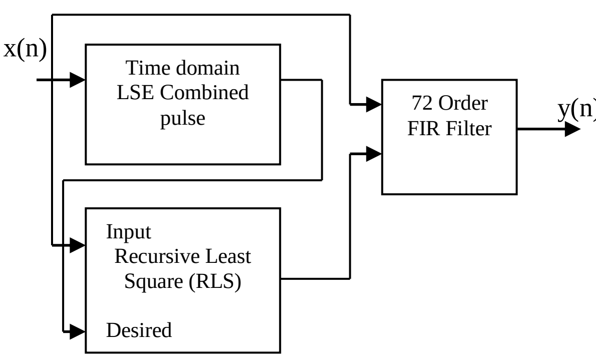



**Fig. 15.Workflow for designing RLS filter**

As shown in **(Fig. 15)** we have used RLS algorithm to obtain FIR filter weights/ coefficients to identify *LSE combined pulse*. It required 72 weights to properly identify the desired UWB pulse. Results from the FIR filter, i.e. y(n) and time domain *LSE combined pulse* are compared in **(Fig. 16).**.

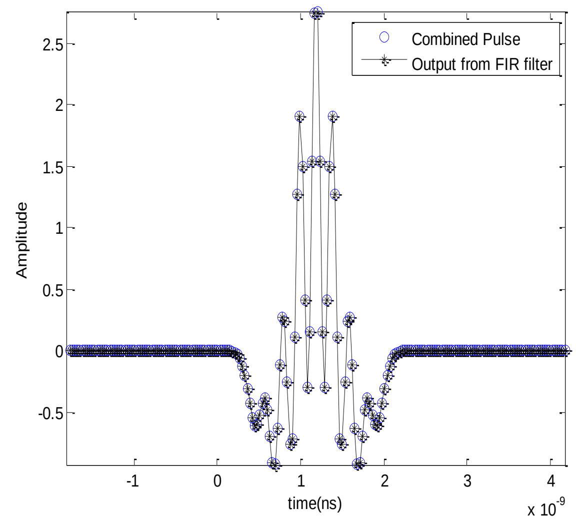



**Fig. 16: Comparison of our FIR Filter output and LSE Combined Pulse**

## 7. DESIGN OF RECURSIVE LEAST SQUARE (RLS) FILTER

We have made use of RLS adaptive filtering approach to model the FIR filter for our pulse shaper of LSE combined pulse. The results obtained and shown in **(Fig. 15)** shows the accuracy of our FIR filter by using the weight values/ filter coefficients obtained by RLS procedure.

The recursive least-squares (RLS) algorithm has the capability to catch up with the desired characteristics which are changing randomly, i.e. and so RLS provides its usefulness in handling non-linear problems. So was the case in our scenario. As could be seen in **(Fig. 11)**, our desired response is highly non-linear; therefore we opted to use RLS for FIR filter identification.

### *A. Problem Statement*

At the start, we are provided with the set of input samples $\{x(1), x(2), \ldots, x(N)\}$ and the set of preferred response$\{d(1), d(2), \ldots, d(N)\}$. The set of input samples is zero order Gaussian pulse and set of desired response is our LSE combined pulse. Using linear filtering theory, output is computed as follows

$$y(n) = \sum_{k=0}^{M} w_k\, x(n-k), \qquad n = 0,1,2, \ldots \ldots \ldots (7)$$

Our problem is to find recursively in time (n) the parameters $\{w_0(n), w_1(n), \ldots, w_{M-1}(n)\}$ such as to minimize the sum of the error squares;

$$\varepsilon(n) = \varepsilon\big(w_0(n), w_1(n), \ldots, w_{M-1}(n)\big) \ldots \ldots \ldots (8)$$

$\varepsilon(n) = \sum_{i=i_1}^{n} \beta(n,i)[e(i)^2] \dots \dots \dots \dots \dots \dots . (9)$

Where$\varepsilon(n)$is the cost function, the error signal is,

$$e(i) = d(i) - y(i) = d(i) - \sum_{k=0}^{M} w_k(n)\, x(i-k) \dots \dots (10)$$

and$\beta(n,i)$is the forgetting factor or weighting factor. It reduces the influence of old data. It is defined by the condition that,

$$\mathbf{0} < \boldsymbol{\beta}(\boldsymbol{n},\boldsymbol{i}) < 1, \quad \boldsymbol{i} = \mathbf{1},\mathbf{2},\dots\dots,n$$

Exponential weighting factor or forgetting factor is defined as,

$$\boldsymbol{\beta}(\boldsymbol{n},\boldsymbol{i}) = \boldsymbol{\lambda}^{\boldsymbol{n}-\boldsymbol{i}} \dots \dots \dots \dots \dots \dots \dots \dots .. (11)$$

Here λ is a positive constant, close to but less than 1. When λ=1, we have ordinary method of least squares (OLS). In the method of exponential weighted least squares, we minimize the cost function.

$$\varepsilon(n) = \sum_{i=i_1}^{n} \lambda^{n-i}[e(i)^2] \dots \dots \dots \dots \dots . (12)$$

The optimum value of the tap-weight vector $\widehat{w}(n)$ for which the cost function $\varepsilon(n)$ achieves its minimum value is defined by the normal equations written in matrix form,

$$\Phi(n)\widehat{w}(n) = \psi(n) \dots \dots \dots \dots \dots . (13)$$

Where $\Phi(n)$ is an $MxM$ correlation matrix and is defined by

$$\Phi(n) = \sum_{i=1}^{n} \lambda^{n-i} x(i) x^H(i) \dots \dots \dots \dots (14)$$

Where $H$ is for the Hermatian matrix or transpose of complex matrix. And $\psi(n)$ is an$M \times 1$ cross correlation vector, defined as,

$$\psi(n) = \sum_{i=1}^{n} \lambda^{n-i} x(i) d^*(i) \dots \dots \dots \dots \dots (15)$$

where * denotes complex conjugation

In our problem we found recursive in time way the required weight values

$$\widehat{w}(n) = [\Phi(n)]^{-1}\psi(n) \dots \dots \dots \dots (16)$$

using the information already available at time n-1, i.e

$$\widehat{w}(n-1) = [\Phi(n-1)]^{-1}\psi(n-1) \dots \dots \dots . (17)$$

The $\widehat{w}(n)$ is the desired set of coefficients for LSE combined pulse shaper.

## 8. CONCLUSION

In this paper we have studied and surveyed different ways to formulate UWB pulses. After understanding this we have worked out to design an FIR filter for the best known design available in the literature survey. The novelty in our research is that so far in our study however theoretical work has been laid out for LSE combined pulse but we did not find any study in which system identification for such a pulse would have had been made. Our contribution is that we have successfully modeled such a system viz. adaptive recursive signal processing technique. In future we tend to further optimize this filter by minimizing its order and implement it on a FPGA or DSP processor.

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