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Enhanced Pulse Shaping Filters For IEEE 802.11 OFDM WLANs

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***Abstract*— Several communication systems such as the IEEE 802.11 Wireless LAN standards use Orthogonal Frequency Division Multiplexing along with pulse shaping filters to mitigate the effect of Inter Symbol Interference (ISI). Although several pulse shaping filters such as Raised Cosine (RC), Square Root Raised Cosine, Flipped Exponential Pulse (FEXP) and Parametric Exponential Pulse (PEXP) have been proposed, it is still possible to improve the performance of these filters. In this paper two enhanced pulse shaping filters have been proposed. The first one is a Modified FEXP (MFEXP) filter which uses a different transfer function that can be implemented at both the transmitter and receiver. The second one is a Hybrid FEXP and PEXP filter (HFPEXP) which is obtained by modifying the transfer function of the FEXP pulse and combining it with the PEXP pulse. Both proposed filters have been incorporated and tested in the IEEE 802.11 WLAN system with Additive White Gaussian (AWGN). Results show that the proposed filters provide superior Bit Error Rate (BER) performance than the conventional ones such as RC, SRCC, FEXP and PEXP for different ISI levels and their impulse response also result in smaller side lobes.**

***Keywords*— Pulse Shaping, FEXP, PEXP, OFDM, WLAN**

I. INTRODUCTION

Inter-Symbol Interference (ISI) which is the spreading of one symbol into another as a result of transmission through a band-limited channel, is a well-known problem in digital communications. In [1], Nyquist identified several conditions which pulse shaping filters have to satisfy so as to mitigate the effect of ISI. The most important condition is that the equivalent impulse response of the transmitting and receiving filters should have zero crossings at multiples of the symbol period, T [1]. Most conventional pulse shaping filters such the Raised Cosine (RC) and Square Root Raised Cosine (SRRC) satisfy this condition, although other filters have also been designed to meet more objectives [2,3,4]. Pulse shaping filters have been widely used in state of the art communication systems. For example square root raised cosine (SRRC) pulses have been proposed for 802.11a WLAN systems [5], Wideband Code Division Multiplex Access (WCDMA) system [6], and 3GPP Long Term Evolution (LTE) [7]. Consequently, several research has been conducted on the development of new pulse shaping filters to better address the requirements of communication systems. An overview of some of the proposed pulse shaping filters is given next.

An ISI-free filter that outperformed the Nyquist pulse by providing a smaller maximum distortion, a wider receiver eye, and smaller probability of error in the presence of symbol timing errors for the same excess bandwidth was proposed in [8]. The filter was also referred as FEXP. Building upon the work of [8], the authors in [9] proposed two new filters that that provide better error probability performance in the presence of sampling errors than the RC filter and the FEXP. The proposed filters were referred as flipped-hyperbolic secant (FSECH) pulse and flipped-inverse hyperbolic secant (FARCSECH) pulse. Further improvements to the these filters were provided in [10] which proposed three novel ISI free pulses that outperformed the ones in [8] and [9]. Moreover in [11] the performances of different time-limited waveforms such as the Rectangular pulse, RC and FEXP were analysed in an OFDM system. Two new pulse shapes that outperformed the FEXP in terms of BER were also proposed. Another analysis of the performance of pulse shaping filters in an OFDM system was performed in [12]. The performance of several pulse shaping filters were evaluated in terms of BER for 16-QAM modulation with an AWGN channel. Results showed that pulse shaped OFDM with SRRC outperformed all other pulse shaping schemes investigated [12]. In [13] the effect of SRRC pulse shaping on an OFDM based WLAN system was evaluated with a view to determine the most appropriate rolloff factor, truncation length, oversampling rate and quantization levels that should be employed. It was observed that in general filters with higher rolloff factor values need shorter truncation lengths, fewer quantization bits and are more resistant to synchronization errors. The tradeoff is a higher excess bandwidth requirement. Finally, the performance of SC-FDMA with Pulse Shaping (PS) was assessed in [14]. It was observed that the conventional RC leads to a trade-off between spectrum efficiency and low PAPR in IFDMA. However, Nyquist pulses such as PEXP and the Nyquist Linear Combination Pulse (NNLCP) can reduce

PAPR of IFDMA significantly while maintaining the same Bandwidth (BW) compared to RC.

In line with the above research direction on pulse shaping filters, this paper analyses the BER performance of several conventional and state of the art pulse shaping schemes in an ODFM system. Additionally, two new Nyquist pulses are proposed. The first one is a Modified FEXP (MFEXP) filter which uses a different transfer function that can be implemented at both the transmitter and receiver. The second one is a Hybrid FEXP and PEXP filter (HFPEXP) which is obtained by modifying the transfer function of the FEXP pulse and combining it with the PEXP pulse. Simulation results showed that the proposed filters provide superior BER performance than the conventional ones such as RC, SRCC, FEXP, PEXP, FSECH and NNLCP for different ISI levels and their impulse responses also result in smaller side lobes. The pulses were implemented for the IEEE 802.11 OFDM WLAN system and tested in AWGN.

This paper is structured as follows. Section II gives some background theories on different conventional and state of the art pulse shaping filters. Section III describes the proposed new pulse shaping schemes as well as the transmitter and receiver system models. Section IV presents the simulation results and analysis. Section V concludes the paper.

II. BACKGROUND

In this section, an overview of the following pulse shaping filters is provided:

i. Raised Cosine (RC)

ii. Square Root Raised Cosine (SRRC)

iii. Flipped Exponential Pulse (FEXP)

iv. Parametric Exponential Pulse (PEXP)

v. New Nyquist Linear Combination Pulse (NNLCP)

vi. Flipped Hyperbolic Secant Pulse (FSECH)

The impulse responses of the above filters and their time-domain plots with a filter length of 81 taps, for different values of roll-off factors, α, are given next. All the impulse responses have been normalised.

II.1 RC Pulse

It is the most commonly used Nyquist pulse in digital communication systems. Its impulse response is as follows:

$$hrc(t) = sinc\left(\frac{t}{T}\right)\frac{\cos(\frac{\pi\alpha t}{T})}{1-\left(\frac{2\alpha t}{T}\right)^2} \quad (1)$$

where,

α is the roll-off factor,

T is the symbol period.

$t = nTs$, where, n is the number of samples and Ts is the sampling frequency.

The plot of the impulse response is given in Fig.1.

From Fig.1, the pulse is seen to decay rapidly for larger values of α. The side lobe level is also lower at higher values of α.

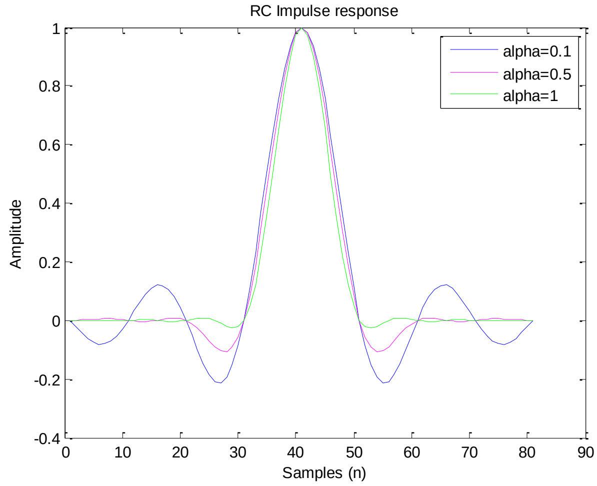

Fig. 1. Impulse response for RC filter.

II.2 SRRC Pulse

This filter is formed by taking the root of the frequency response of the RC pulse. It is implemented at both the transmitter and receiver as a matched filter. It maximises the SNR of the signal and matches its shape to that of the original signal. Its impulse response is expressed as:

$$hsrrc(t) = \frac{\sin\left(\frac{\pi t}{T}(1-\alpha)\right)+\frac{4\alpha t}{T}\cos(\frac{\pi t}{T}(1+\alpha))}{\frac{\pi t}{T}\left(1-\left(\frac{4\alpha t}{T}\right)^2\right)} \quad (2)$$

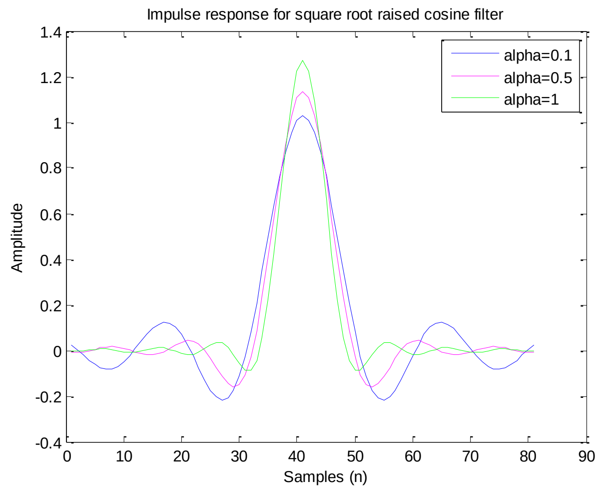

Fig.2. Impulse response for SRRC filter.

In Fig.2, it can be observed that as α increases, the side lobe levels also get reduced. However, the SRRC pulse results in slightly faster transitions than the RC filter. [17] This is because the main side lobe of the SRRC filter for α = 0.5 occurs at the 53rd while that for the RC pulse occurs at the 54th sample. At α=1, the SRRC pulse has its main side lobe at the 50th sample whereas that for RC occurs at the 51st sample. Hence, there is an average delay of 1 sample between the RC and SRRC filter.

II.3 FEXP Pulse

It is a new pulse which has been proposed in [8]. It is also referred to as the "Better Than" Raised Cosine Pulse. Its impulse response is described as:

$$hfexp(t) = \frac{1}{T} sinc(\frac{t}{T}) \frac{4\beta\pi t sin\left(\frac{\pi\alpha t}{T}\right)+2\beta^2 \cos\left(\frac{\pi\alpha t}{T}\right)-\beta^2}{(2\pi t)^2+\beta^2} \tag{3}$$

where,

$\beta = ln\ 2/ (\alpha B)$,

$B = (1/2T)$, the Nyquist frequency,

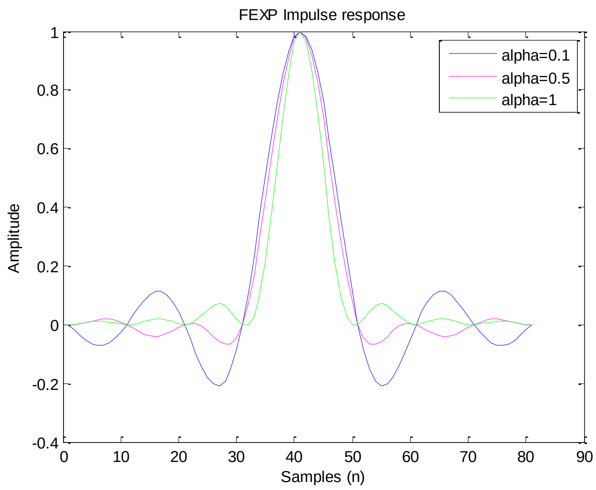

Fig. 3. Impulse response for FEXP filter.

Compared to the RC pulse in Fig.1, the FEXP pulse has lower side lobe amplitude which can better control ISI as shown in Fig.3.

II.4 PEXP Pulse

The PEXP filter belongs to the parametric family of Nyquist pulses which is characterised by a parameter n. The value of n determines a new pulse with an arbitrary decay rate. [16] Since the Peak-to-Average Power Ratio (PAPR) is affected greatly by the decay rate, the value of n was chosen to reduce PAPR in an SC-FDMA signal as was described in [16]. The impulse response was made to decay exponentially as t^{-2} by setting n to 1 [16]. Hence, the impulse response is defined as:

$$hpexp(t) = sinc(\tau).m(t) \tag{4}$$

$$m(t) = \frac{2\{(\pi\alpha)/(\ln 2)\}\tau \sin(\pi\alpha\tau)+2\cos(\pi\alpha\tau)-1}{((\pi\alpha)/(\ln 2)\tau)^{\wedge}2+1}, \tag{5}$$

where,

$\tau = t/T$ is the normalized time.

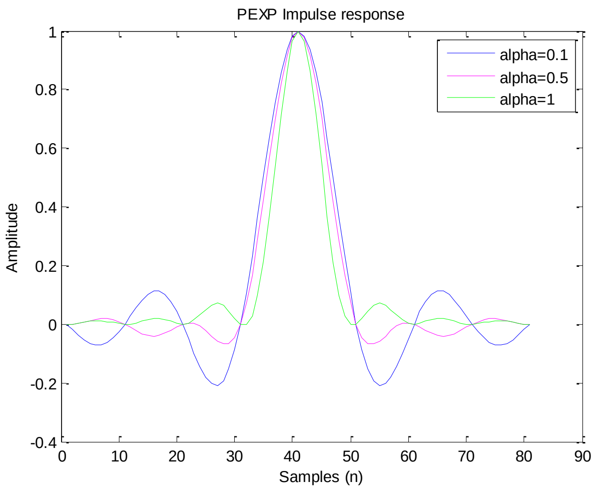

Fig.4. Impulse response for PEXP.

From Fig.4, the PEXP pulse can be seen to have the same time-domain response as the FEXP pulse when n=1. Hence, it maintains zero ISI condition and helps to improve PAPR reduction as compared to the RC filter [16].

II.5 NNLCP Pulse

This pulse shape is a linear combination of the conventional RC and PEXP pulses. It is designed to reduce Peak-to-Average Power Ratio (PAPR) of the subcarrier mapping scheme known as Single Carrier-Interleaved Frequency Division Multiple Access (SC-IFDMA) in uplink transmission of Long Term Evolution Advanced (LTE-A) [14]. The impulse response of the NNLCP filter is given as:

$$hnnlcp(t) = C.hpexp(t) + B.hrc(t) \tag{6}$$

C and B are linear combination constants, defined for all real numbers. B=1-C, so that Nyquist first criterion is respected while C minimizes the PAPR for a given α. The optimum value of C is set to 1.5 to reduce PAPR [14]. The overall impulse response for NNLCP pulse is given as:

$$hnnlcp(t) = sinc(\tau)\left[C.m(t) + (1-C).\frac{\cos(\pi\alpha\tau)}{1-(2\alpha\tau)^2}\right] \tag{7}$$

where $m(t)$ is taken from Equation (5).

From Fig. 5, it can be observed that for a given value of α, the NNLCP pulse exhibits smaller main side lobe amplitude in comparison to the RC filter.

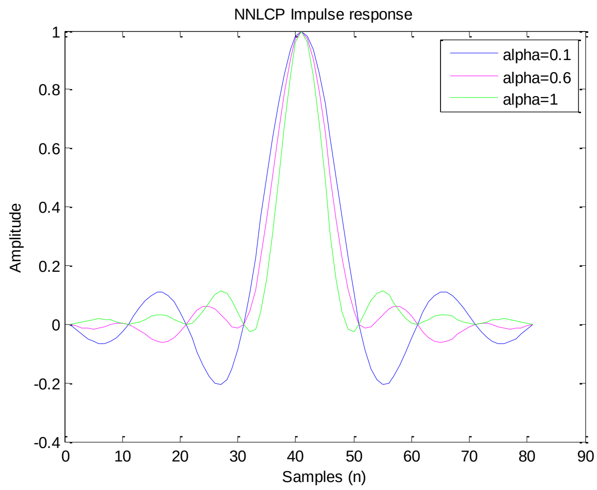

Fig. 5. NNLCP Impulse Response.

II.6 FSECH Pulse

It is a category of Nyquist pulses which decays at a rate of t^{-3} [9] and its impulse response is obtained through the expansion of a series of exponentials as follows:

$$hfsech(t) = \frac{1}{T} sinc(t/T) \left\{ 8\pi t sin\left(\frac{\pi\alpha t}{T}\right) F1(t) + 2\cos\left(\frac{\pi\alpha t}{T}\right)[1 - 2F2(t)] + 4F3(t) - 1 \right\} \tag{8}$$

where,

$$F1(t) = \sum_{k=0}^{+\infty}(-1)^k \frac{(2k+1)\gamma}{\left((2k+1)\gamma\right)^2 + (2\pi t)^2} \tag{9}$$

$$F2(t) = \sum_{k=0}^{+\infty}(-1)^k \frac{(2\pi t)^2}{\left((2k+1)\gamma\right)^2 + (2\pi t)^2} \tag{10}$$

$$F3(t) = \sum_{k=0}^{+\infty}(-1)^k \frac{(2\pi t)^2}{\left((2k+1)\gamma\right)^2 + (2\pi t)^2} e^{-(2k+1)\frac{\alpha\gamma}{2T}} \tag{11}$$

and $\gamma = \ln(\sqrt{3}+2)/(\alpha B)$ while k is set to a realistic value of 50.

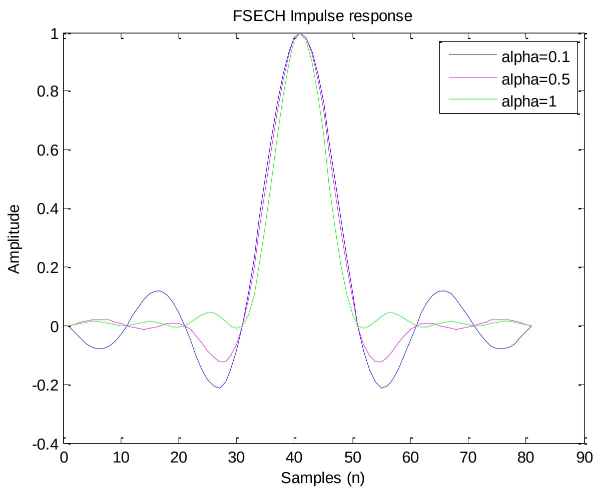

Fig.6. Impulse response for FSECH.

From Fig.6, the FSECH pulse is seen to behave in the same trend as the RC pulse except that it displays slightly smaller main side lobe levels than the RC pulse.

III. PROPOSED FILTERS AND SYSTEM MODEL

In this work two new pulse shaping filters have been proposed and integrated into the IEEE 802.11 OFDM system.

III.1 MFEXP Filter

This filter is a modified form of the FEXP filter which can be employed at both transmitter and receiver. It is designed to further reduce ISI by decreasing the side lobe power without a considerable cost. The impulse response is specified as follows:

$$hmfexp(t) = sinc(2Bt)\frac{4\beta 1\pi t sin(2\pi\beta 1\alpha t) + 2\beta 1^2\cos(2\pi\beta 1\alpha t) - \beta 1^2}{4\pi^2 t^2 + \beta 1^2} \tag{12}$$

where,

$\beta 1 = \frac{ln\,3}{\alpha B}$. The value, $ln\,3$ was experimentally determined and it makes the main lobe width quite large and decreases the amplitude of the side lobe.

The time domain response is plotted in Fig.7:

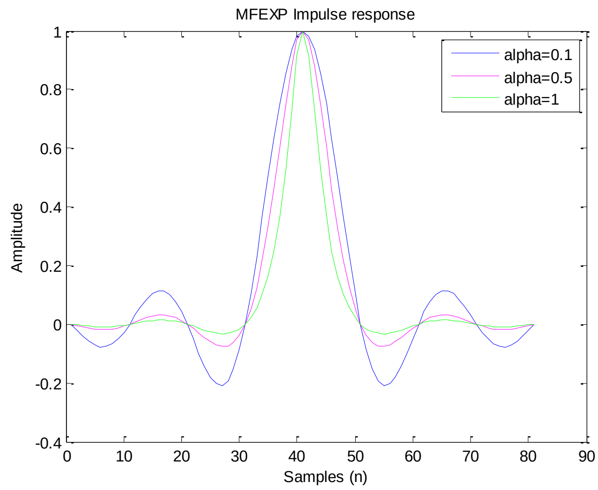

Fig.7. MFEXP Impulse Response.

As observed from Fig.7, the MFEXP filter has even lower side lobe levels as α increases. However, there is a tradeoff between side lobe amplitude and main lobe width for larger values of α. If the main lobe width becomes too narrow, more bandwidth will be required and as such the filter will not be preferred to be used.

III.2 HFPEXP Filter

This filter is formed by the linear combination of the PEXP and FEXP pulses. It can be implemented at both the transmitter and receiver. However, the FEXP pulse has been slightly modified to give smaller amplitude of the side lobe. Its impulse response is given as follows:

$$hfexp1(t) = \frac{1}{T} sinc(\frac{t}{T}) \frac{4\beta 2\pi t sin\left(\frac{\pi\alpha t}{T}\right) + 2\beta 2^2 \cos\left(\frac{\pi\alpha t}{T}\right) - \beta 2^2}{(2\pi t)^2 + \beta 2^2} \quad (13)$$

where,

$\beta 2 = ln\ 4/\ (2.5\alpha B)$, where *ln* 4 and the value of 2.5 were experimentally determined.

$$hfpexp(t) = B.hpexp(t) + sinc(\tau).C.hfexp1(t) \quad (14)$$

Hence,

$$hfpexp(t) = sinc(\tau)\ ([(1 - C).m(t)] + [\ C.hfexp1(t)]) \quad (15)$$

The value of C is taken as 1.5 to evaluate the impulse response of this filter as it gives smaller side lobe levels.

The impulse response of the HFPEXP filter is shown in Fig.8.

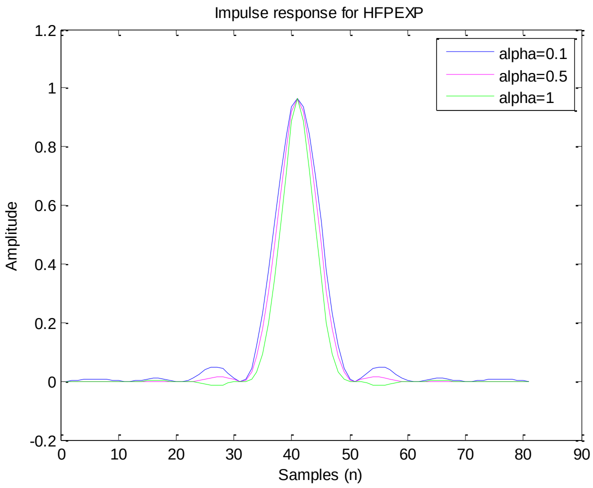

Fig.8. HFPEXP Impulse Response.

The HFPEXP pulse has decreasing side lobe levels for larger values of α as shown in Fig.8. This feature makes the pulse more robust against ISI distortion and helps in minimizing PAPR.

III.3 OFDM System

An OFDM system with BPSK modulation was adopted in this work. The system model is shown in Fig.9.

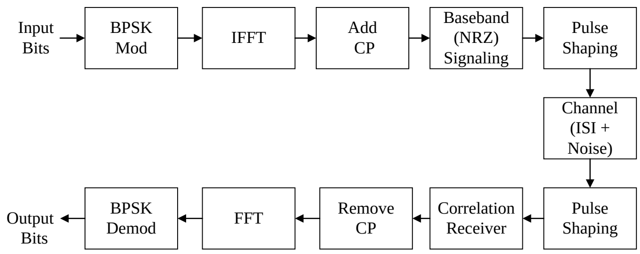

Fig.9. System Model

On the transmitter side, random bits are generated and mapped to BPSK symbols. Data subcarriers are assigned to the bit stream as per the IEEE 802.11 Wi-Fi standard [5]. The IFFT operation converts the data into time domain followed by the addition of a cyclic prefix. The signal is then converted into NRZ pulses by using an oversampling factor of 10. Different pulse shaping filters with a constant length of 41 taps and α = 0.6, are applied to the baseband signal. The channel is bandlimited by a Butterworth filter of length 7 and a variable cut-off frequency is used to introduce different levels of ISI. Complex AGWN noise is also added to the transmitted signal. At the receiver, matched filtering is performed so as to match the incoming noisy signal to the true shape of the original signal and maximize the SNR. A correlation receiver is used to interpolate the samples to form a smooth signal. The baseband signals are down sampled followed by the removal of the cyclic prefix. The data is converted back to frequency domain by FFT and the data subcarriers are then extracted. BPSK de-mapping is lastly performed to recover the bits. Table 1 below specifies the parameters used for the OFDM simulator.

Table 1.OFDM parameters specifications for IEEE 802.11a/g WLAN standard. [5]

Parameter	Value
Modulation Type	BPSK
Bit rate	6 Mbps
FFT size, N	64
No. of data subcarriers, N_{sd}	48
No. of pilot subcarriers, N_{sp}	4
Total No. of used subcarriers, N_{st}	52 (N_{sd} + N_{sp})
No. of unused subcarriers	12 (N - N_{st})
OFDM bandwidth, ofdmBW	20MHz
Subcarrier frequency spacing, Δf	0.3125MHz (ofdmBW/N)
IFFT/FFT period, T_{fft}	3.2μs (1/ Δf)
Guard interval duration, T_{gi}	0.8μs (T_{fft}/4)
Duration of BPSK OFDM symbol, T_{signal}	4.0μs (T_{gi} + T_{fft})
No. of symbols for cyclic prefix, N_{cp}	16 (N*T_{gi}/T_{fft})

IV. SIMULATION RESULTS AND ANALYSIS

The performances of the following pulse shaping filters with AWGN have been evaluated for two different ISI levels namely ISI levels at bandwidth of 12 MHz and 20 MHz respectively. Matlab software was used to carry out the simulation.

i. RC

ii. SRRC

iii. FEXP

iv. PEXP

v. NNLCP

vi. FSECH

vii. MFEXP

viii. HFPEXP

For each filter at different ISI levels, the number of samples that are removed from the start of the signal at the receiver during matched filtering, are listed below. This is important for detecting the peak value for each pulse shaped data at the correct sampling instant before recovering the bits at the correlation receiver. The number of samples removed differs for each filter.

Table 2. No. of Samples extracted for each filter at receiver.

Filter	**No. of samples removed**	
	ISI level 1 (12 MHz)	**ISI level 2 (20 MHz)**
RC	0	1
SRRC	2	1
FEXP	2	3
PEXP	2	3
NNLCP	2	3
FSECH	1	1
MFEXP	3	3
HFPEXP	3	3

The transmit filters are compared in Fig.10 below.

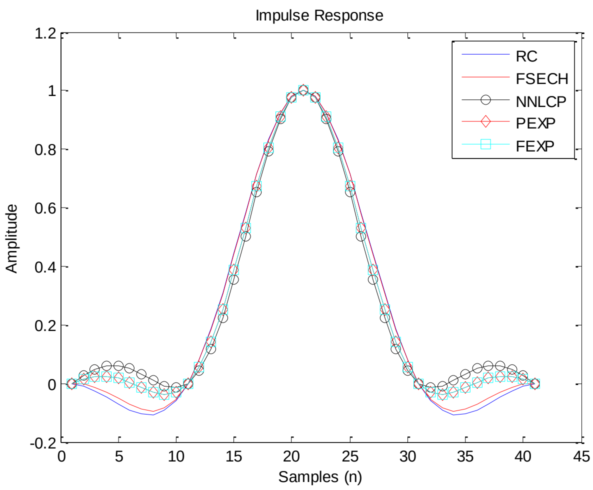

Fig.10. Impulse response for transmit filters.

It is observed that the FSECH pulse has lower side lobe compared to the RC pulse. However, NNLCP, PEXP and FEXP lead to even smaller side lobe amplitude. PEXP and FEXP lead to the same pulse shape in time-domain. Comparing FEXP and NNLCP, the latter has a slighlty larger side lobe level. Hence, FEXP handles ISI slighlty better than NNLCP.

The filters implemented at both the transmitter and receiver are compared in Fig.11 below.

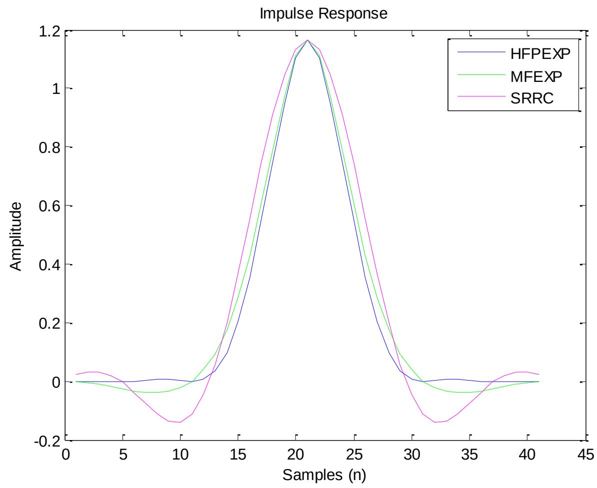

Fig.11. SRRC, MFEXP and HFPEXP Impulse response.

As observed from Fig.11, the MFEXP and HFPEXP pulses have lower side lobe levels compared to the SRRC filter at α=0.6.

After implementation at both transmitter and receiver, the auto-convolution of the SRRC, MFEXP and HFPEXP filters lead to the impulse response shown in Fig.12.

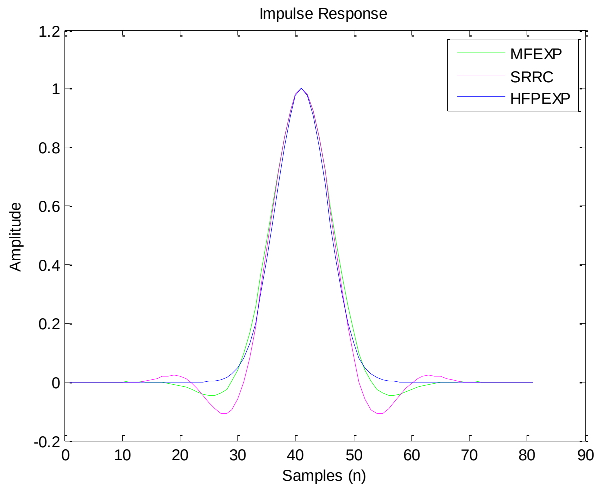

Fig.12. Auto-convolution of filters after implementation at both transmitter and receiver.

After auto-convolution of the pulses at the receiver side, the SRRC filter is seen to behave as the RC filter as shown in Fig.12. In contrast to the SRRC filter, the auto-convolution of the MFEXP pulse leads to lower side lobe amplitude while that for HFEXP leads to almost flat side lobe levels. Hence, both the MFEXP and HFPEXP pulses handle ISI more effectively than the SRRC pulse.

IV.1 Simulation Results with AWGN under ISI level at bandwidth 12 MHz.

The graph of BER against Eb/No is shown in Fig.13 for BPSK OFDM under ISI level at 12 MHz for all the above filters. Considering only the transmit filters, the FSECH filter has a gain of 1.8 dB in Eb/No over the RC filter at a BER close to 10^{-1}. The FEXP pulse has the lowest BER and the PEXP pulse follows the same BER curve as the FEXP pulse. The latter outperforms NNLCP and FSECH pulses by gains of 0.42 dB and 1.33 dB respectively at a BER of 10^{-1}. The transmit and receive filters namely SRRC, MFEXP and HFPEXP have improved BER performance than the transmit filters only. The MFEXP and HFPEXP filters provide gains of 1.2 dB and 1 dB respectively in Eb/No over the SRRC pulse at a BER of 10^{-2}. At a BER value of 10^{-4}, the curves for MFEXP and HFEXP both converge and have a gain of 1.5 dB in Eb/No over the SRRC filter.

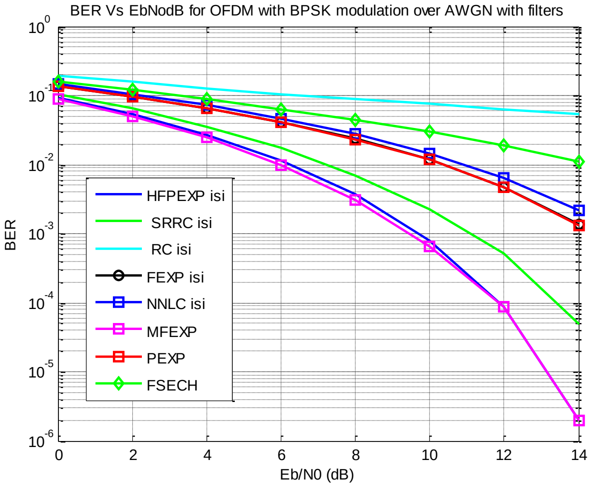

Fig.13. Graph of BER against Eb/No at bandwidth 12 MHz.

IV.2 Simulation Results with AWGN under ISI level at bandwidth 20 MHz.

The graph of BER against Eb/No is shown in Fig.14 for BPSK OFDM under ISI level at 20 MHz for all the above filters. Under reduced ISI, that is, at a higher bandwidth, the filters show a significantly improved BER performance. The curves for both RC and FSECH converge at a BER value close to 10^{-4}. The FEXP pulse outperforms NNLCP and FSECH pulses by a gain of 0.4dB and 1.2dB respectively in Eb/No at 10^{-4}. At a BER of 10^{-3}, the MFEXP and HFPEXP pulses each provide a gain of 0.4 dB and 0.2 dB over the SRRC filter respectively in Eb/No. All the 3 transmit and receive pulses converge below a BER of 10^{-4}.

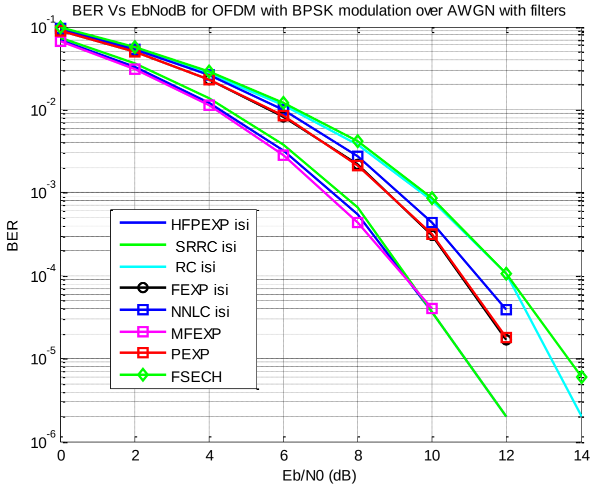

Fig.14. Graph of BER against Eb/N0 at bandwidth 20 MHz.

Under a higher ISI level, the filters show a worse error performance and there is quite a large gap between the curves of the different transmit filters due to ISI distortion effects. The MFEXP and HFPEXP pulses demonstrate better error performance compared to the SRRC pulse. The MFEXP and HFPEXP pulses have almost the same BER performance. Under lower ISI condition, the filters exhibit a relatively better BER performance. The gap difference between the transmit filters also diminishes to a great extent.

V. CONCLUSION

This paper proposed two new pulse shaping filters namely MFEXP and HFPEXP which can be implemented at both transmitter and receiver. Their BER perfromance has been evaluated in an IEEE 802.11 OFDM WLAN system with BPSK modulation under AWGN and ISI. After investigating the performance of the pulse shaping filters under the two ISI conditions, it can be deduced that the lower the side lobe levels of the pulses, the better will be their error performance. It has been demonstrated that the two newly proposed filters show an improved error performance compared to the SRRC filter and other transmit filters in different ISI conditions. The impulse response of the proposed filters also exhibit significant lower side lobe levels which makes them more immune to ISI.

VI. ACKNOWLEDGMENT

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