Performance Evaluation of OFDM Mutlicarrier Modulation over Rayleigh and Rician Standard Channels Using WPT-OFDM Modulations

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***Abstract*-Last years, Wavelet Packet Modulation (WPM) or Wavelet Packet Transform based Orthogonal Frequency Division Multiplexing (WPT-OFDM) have been introduced to wired and wireless communication fields as efficient Multicarrier Modulation (MCM) techniques. The wavelets have interesting features such as flexibility, compatibility and localization in both time and frequency domains with no need to use rectangular window function. As a result, the transmitted signal is naturally less sensitive to inter-symbol and inter-carrier interferences (ISI and ICI). Also, it is possible to implement OFDM modulation without adding cyclic prefix (CP) and it is enough only to use time domain or overlap frequency domain equalization (TEQ or overlap FEQ) in order to shorten the effective channel impulse response length with the purpose of avoiding the ISI and decreasing the ICI. In this paper, we compare BER performance for FFT-OFDM and WPT-OFDM in the presence of two types of channels defined by ETSI (i.e. Rayleigh P1 and Rician F1 channels). In our simulation Haar, Daubechies6, Symlet5 and Coiflet5 wavelets and overlap frequency domain equalization (overlap FEQ) are used for WPT-OFDM in contrast with FFT-OFDM which uses FEQ equalization. Simulation results show that the performance of OFDM will be improved by using WPT transform and due to no need of CP, the power/bandwidth efficiency of OFDM modulation will be improved as well.**

***Index Terms*-**FFT-OFDM, FEQ, Overlap FEQ, F1 channel, P1 channel and WPT-OFDM.

I. INTRODUCTION

Multicarrier modulation (MCM) is an effective popular transmission technique for high data rate communication, in which transmission is carried out on different frequencies in parallel and sub-channels are orthogonal and they have overlap with each other in frequency domain. It leads to spreading fading effect on many bits while the spectral efficiency is preserved [1].

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This modulation technique provides many low rate narrow band signals instead of one high rate modulated wideband signal by dividing the original bandwidth to many narrow-band sub-channels. Since the data is transmitted over narrow sub-channels in parallel, the total data rate is the same as that of fast serial transmission [2]-[4]. Some interesting features of OFDM modulation, by using Fast Fourier Transform (FFT), are low complex modulation/demodulation implementation, simple and fast frequency domain channel estimation and equalization and the spectrum efficiency caused by overlapping between sub-channels [2],[4]. In the other hand, when the data is transmitted over different frequencies in parallel, symbol length is increased and it causes more immunity over fading channels [3],[5]. But besides all these benefits, the conventional OFDM has a main drawback due to the using rectangular window function to limit sine and cosine basis functions of FFT transform in time domain. Using rectangular window function introduces high level side lobes in frequency domain and makes system more sensitive to inter-carrier and inter-symbol interferences (ICI and ISI). As a solution for this problem, the Cyclic Prefix (CP) will be added at the beginning of the OFDM symbol and results in bandwidth and power inefficiency[4],[6]-[8].

In recent years, Discrete Wavelet Modulation (DWM) and Wavelet Packet Modulation (WPM) have been introduced and their performance over different channels is investigated and compared with FFT-OFDM in several papers. In wavelet-based modulations, time and frequency localized basis functions are used to provide better spectrum shape with lower side lobes and are less sensitive to ISI and ICI. It allows us to use time domain equalization (TEQ) or overlap frequency domain equalization (overlap FEQ) in the absence of CP to mitigate the interferences effectively. Since there is no need to use CP, the bandwidth and power efficiency will be increased [7],[9].

WPM modulation was introduced for the first time by Alan R. Lindsey as an alternative of FFT-OFDM in 1997 [10]. In [11], Antony Jamin and Petri Mahonen widely studied wavelet theory and wavelet modulation over wireless channels in 2005. The performance of FFT-OFDM and WPT-OFDM was studied over AWGN channel in [1],[2],[5],[8],[12]-[14], optical fiber channel in [15] and simple multipath fading channels[16] by using various techniques such as MIMO in [7] and frequency and time domain ZF and MMSE equalizations in [17]-[21]. Using WPT in WiMAX systems was studied in [22].

In this paper, we investigate the BER performance of FFT-OFDM and WPT-OFDM modulations over two types of multi path wireless channels introduced by ETSI (i.e. Rayleigh P1 and Rician F1 channels) by simulation. We use the valid values of related parameters defined in ETSI [23]. We also use frequency domain equalization (FEQ) for FFT-OFDM and overlap FEQ equalization for WPT-OFDM. Haar, Daubechies6, Symlet5 and Coiflet5 are used as the wavelet families. The number of subchannels which is an important factor impacting the sensitivity of orthogonalizaton transform in OFDM [24], is considered as 2048.

The rest of this paper is organized as follows. The MCM is described in SectionII. Section III and IV explain FFT-OFDM and WPT-OFDM respectively. SectionV covers overlap FEQ equalization. Section VI is assigned to simulation results and in section VII, conclusions are presented.

II. MULTICARRIER MODULATION (MCM)

Multicarrier modulation (MCM) technique, firstly introduced in the 1960s [25], is a popular efficient technique for high rate data communication with high quality.In MCM modulation, data is transmitted over different orthogonal frequencies in parallel to be more immune of multipath fading channels due to interference degradation by spreading fading effects over several bits [2],[26]. Figure 1 shows the structure of filter bank-based MCM systems [26]. In Fig. 1, $F_k(z)$ and $H_k(z)$ are synthesis and analysis filters respectively and $q(n)$ is an additive channel noise. The MCM system output can be written as:

$$\hat{x}_i(n) = \sum_{m=0}^{M-1} x_m(n) * (S_{mi}(n))_{\downarrow M} + (q(n) * h_i(n))_{\downarrow M} \tag{1}$$

where$M$ is the number of sub-carriers and $(.)_{\downarrow M}$ indicates downsampling by M. . We define $S_{mi}(n)$ as the effective impulse response from mth expander to ith decimator by considering the channel effect and $g_{mi}(n)$ as the corresponding impulse response without considering channel effect, in accordance with

$$g_{mi}(n) \overset{\Delta}{=} f_m(n) * h_i(n) \tag{2}$$

$$S_{mi}(n) \overset{\Delta}{=} g_{mi}(n) * c(n) \tag{3}$$

Then the following conditions should be satisfied to have a perfect reconstruction MCM system.

$$g_{mi}(n)_{\downarrow M} = \delta(n) \qquad \text{for } m = i \tag{4}$$

$$g_{mi}(n)_{\downarrow M} = 0 \qquad \text{for } m \neq i \tag{5}$$

III. FFT-BASED OFDM

Fast Fourier Transform (FFT) based OFDM or OFDM is a special form of MCM modulation in which N_c complex symbols $\{s_n, n=0,1,2,\ldots,N_c-1\}$are carried by N_c parallel subcarriers. If the duration of each serial symbol is T_d, the parallel symbols duration T_s at the output of serial to parallel convertor block will be,

$$T_s = N\,T_d \tag{6}$$

The principle of OFDM is to modulate the N_c sub-streams on sub-carriers with a spacing of $F_s = 1/T_s$. In order to achieve orthogonality between sub-channels, the signals are shaped by a rectangular window function. Each OFDM symbol consists of N_c source symbols with a complex envelop with rectangular pulse shape as bellow:

$$x(t) = \frac{1}{N_c}\sum_{n=0}^{N_c-1} s_n \exp(j2\pi f_n t) = \frac{1}{N_c}\sum_{n=0}^{N_c-1} s_n \exp(j2\pi nF_s t) = \frac{1}{N_c}\sum_{n=0}^{N_c-1} s_n \exp(j2\pi \frac{n}{T_s} t) \qquad o \le t \le T_s \tag{7}$$

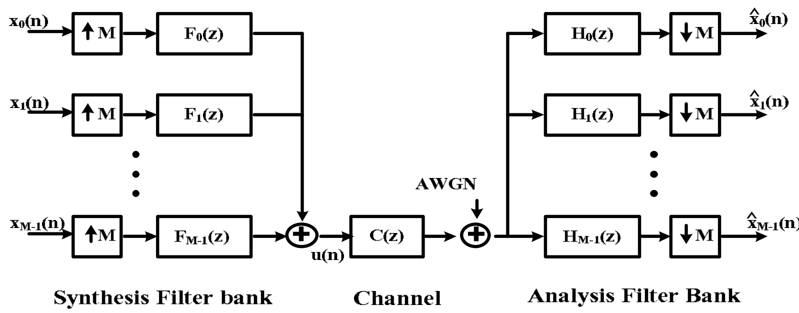


Fig. 1. Block diagram of filter bank-based MCM system

where T_s is the time dration of parallel symbols and $\{f_n=n/T_s\ ,\ n=0,1,2,\ldots,N_c\text{-}1\}$ are the N_c orthogonal subcarriers frequency. Therefore, as N_c becomes large, the power density spectrum approaches that of single carrier modulation with ideal Nyquist filtering [27]. Figure 2 shows the structure of transceiver of FFT-OFDM system. As it can be seen, at the transmitter side, initially the input signal is converted from serial to parallel. After constellation mapping, IFFT transform, CP insertion and parallel to serial blocks are applied to signal respectively. The transmitted signal is defined by (7). At the receiver side, after serial to parallel conversion and CP removing, the FFT transform is applied to the parallel samples. Then FEQ equalizer is used to mitigate the channel effects of the signals. Finally, by constellation demapping and parallel to serial conversion the original symbols can be reached [27].

IV. WPT-BASED OFDM

The structure of WPT-OFDM transceiver system is shown in Fig. 3. Comparing Fig.2 and Fig. 3, it is obvious that the only difference between these two schemes at the transmitter side is using IWPT transform instead of IFFT transform. In the receiver, WPT-OFDM uses WPT transform as the alternative of FFT transform and serial to parallel converter. The other difference is in the types of equalization. For FFT-OFDM, we can use the FEQ for decreasing ICI. But in WPT-OFDM with no CP, we should use the TEQ or the overlap FEQ to shorten the effective length of channel in order to reduce ISI and ICI.

WPT-OFDM uses wavelet packet bases defined as [6],[28]:

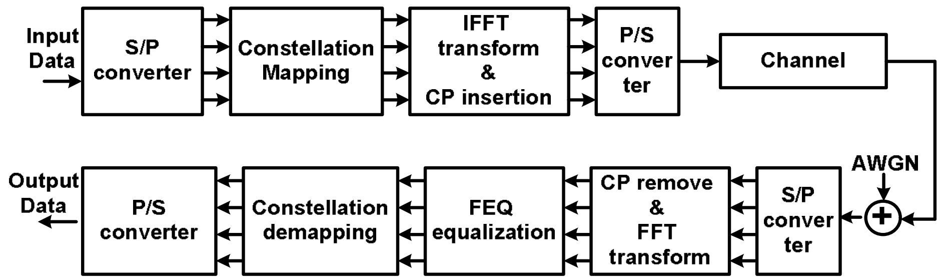


Fig. 2. Transceiver structure of FFT-OFDM system

$$\tau_{j,k}^{n}(t) = 2^{j/2}\tau^{n}(2^{j}t - k) \tag{8}$$

where $\tau_{j,k}^{n}(t)$ is the *n*th wavelet packet base in *j*th scale with time translation of *k* (*n*, *j* and *k* are integers) so that:

$$\tau^{0}(t) = \phi(t) \tag{9}$$

$$\tau^{1}(t) = \psi(t) \tag{10}$$

where $\phi(t)$ and $\psi(t)$ are scaling and wavelet function respectively. We can also find low pass and high pass filters ($h(n)$ and $g(n)$ respectively) which make a relationship between the consequative laysers as:

$$\tau^{2n}(t) = \sum_{k=-\infty}^{\infty} h(k)\sqrt{2}\,\tau^{n}(2t - k) \tag{11}$$

$$\tau^{2n+1}(t) = \sum_{k=-\infty}^{\infty} g(k)\sqrt{2}\,\tau^{n}(2t - k) \tag{12}$$

In this scheme, the transmitted signal is as bellow. The j_0 is the lowest scale which is usually considered to be equal to zero [3],[29]-[31].

$$S_{WPM}(m) = \sum_{n=0}^{N_c-1}\sum_{k=0}^{\infty} s_n(k)\tau_{j_0,k}^{n}(m - kN_c) \tag{13}$$

In the WPT-OFDM approach, there is no need for time and frequency synchronization, however features of the perfect reconstruction and the orthogonality between bases are required [32],[33]. It means equations (14-16) should be satisfied [34] where *h'*(*k*) and *g'*(*k*) are the impulse responses of lowpath and highpash synthesis filters respectively.

$$g(k) = (-1)^{N-k-1}h(N-1-k) = (-1)^{k}h(N-1-k) \tag{14}$$

$$h'(k) = h(-k) \tag{15}$$

$$g'(k) = g(-k) \tag{16}$$

The WPT transform provides bases which preserve orthogonality, smoothness, flexibility and localization of their parent wavelets. Because of the localization property of wavelets, there is no need to use rectangular window function. Therefore, this scheme provides better spectrum shape and

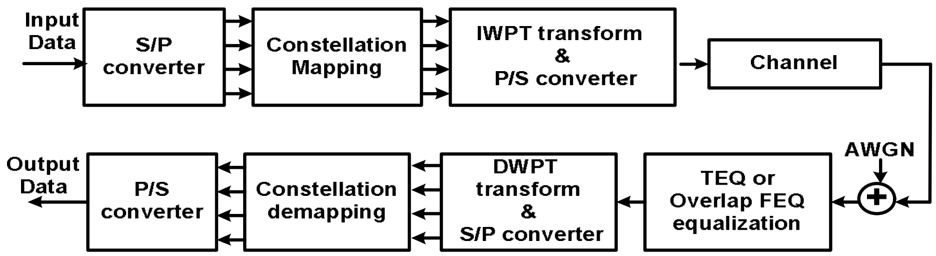


Fig. 3. Transceiver structure of WPT-OFDM system

represents very lower side lobes compared to the FFT-OFDM and it results in decreasing ISI, ICI, narrow-band interference(NBI) and multipath propagation losses [1],[2],[8],[11],[35],[36]. Thus, the WPT-OFDM is known as an effective technique with interesting properties such as adaptation, flexibility and improved characteristics compared to the FFT-OFDM [1],[8]. Furthermore, wavelet-based systems can operate without adding CP and provide proper performance over multipath channels by using TEQ or overlap FEQ equalizers. It is observed that the CP includes only redundant data and decreases spectrum efficiency. As a result, from bandwidth and power point of view this scheme is more efficient than the FFT-OFDM scheme [8] The transceiver filter bank structure of WPT-OFDM is shown in Fig. 4. [6],[37]-[39].

V. OVERLAP FEQ EQUALIZATION

The structure of this equalizer is shown in Fig.5. This method which has been introduced in [14], is used as well as TEQ equalizers to reduce the effect of multipath channels on the received signals. The received signal is first passed through $2N_c$-FFT block, and then it is equalized by FEQ equalizer. Then, $2N_c$-IFFT block is applied and N_c subchannels existing at the beginning of the data will be utilized for the rest of the process. Then these subchannels are processed by Discrete Wavelet Packet Transform (DWPT) and demodulation sub-systems and finally are converted from parallel to serial.

Compared with TEQ methods, the overlap FEQ is very simply implemented, but achieves the same performance. In this paper, we use overlap FEQ equalizer according to MMSE criteria as bellow:

$$W(f) = \frac{C^*(f)}{|C(f)|^2 + (Es/N_0)^2} \tag{17}$$

where $W(f)$ and $C(f)$ are FEQ filter and channel frequency responses respectively and Es/N_0 indicates SNR at the receiver input. Due to the lower complexity and identical performance of overlap FEQ equalizer in comparison with TEQ methods, we can use it in WPT-OFDM receivers [21].

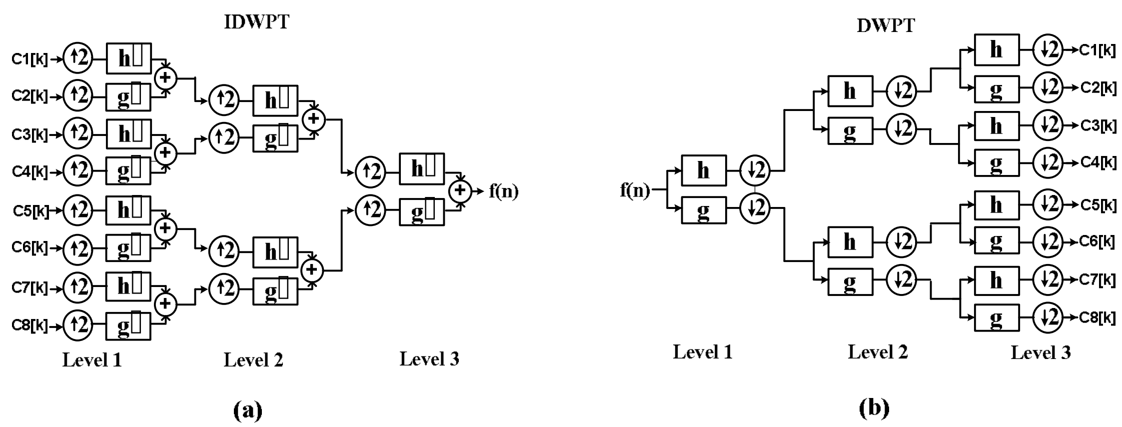


Fig. 4. The structure of (a) WPT synthesis filter bank used in the transmitter (b) WPT analysis filter bank used in the receiver

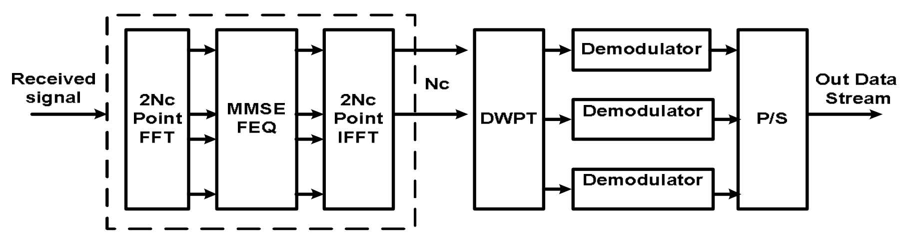


Fig . 5. The structure of overlap FEQ equalizer

VI. SIMULATION

In this paper, we have simulated two schemes of OFDM modulation, i.e. FFT-OFDM and WPT-OFDM over two channels assigned for DVB-T2 standard, i.e. Rayleigh P1 and Rician F1 channels. We also used the parameters values of DVB-T2 standard for our simulations. Different modulation mappings such as QPSK, 16-QAM, 64-QAM and 256QAM with various wavelet families have been used. The simulation parameters and channels characteristics are shown in Table I and Table II.

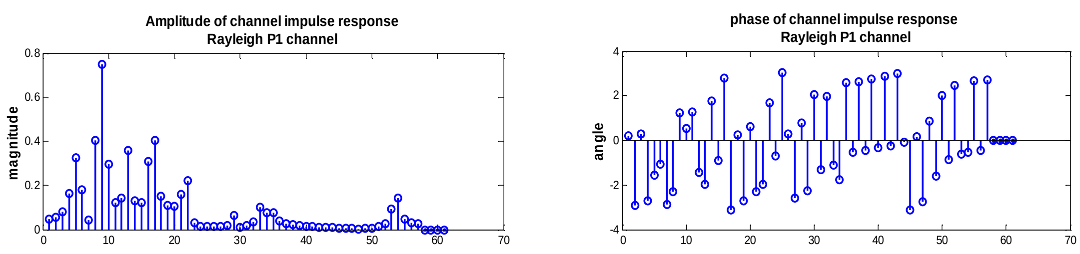
Figures 6 and 7 show the typical instance of impulse responses of Rayleigh P1 and Rician F1 channels respectively. In figures 8 and 9 the BER performance of FFT-OFDM and WPT-OFDM techniques using QPSK, 16-QAM, 64-QAM and 256-QAM in presence of these channels are shown. For more details, the required SNR for achieving to BER=$5*10^{-4}$ in different constellations by FFT-OFDM and WPT-OFDM are presented in Table III and Table IV.

TABLE I. SIMULATION PARAMETERS

Parameters	**FFT-OFDM**	**DWT-OFDM**
Sample time (t_s)	$7/64*10^{-6}$(s)	$7/64*10^{-6}$ (s)
Constellation Mappings	4-QAM, 16-QAM,64-QAM, 256-QAM	4-QAM,16-QAM,64-QAM, 256-QAM
No. of Sub-channels	2048	2048
CP	128	-
FFT Size	2048	-
No. of Wavelet levels	-	11
Wavelet Families	-	Haar, Daubechies6,Sym5,Coif5
Equalization Method	FEQ	Overlap FEQ
Channels	P1 and F1 channel	P1 and F1 channel
Doppler Frequency	10 Hz	10 Hz

TABLE II. Channel Characteristic

Channel Power(dB)	-25.4090 -15.6703 -8.4251 -10.9748 -12.3618 -24.7963 -17.0789 -26.3786 -15.2735 -8.5583 -11.2027-9.7186 -12.2243 -13.5423 -15.9607 -17.1147 -13.0111 -19.2874 -13.7265 -12.3300	[-0.4139, -35.8166, -26.0843, -18.8390, -21.3888, -22.7757, -35.2103, -27.4929, -36.7925, -25.6875, -18.9722, -21.6167, -20.1326, -22.6383, -23.9563, -26.3747, -27.5286, -23.4251, -29.7014, -24.1404, -22.7439]
Distribution	Rayleigh	Rician
Channel Delay(s)	[1.003019, 5.422091, 0.518650,2.751772, 0.602895, 1.016585, 0.143556, 0.153832, 3.324866, 1.935570, 0.429948, 3.228872, 0.848831, 0.073883, 0.203952, 0.194207, 0.924450, 1.381320, 0.640512 1.368671]* 10^{-6} (s);	[1.003019, 5.422091, 0.51865, 2.751772, 0.602895, 1.016585, 0.143556, 0.153832, 3.324866, 1.935570, 0.429948, 3.228872, 0.848831, 0.073883, 0.203952, 0.194207, 0.924450, 1.381320, 0.640512, 1.368671]* 10^{-6} (s)



(a) (b)

Fig. 6. Typical impulse response of P1 channel

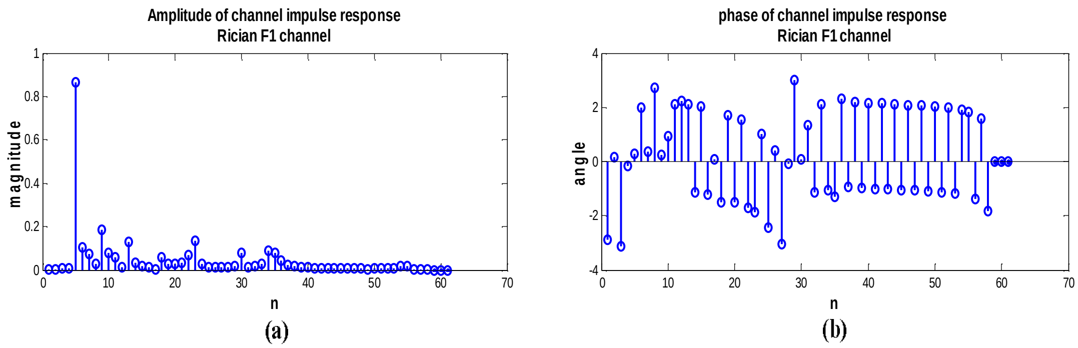


Fig. 7. Typical impulse response of F1 channel

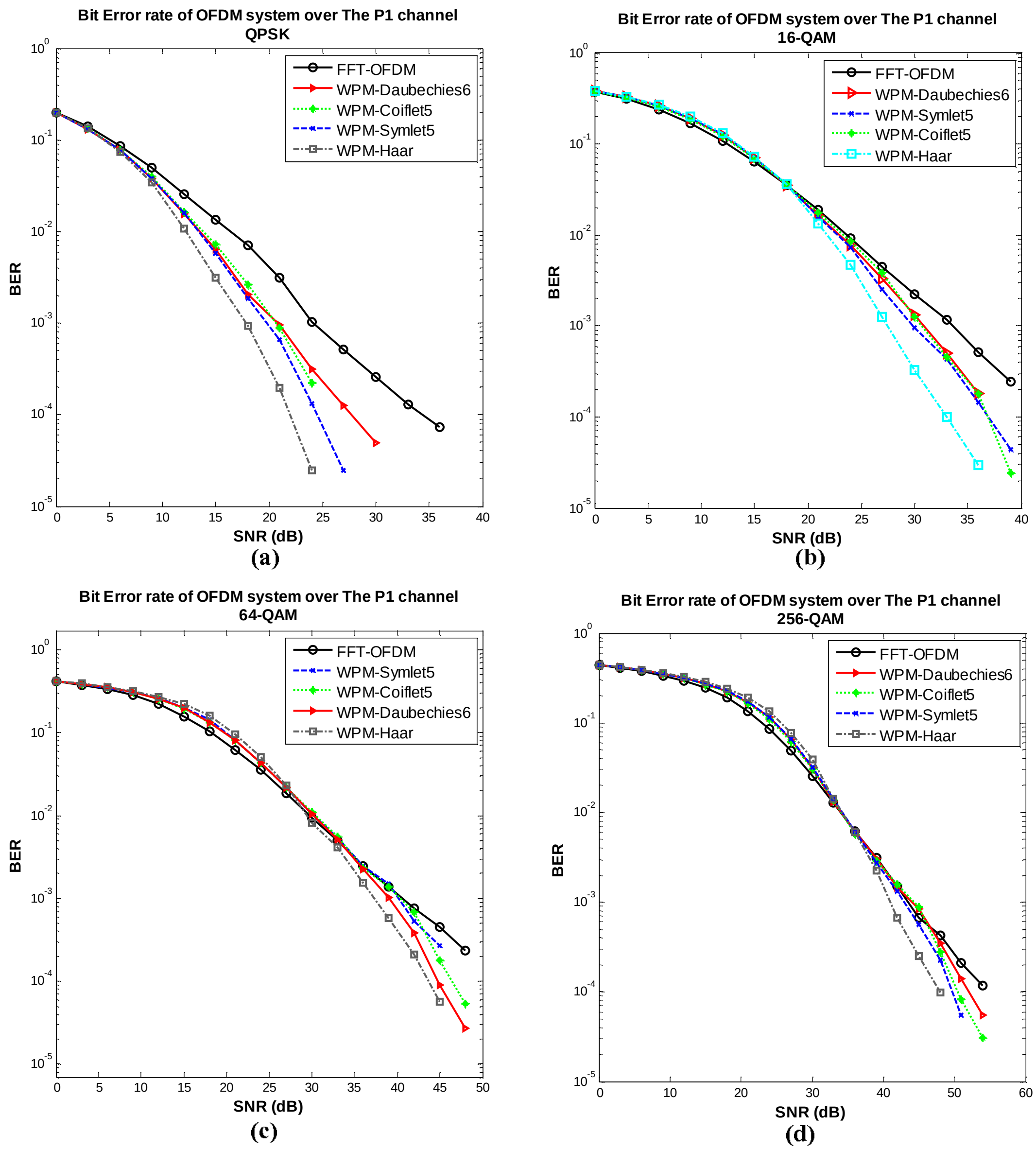


Fig. 8. BER of FFT-OFDM and WPM in P1 channel with (a) QPSK (b) 16-QAM (c) 64-QAM (d) 256-QAM

According to these Tables, for both P1 and F1 channels in all constellation mappings, WPT-OFDM using Haar wavelet family has better performance than FFT-OFDM. Thus, for P1 channel using QPSK, 16-QAM, 64-QAM and 256-QAM, we can reach 7.5081, 7.5905, 3.2514 and 3.2209 dB improvements respectively in required SNR for achieving BER=$5*10^{-4}$. Also, for F1 channel using QPSK, 16-QAM, 64-QAM and 256-QAM we can achieve 2.9122, 2.7955, 1.1468 and 0.8464 dB reduction respectively in required SNR.

TABLE III. REQUIRED SNR FOR BER=$5*10^{-4}$ IN P1 CHANNEL

Mapping	SNR(dB)				
	FFT-OFDM	WPM			
		Haar	Daub6	Symlet5	Coiflet5
QPSK	27.2601	19.7520	22.5040	22.0867	22.2745
16-QAM	36.1419	31.5517	33.0046	32.5937	33.3212
64-QAM	44.2582	41.0428	42.3910	43.1337	43.0916
256-QAM	47.0771	43.8562	47.0780	45.8310	46.9034

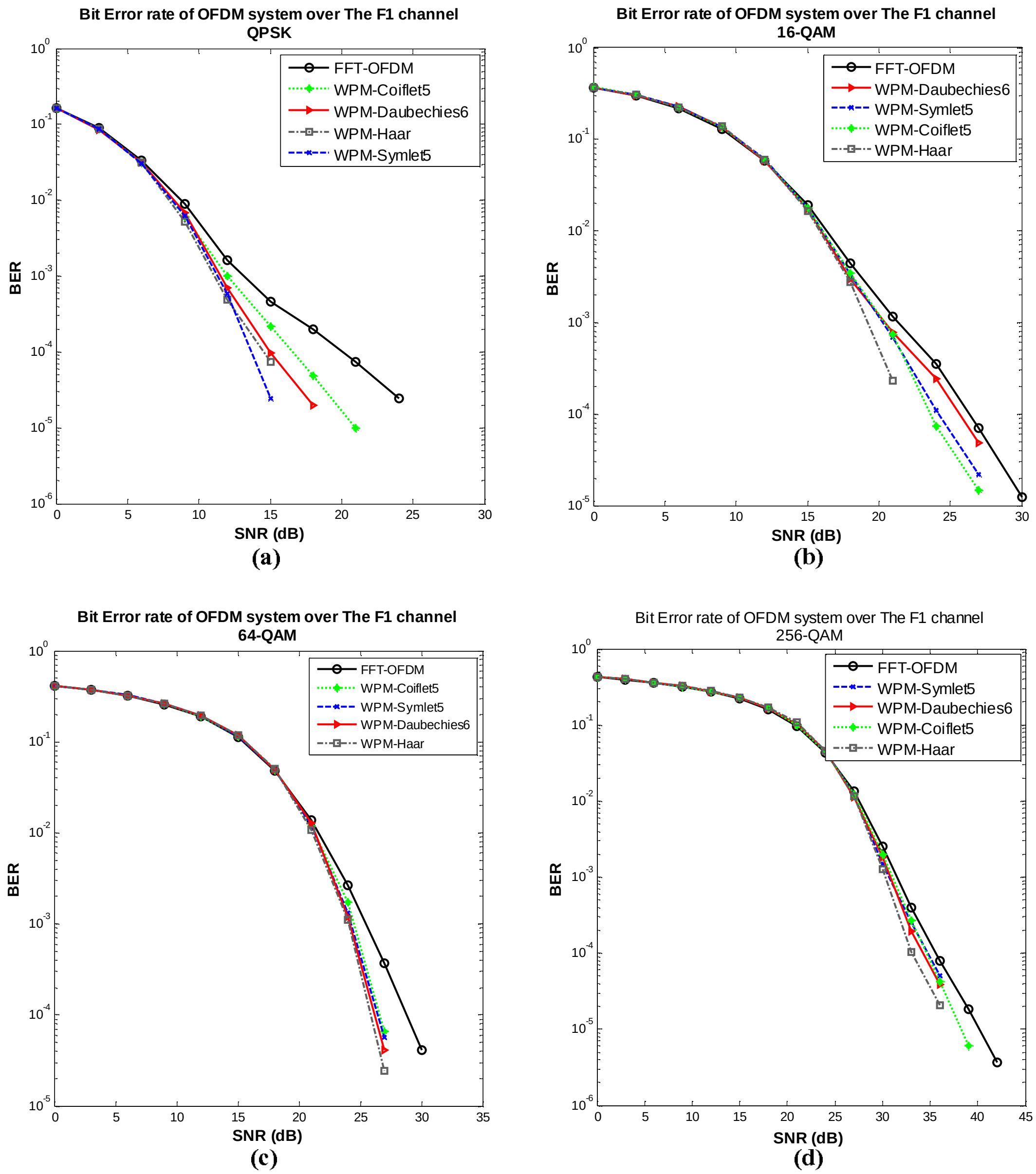


Fig. 9. BER of FFT-OFDM and WPM for F1 channel with (a) QPSK, (b 16-QAM, (c) 64-QAM and (d) 256-QAM

TABLE IV. Required SNR For BER=$5*10^{-4}$ in F1 Channel

Mapping	SNR(dB)				
	FFT-OFDM	**WPM**			
		Haar	**Daubechies6**	**Symlet5**	**Coiflet5**
QPSK	14.9049	11.9924	13.0224	12.4591	13.9224
16-QAM	23.4823	20.6868	22.5709	22.0600	22.0578
64-QAM	26.8203	25.6735	25.8114	25.9308	26.2020
256-QAM	32.8527	32.0063	32.4301	32.4120	32.5990

VII. CONCLUSION

In this paper, two schemes of OFDM modulation systems i.e. FFT-OFDM and WPT-OFDM are simulated to investigate the transmission through the Rayleigh P1 and the Rician F1 channels. In the simulations QPSK, 16-QAM, 64-QAM and 256-QAM constellation mappings for both modulation systems are used. Also Haar, Daubechies6, Symlet5 and Coiflet5 wavelet families for WPT-OFDM are used. In the case of using FEQ equalizer for FFT-OFDM and overlap FEQ equalizer for WPT-OFDM, we see that WPT-OFDM using Haar wavelet family has better performance than FFT-OFDM. As a result, for low SNR, the BER of two systems are almost identical. But for high SNRs, the BER performance of WPT-OFDM gets much better than FFT-OFDM. Moreover, the elimination of CP improves bandwidth and power efficiency. We also concluded that Haar wavelet is the most reliable wavelet family for WPT-OFDM because of the best performance for all modulation mappings and for both P1 and F1 channels.

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