# Performance Of Ieee 802.11 OFDM With Multiple Frequency Transforms And Pulse Shaping Schemes

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***Abstract*: *Orthogonal Frequency Division Multiplexing (OFDM) is employed in various communication systems such as the IEEE 802.11 wireless standards, in which both frequency transform, Fast Fourier Transform (FFT) and pulse shaping filter, Square Root Raised Cosine (SRRC) are used. The main contribution of this paper is the analysis of the performance of different combinations of frequency transforms and pulse shaping schemes for the 802.11n standard. The frequency transforms which have been used are: Fast Fourier Transforms (FFT), Discrete Wavelet Transforms (DWT) and Discrete Hartley Transform (DHT). The pulse shaping filters are the Raised Cosine (RC), SRRC and Flipped Exponential Pulse (FEXP). The IEEE 802.11 WLAN system with Additive White Gaussian (AWGN) has been used as the modelling environment. The results showed that the DWT-based OFDM system has a better performance than the DHT and FFT schemes and upon comparing the pulse shaping filters, the SRRC filter outperforms the FEXP and RC filters.***

***Keywords*: OFDM, Frequency Transforms, Pulse shaping filters, ISI**

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## I. INTRODUCTION

Wireless communication systems have evolved to a large extent over the past decades due to the advent of a panoply of wireless devices and an ever-growing number of mobile users. Hence, there is a demand for higher data rates and improved quality of service. These can be achieved by employing a technique known as orthogonal frequency division multiplexing (OFDM) for reliable transmissions due to its characteristics such as robustness to multipath and high bandwidth efficiency and data rates [1].

Since wireless channels are very unpredictable, it is therefore necessary to improve the BER performance and reduce the complexity of the OFDM system; this can be achieved by using other discrete frequency transforms than the conventional FFT. Another important challenge in data communication is Inter-Symbol Interference (ISI). It is the overlapping of one symbol into another due to transmission of data through a band-limited channel. Nyquist has identified different conditions which need to be satisfied by pulse shaping filters in order to curb the effect of ISI. The most essential criterion is that the equivalent impulse response of the transmitting and receiving filters should have zero crossings at multiples of the symbol period, T [2]. Most conventional pulse shaping filters such as the Raised Cosine (RC) and Square Root Raised Cosine (SRRC) satisfy this condition. Pulse shaping filters have been widely used in state of the art communication systems. As such, SRRC pulses have been proposed to be used in 802.11a WLAN systems [3], Wideband Code Division Multiple Access (WCDMA) system [4], and 3GPP Long Term Evolution (LTE) [5]. An overview of previous works including frequency transform techniques and pulse shaping filters used in OFDM systems is given next.

The applicability of OFDM for the next generation of mobile networks is quite uncertain with the higher data rates and massive number of machine subscribers in 5G. In [6], the various trends of 5G waveforms such as OFDM, SC-FDM and WOLA; and multiple access techniques are investigated and it has been concluded that the waveforms should be enhanced to support parameters such as maximised spectral efficiency and minimal out-of-band emission and new waveforms should be proposed to optimise OFDM so that it can be used in the upcoming 5G. A comparative study of the new waveforms to be used for the 5G air interface is also provided in [7]; the performances of the waveforms filter-bank multi-carrier (FBMC), universal filtered multi-carrier (UFMC), generalized frequency division multiplexing (GFDM), resource-block filtered orthogonal frequency-division multiplexing (RB-F-OFDM) have been compared to OFDM used in 4G/LTE in terms of spectral efficiency and energy efficiency and it was observed that that GFDM followed by FBMC are most convenient in 5G. Moreover, in [8], a modified selected mapping (SLM) known as C-SLM is proposed to minimise PAPR and an alternative side information (SI) estimation technique using hard binary decision rule is adopted which has a reduced computational complexity when compared to the existing frequency-domain correlation (FDC) scheme.

Several studies on OFDM systems have been published where the use of discrete frequency transforms other than the FFT have been proposed to improve the performance of OFDM systems. In [9], the performance of different mother wavelets was examined and it was found the Haar wavelet produced the best results. The effect of removing the cyclic prefix in a DWT-system was analysed in an AWGN channel in [10,11]. A simple zero forcing (ZF) equalisation was proposed in [12] for the channel equalisation in DWT-based systems and the performance was analysed in both an AWGN and fading channel. The performance of DFT, DWT and DCT-based OFDM system were compared in a 60 GHz Band using a Saleh-Valenzuela (SV) model in [13]. In [14], the performance of a FFT, DCT and DHT-based OFDM systems are compared in an AWGN channel using the IEEE 802.15.3c parameters and BPSK as modulation order. It was generally observed that the DWT-based OFDM system performed better than the FFT-based system in both fading and AWGN channels; The DHT-based system performed similarly as the FFT but with a reduced complexity.

Various researches have been performed on the development of novel pulse shaping filters to suit the needs of communication systems. In [15], an ISI-free filter, known as FEXP, was proposed which 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. In addition, in [16] the performances of several time-limited waveforms such as the Rectangular pulse, RC and FEXP were evaluated in an OFDM system. Two new pulse shapes with improved BER performance over the FEXP filter were also proposed. In [17], the performance of several pulse shaping filters were evaluated in terms of BER for 16-QAM modulation with an AWGN channel. The results demonstrated that pulse shaped OFDM with SRRC outperformed all other pulse shaping schemes investigated [17]. The effect of SRRC pulse shaping on an OFDM based WLAN system was analysed in [18] in order to find the most appropriate roll-off factor, truncation length, oversampling rate and quantization levels that should be used. The findings indicated that generally filters with higher roll-off factor values require shorter truncation lengths, fewer quantization bits and are more resistant to synchronization errors. The trade-off is the need for an excess bandwidth. Moreover, in [19], the performance of SC-FDMA with Pulse Shaping (PS) was investigated. A trade-off between spectrum efficiency and low PAPR in IFDMA was observed with the RC filter. However, Nyquist pulses such as PEXP and the Nyquist Linear Combination Pulse (NNLCP) can decrease PAPR of IFDMA to a greater extent while maintaining the same bandwidth compared to RC. Finally, in [20] two new pulse shaping filters namely a Modified FEXP (MFEXP) filter and a Hybrid FEXP and PEXP filter (HFPEXP) were proposed. Both proposed filters provided superior Bit Error Rate (BER) performance than conventional ones. In [21], a new pulse shape design method was proposed with arbitrary length constraint, which maintains orthogonality while providing good time-frequency localization property. In addition, suitable parameterizations for the pulse shape design were described to address requirements of the diverse services envisaged for the 5G system. The implementation complexity of pulse-shaped OFDM systems was also analyzed.

In line with the above research direction on frequency transforms and pulse shaping filters, this paper analyses the BER performance of several conventional and state of the art of frequency transforms and pulse shaping schemes in an ODFM system. It is to be noted that most papers have analysed the effect of different frequency transforms and pulse shaping filters separately but this paper performs a joint analysis to reveal which frequency transform and pulse shaping combination provides the best performance. The frequency transforms, that is, FFT, DHT and DWT were each combined with the three filters: RC, FEXP and SRRC and implemented for the IEEE 802.11n OFDM WLAN system and tested in AWGN. It was mainly observed that the DWT-based system and the SRRC filter provided the lowest BER.

This paper is structured as follows. Section 2 gives some background theories on different discrete frequency transforms and pulse shaping filters. Section 3 describes the transmitter and receiver system models. Section 4 presents the simulation results and analysis. Section 5 concludes the paper.

## II. BACKGROUND

This section presents an overview of the following frequency transforms and pulse shaping filters.

Frequency transforms:

1. Discrete Fourier Transforms (DFT)
2. Discrete Wavelet Transform (DWT)
3. Discrete Hartley Transform (DHT)

Pulse shaping filters:

1. Raised Cosine (RC)
2. Square Root Raised Cosine (SRRC)
3. Flipped-Exponential Pulse (FEXP)

### Discrete Frequency Transforms

Discrete transforms are mathematical or linear transforms of signals from the time domain to the frequency domain.

#### *Discrete Fourier Transform (DFT)*

The Discrete Fourier transform (DFT) converts a real sequence of equally spaced samples of a signal into a sequence of complex numbers of the same length. The DFT represents the signal from time to frequency domain. The Fast Fourier Transform (FFT) is a resourceful algorithm which rapidly computes the DFT yielding the same results [22].

The DFT is represented by

$$X(k) = \sum_{n=0}^{N-1} x(n)\left(\cos\frac{-2\pi kn}{N} + i\sin\frac{-2\pi kn}{N}\right), k \in \mathbb{Z} \quad (1)$$

The inverse DFT (IDFT) is given by:

$$x(n) = \frac{1}{N}\sum_{k=0}^{N-1} X(k)\left(\cos\frac{2\pi kn}{N} + i\sin\frac{2\pi kn}{N}\right), n \in \mathbb{Z} \quad (2)$$

Where,

***N*** is the number of samples
***n*** is the current sample
***x(n)*** is value of the signal at time n
***k*** is current frequency
***X(k)*** is amount of frequency k in the signal

*Discrete Hartley Transform (DHT)*

A Discrete Hartley Transform is a Fourier-based transform and is similar to the DFT except that it transforms real inputs into real outputs without involving complex numbers. The DHT and Inverse DHT (IDHT) definitions are identical; hence it decreases the computational complexity if it is used in an OFDM system instead of DFT which involves numerous complex multiplications [14].
The DHT is represented by:

$$X(k) = \sum_{n=0}^{N-1} x(n)\left(\cos\frac{2\pi kn}{N} + \sin\frac{2\pi kn}{N}\right), k \in \mathbb{Z} \quad (3)$$

where, the parameters are the same as explained in section 2.1.1.

**Discrete Wavelet Transform (DWT)**

A wavelet is an oscillation similar to a seismic graph whose amplitude varies from zero to a certain amplitude and decreases back to zero. Wavelet Transforms are mathematical functions that split data into different frequency components; then each component is studied with a resolution matched to its scale [23]. Some examples of wavelets are Haar, Symlets and Biorthogonal wavelets.

A discrete wavelet transform (DWT) is a wavelet transform in which the wavelets are discretely sampled. The DWT of a signal *x* is calculated by:

1. Convolving the samples with an impulse response *p* through a low-pass filter,
2. Decomposing the signal at the same time using a high-pass filter *q*.

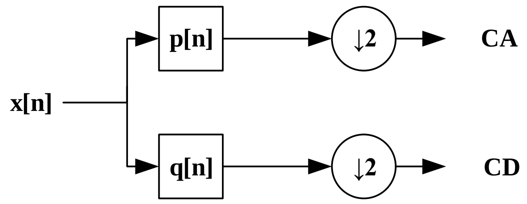



**Figure 1:** Filter-analysis of a one dimensional DWT [24]

Figure 1 shows a block diagram of the filter analysis of a one-level DWT. In the filtering process illustrated above, the outputs of the filters are down sampled by a factor of 2 to discard the redundant samples so as to obtain the approximation coefficients (CA) and the detail coefficients (CD). The decomposition of the signal is expressed as [11]:

$$y_{low}[n] = \sum_{k=-\infty}^{\infty} (x[k]p[2n-k]) \quad (4)$$

$$y_{high}[n] = \sum_{k=-\infty}^{\infty} (x[k]q[2n-k]) \quad (5)$$

Where,
*x* is the input signal,
*y* is the output coefficients,
*p* is the low pass decomposition filter and
*q* is the high pass decomposition filter

The filter analysis block of the IDWT process is illustrated in Figure 2 below:

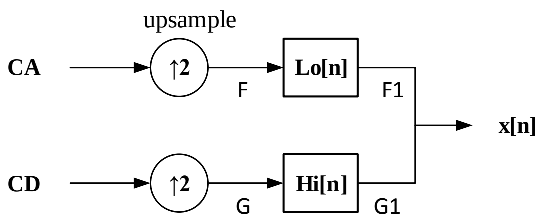



**Figure 2:** One dimensional IDWT [25]

The approximation and detail coefficients are upsampled, that is, zeros are inserted at odd-indexed positions, and then the upsampled data are passed through reconstruction filters, Lo[n] and Hi[n] to obtain back the input x[n] [25].

The wavelet type used in this paper is the Haar wavelet. The mother wavelet function *ψ (t)* of the Haar wavelet is given by [26]:

$$\psi(t) = \begin{cases} 1 & 0 \le t < \frac{1}{2} \\ -1 & \frac{1}{2} \le t < 1 \\ 0 & otherwise \end{cases} \quad (6)$$

Where, $\psi$ is the mother wavelet.

The low pass decomposition filter, $p$ and the high pass decomposition filter, $q$ of the Haar wavelet are as follows [26,27]:

$$p[n] = \left[\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}\right] \quad (7)$$

$$q[n] = \left[-\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}\right] \quad (8)$$

DWT-based OFDM offer the same advantages as the FFT-based OFDM with an added benefit of peak-to-average power ratio (PAPR) combat and carrier frequency timing offset. Wavelet-based OFDM does not require a cyclic prefix since wavelet transform signals overlap both in time and frequency domain and it satisfies the condition for orthogonality and attain perfect reconstruction which means that there is an increase in spectral efficiency, a reduction in complexity and a better symbol rate [12].

**Pulse Shaping Schemes**

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, $\alpha$, are given next. All the impulse responses have been normalised.

*RC Pulse*

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

$$hrc(t) = sinc\left(\frac{t}{T}\right)\frac{\cos(\frac{\pi\alpha t}{T})}{1-\left(\frac{2\alpha t}{T}\right)^2} \quad (9)$$

where,

$\alpha$ 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 impulse response of RC is given in Figure 3.

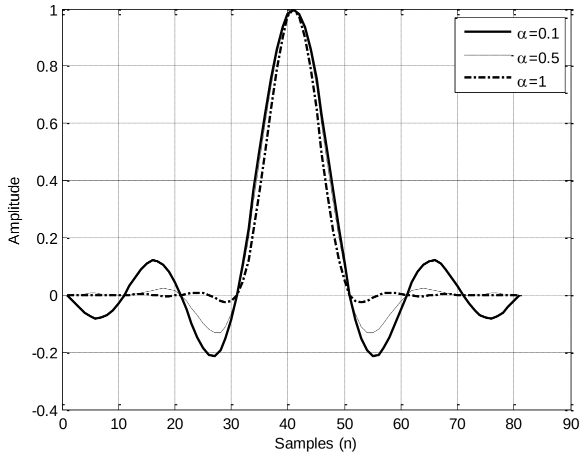



**Figure 3:** Impulse response for RC filter [16].

From Figure 3, the pulse is seen to decay rapidly for larger values of $\alpha$. The side lobe level is also lower at higher values of $\alpha$.

*SRRC Pulse*

This filter is developed 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 given as:

$$hsrrc(t) = \frac{\sin\left(\frac{\pi t}{T}(1-\alpha)\right)+\frac{4\alpha t}{T}\cos(\frac{\pi t}{T}(1+\alpha))}{\frac{\pi t}{T}\left(1-\left(\frac{4\alpha t}{T}\right)^2\right)} \quad (10)$$

It can be observed in Figure 4 that as $\alpha$ increases, the side lobe levels get reduced. It is also noted that the main side lobe of the SRRC filter for $\alpha$ = 0.5 occurs at the 53$^{rd}$ while that for the RC pulse occurs at the 54$^{th}$ sample and at $\alpha$=1, the SRRC pulse has its main side lobe at the 50$^{th}$ sample whereas that for RC occurs at the 51$^{st}$ sample. Hence, there is an average delay of 1 sample between the RC and SRRC filter and consequently the SRRC pulse results in slightly faster transitions than the RC filter.

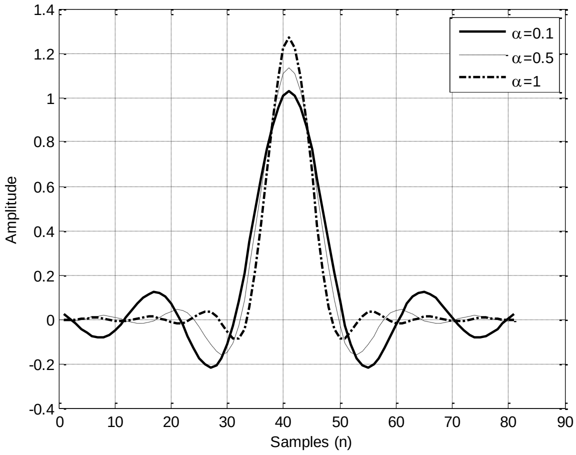



**Figure 4:** Impulse response for SRRC filter [18].

*FEXP Pulse*

It is a novel pulse which has been proposed in [15] and is also known as the “Better Than” Raised Cosine Pulse. Its impulse response is expressed in Eq. (11):

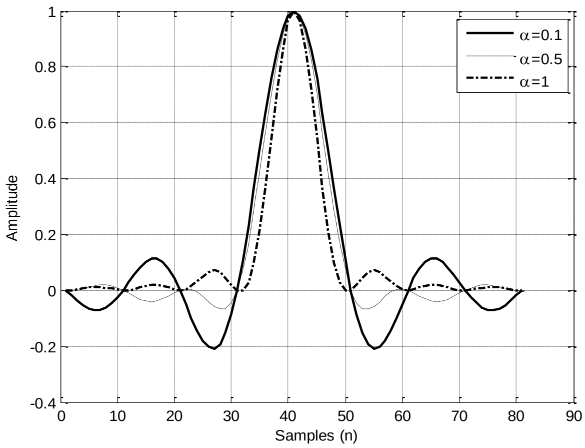



**Figure 5:** Impulse response for FEXP filter [15].

$$hfexp(t) = \frac{1}{T} sinc\left(\frac{t}{T}\right) \frac{4\beta\pi t sin\left(\frac{\pi\alpha t}{T}\right) + 2\beta^2 \cos\left(\frac{\pi\alpha t}{T}\right) - \beta^2}{(2\pi t)^2 + \beta^2} \quad (11)$$

where,

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

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

Compared to the RC pulse in Figure 3, the FEXP pulse has lower side lobe amplitude which can better control ISI as shown in Figure 5.

## III. System Model

A review of the OFDM model with BPSK modulation technique adopted in this work is now given. An OFDM transmitter can be described using sinusoidal components and generally represented by the following equation:

$$c(t) = \sum_{n=0}^{N-1} s_n(t) \sin(2\pi f_n t) \quad (12)$$

Where,
c(t) is the OFDM signal
s(t) is the symbols mapped to constellation (BPSK)
fn is the orthogonal frequencies

As the OFDM signal in Eq. (12) is in time domain, IFFT can be used in the transmitter since it is suitable for converting frequency domain samples into time domain samples [28].

In wavelet based OFDM, wavelet carriers at different scales and positions on the time-axis are used instead of the time-windowed complex exponentials. Hence, a DWT-OFDM symbol is considered as the weighted sum of wavelet and scale carriers, this is expressed in Eq. (13) which is close to the IDWT [9].

$$s(t) = \sum_{j \le J} \sum_{k} w_{j,k}(t).\Psi_{j,k}(t) + \sum_{k} a_{J,k}.\Phi_{J,k}(t) \quad (13)$$

Where,

$a_{j,k}$ is the approximation coefficients

$J$ is number of iterations
$j$ is scale index
$k$ is the time location
$w_{j,k}$ is the sequence of wavelet
Φ(t) is the scaling function

The system model is shown in Figure 6. 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 802.11a Wi-Fi standard [3]. An inverse frequency transform block converts the data into time domain. This is followed by the addition of a cyclic prefix in front of the OFDM symbol for the FFT and DHT based system. In the DWT-based OFDM system, the Haar wavelet is used and a zero-padding guard interval of length 16 is added [9].

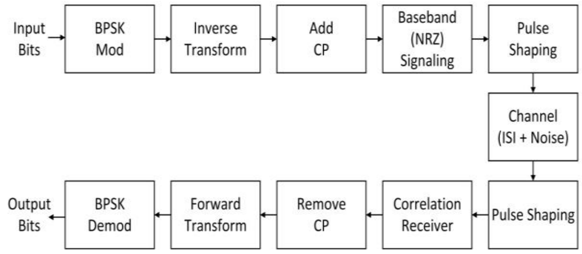



**Figure 6:** System Model

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 $\alpha$ = 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 AWGN 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. It is to be noted that the OFDM and pulse shaping blocks can be integrated seamlessly since they have independent functions in the system as shown in Figure 6.

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 in the FFT/DHT based system and removal of zero-padding guard interval in the DWT-based system.

The data is converted back to frequency domain by the forward transform, that is FFT, DHT or DWT; and the data subcarriers are then extracted. BPSK de-mapping is lastly performed to recover the bits. Table 1 above specifies the parameters used for the OFDM simulator. However, in this work no equalisation and channel estimation have been carried out, because the channel model is AWGN. Hence, the pilot sub-carriers were not required. The bit-rate is in line with that achieved by the IEEE 802.11 standard using BPSK modulation.

**TABLE 1:** OFDM parameters specifications for IEEE 802.11a/g WLAN standard. [3]

| Parameter | Value |
|---|---|
| Modulation Type | BPSK |
| Bit rate | 6 Mbps |
| FFT size, N | 64 |
| No. of data subcarriers | 48 |
| No. of pilot subcarriers | 4 |
| Total No. of used subcarriers | 52 |
| No. of unused subcarriers | 12 |
| OFDM bandwidth | 20MHz |
| No. of symbols for cyclic prefix | 16 |

The conversion of a random stream of 52 bits (1 OFDM symbol) through each processing block of the system model is illustrated in the following figures.

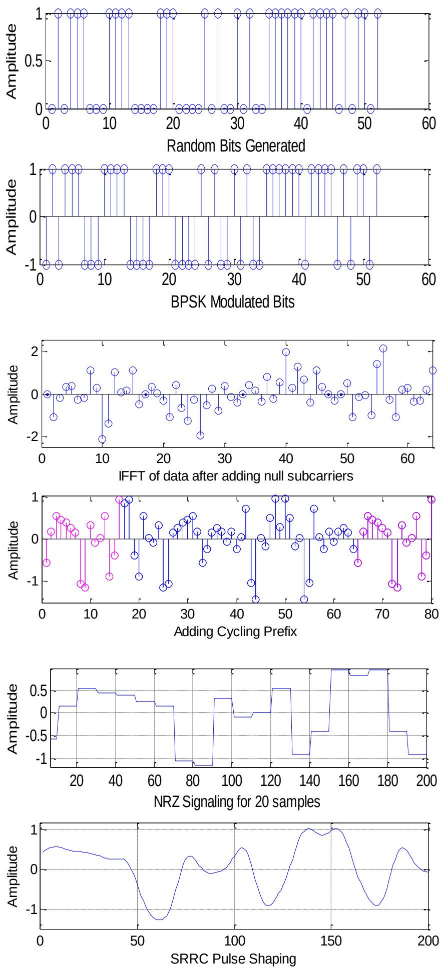



**Figure 7:** OFDM Transmitter Processing Blocks

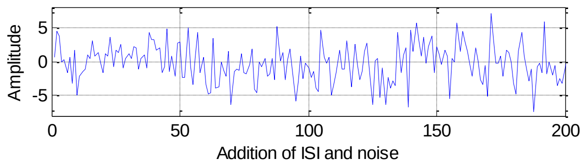
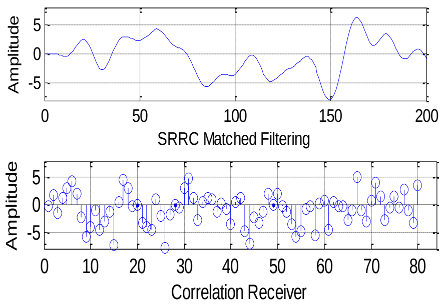



**Figure 8:** Impact of the channel on the signal



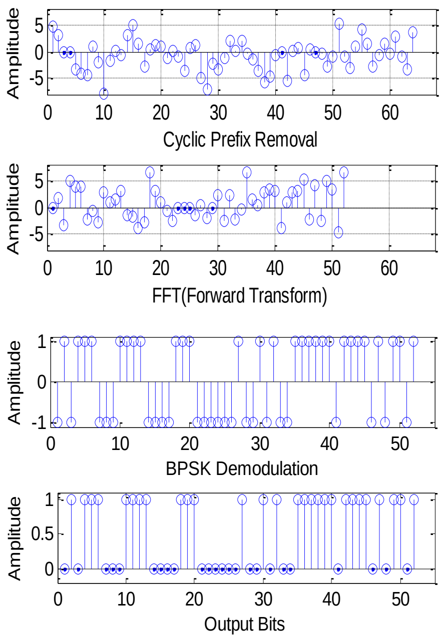



**Figure 9:** OFDM Receiver Processing Blocks

## IV. Analytical Model of OFDM System

The FFT-based OFDM system in an AWGN channel with BPSK as modulation technique has the analytical BER expression as for BPSK signaling for AWGN channel and is derived as follows [1], [28]:

A BPSK transmitter is represented by:

Bit 0 for symbol $s_1 = +d$
Bit 1 for symbol $s_2 = -d$

The received signal is r = s + n where n is the AWGN variable with 0 mean and variance $\sigma^2$.
Using the decision boundary, r = 0, the threshold decision rule is:

If r > 0, receiver assumes $s_1$ was transmitted
If $r \leq 0$, receiver assumes $s_2$ was transmitted

Using Bayes theorem, the bit error probably is given by:

$$P_e = P_1 P_{e1} + P_2 P_{e2} \tag{14}$$

Where,
$\boldsymbol{P_e}$ is bit error probability,
$\boldsymbol{P_1}$ is probability of transmitting $s_1$,
$\boldsymbol{P_{e1}}$ is probability of receiving $s_1$ in error.

Given $s_2$ = -d was transmitted, the decision of receiving $s_2$ in error means that r = -d + n > 0 or n>d.

Hence, the conditional probabilities $\boldsymbol{P_{e1}}$ and $\boldsymbol{P_{e2}}$ is

$$\begin{aligned} P(n > d) &= \int_d^{\infty} \frac{1}{\sqrt{2\pi}\sigma} exp\left(-\frac{x^2}{2\sigma^2}\right) dx \\ &= \frac{1}{\sqrt{2\pi}} \int_{d/\sigma}^{\infty} exp\left(-\frac{y^2}{2}\right) dy \\ &= Q\left(\frac{d}{\sigma}\right) \end{aligned} \tag{15}$$

The average signal power $\boldsymbol{E_s}$ is given by:

$$E_s = \frac{1}{2}(d^2 + d^2) = d^2 \tag{16}$$

Where ***d*** is the analog level

Given that the noise power $N_0/2$ is equal to the variance $\sigma^2$ and probability of transmitting $s_1$ and $s_2$ are equi-probable, BPSK BER is hence given by [28]:

$$\begin{aligned} P_e &= \frac{1}{2} Q\left(\frac{d}{\sigma}\right) + \frac{1}{2} Q\left(\frac{d}{\sigma}\right) = Q\left(\frac{d}{\sigma}\right) = Q\left(\sqrt{\frac{2E_s}{N_0}}\right) \\ &= Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \end{aligned} \tag{17}$$

Where $\boldsymbol{E_b}$ is the average bit energy.

The results obtained for the analytical model for OFDM are compared with the simulation results of the system and illustrated in the results section.

## V. Simulation Results and Analysis

The performances of the following combinations of discrete frequency transforms and 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. The channels were modeled with a Butterworth filter, $W_1$ =12MHz and $W_2$=20MHz. The data rates were kept the same for all schemes to ensure a fair comparison. Matlab software was used to carry out the simulation.

1. FFT-RC, FFT-SRRC and FFT-FEXP
2. DHT-RC, DHT-SRRC and DHT-FEXP
3. DWT-RC, DWT-SRRC and DWT-FEXP

For each filter at different ISI levels under different frequency transforms, the number of samples that are removed from the start of the signal at the receiver during matched filtering, are listed below in Table 2. 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** | **ISI level 2** |

| Frequency Transform | (12 MHz) | | | (20 MHz) | | |
|---|---|---|---|---|---|---|
| | FFT | DWT | DHT | FFT | DWT | DHT |
| **RC** | 0 | 0 | 1 | 1 | 1 | 1 |
| **SRRC** | 2 | 2 | 3 | 1 | 1 | 2 |
| **FEXP** | 2 | 2 | 2 | 3 | 3 | 2 |

It is to be noted that for DWT, a single level transform has been used.

### 5.1. Simulation Results with AWGN for analytical and simulated OFDM model

The BER performance of the analytical model for an OFDM system expressed by Eq. (17) is compared with the simulation model using FFT as the discrete frequency transform with no ISI and additionally with the two different ISI levels at bandwidth of 12 MHz and 20 MHz using the SRRC filter.

It is observed in Figure 10 that the BER performances of the analytical and simulation models are consistent.

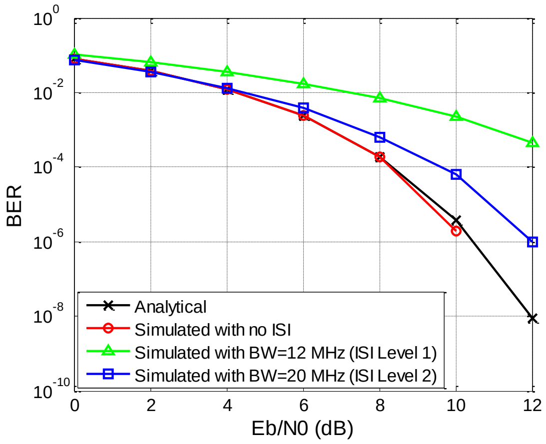



**Figure 10:** Graph of BER against Eb/N0 for analytical analysis

### 5.2. Simulation Results with AWGN under ISI level at bandwidth 12 MHz.

It is observed in Figure 11 that the combination of DWT with the SRRC filter provides the best BER performance and achieves a BER of $2\times10^{-5}$ at an $E_b/N_0$ value of 10 dB.

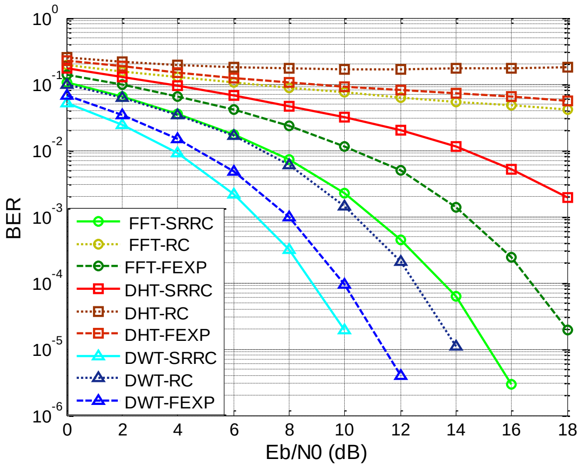



**Figure 11:** Graph of BER against Eb/N0 for 12MHz BW

This is significantly better than the BER performance of FFT scheme with the SRRC filter which achieves a BER of $2.2\times10^{-3}$ at an $E_b/N_0$ value of 10 dB. The worst performance is achieved by the combination of DHT with the RC filter which has a BER of $1.7\times10^{-1}$ at the same $E_b/N_0$ value of 10 dB.

### 5.3. Simulation Results with AWGN under ISI level at bandwidth 20 MHz.

Under reduced ISI, that is, at a higher bandwidth, the filters for each transform show a significantly improved BER performance. From Figure 12, it is observed that the combination of the DWT-based system with the SRRC filter outperforms the other combinations and achieves a BER of $1\times10^{-6}$ at an $E_b/N_0$ value of 10 dB. It is considerably better than the FFT based OFDM with the SRRC filter which has a BER value of $6.4\times10^{-5}$ at an $E_b/N_0$ value of 10 dB. The combination of the DHT with RC filter provides the worst performance and achieves a BER of $2\times10^{-2}$ at an $E_b/N_0$ value of 10 dB.

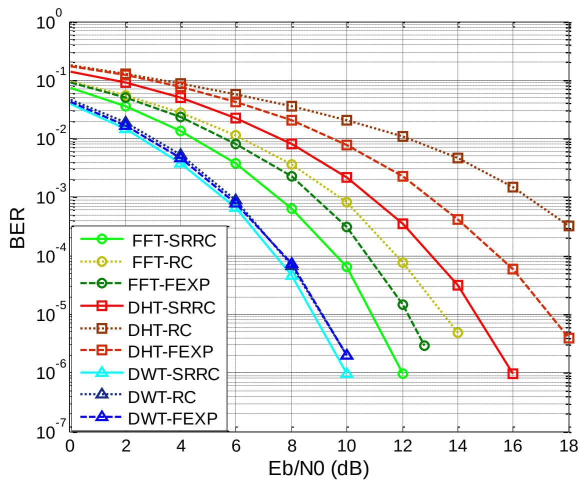



**Figure 12:** Graph of BER against Eb/N0 for 20MHz BW

Under a higher ISI level, the transforms with the filters experience a worse error performance and there is quite a large gap between the curves for each transforms due to ISI distortion effects. The DWT transform with the SRRC pulse shows a better error performance compared to the RC and FEXP pulse for both FFT and DHT transforms. Under lower ISI condition, the transforms with the filters exhibit a relatively better BER performance. The gap difference between the BER curves also diminishes to a great extent.

The combination of DWT with the OFDM system appears to be a better alternative than the FFT based system; also the use of SRRC which is already present in the real time implementation of the 802.11 standard performs well with DWT, hence the system investigated can be used in standards such as the 802.11. The frequency domain plot for the combination of DWT with SRRC pulse shaping is shown in Figure 13:

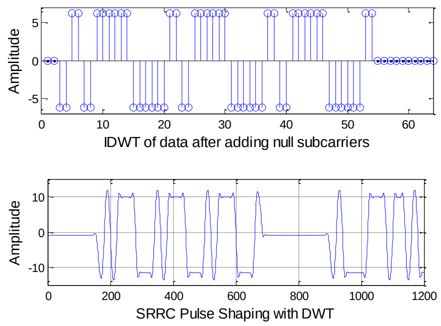



**Figure 13:** SRRC Filter used with DWT-OFDM

Moreover, since increasing the modulation order has the general effect of increasing the BER, it is expected that all the schemes will exhibit a higher bit error rate. However, the same trend with regards to the gains obtained is expected. Compared to the works in [9] and [14] which have analysed the use of different frequency transforms such as DWT, DHT and DCT in OFDM in an AWGN channel, this paper has investigated the effect of pulse shaping techniques discussed in [20] on different frequency transform with OFDM in an AWGN channel under the effect of ISI.

## VI. 6. CONCLUSIONS

This paper has investigated the performance of the IEEE 802.11 OFDM WLAN system with BPSK modulation under AWGN and ISI with different frequency transforms and pulse shaping filters. After investigating the performance of the OFDM system under the two ISI conditions it can be concluded that the lower the side lobe levels of the pulses, the better will be their error performance for a given frequency transform in a severe ISI condition; and secondly, the DWT transform has an enhanced BER performance over both DHT and FFT transforms since it is localised in both time and frequency and there is a higher suppression of the side lobes compared to those of the rectangular window of the Fourier transform [27]. Moreover, the SRRC filter outperforms both FEXP and RC filters due to the use of matching transmitter and receiver filters for SRRC filtering. Hence, the DWT-SRRC gives the best performance with gains of 4.7 dB in the higher ISI level with bandwidth 12 MHz and 2.2 dB in the lower ISI level over the FFT-SRRC combination at a BER value of 10-4. However, there is a complexity trade-off since DWT is more computationally intensive than the FFT or DHT and the SRRC filter involves a matched filter at its receiver. A possible further work is to implement the OFDM-system proposed in a fading channel using higher order modulation such as 16-QAM or 64-QAM and investigate with different roll off and oversampling factors.

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