International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-10 Issue-2, July 2021

Design and Analysis of MIMO F-OFDM Systems for 5G and Beyond Wireless Communications

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***Abstract:** F-OFDM (Filtered-OFDM) is a flexible waveform that has been considered suitable for 5G and beyond systems for its improved spectrum utilization, moderates PAPR, low OOB emission, multiple asynchronous sub-band transmission, and high robustness to frequency selectivity. It can attain a desirable balance between frequency and time localizations for narrow bandwidths. It is also MIMO friendly. In this paper, a comprehensive design and analysis have been made to evaluate the performance of MIMO (4×4) CP-OFDM and F-OFDM systems for message bits transmission using several digital modulation techniques (16-QAM, 16-PSK, 16-DPSK, 64-QAM, 64-PSK, and 64-DPSK), RA channel coding, different windowed (Hanning, Hamming, Blackman, Blackman-Harris, RRC) sinc FIR filters for length N = 513, and MMSE signal detection technique. From MATLAB based simulation results, it is observed that F-OFDM reduces spectrum leakage thus enhances spectrum efficiency than conventional CP-OFDM. F-OFDM based system offers lower BER (Bit Error Rate) performance than CP-OFDM based system.*

***Keywords:** OFDM, F-OFDM, MIMO, FIR Filter, RA coding, OOB, PAPR, BER, MMSE*

I. INTRODUCTION

In perspective of socioeconomic developments in both developed and developing countries, at present mobile communications are becoming largest and most significant platforms and contributing positively through transforming the way we communicating , experiencing entertainment and making use of the Internet. With never-ending growth in the global mobile data traffic, it is expected to experience a 23 times increased in 2021 in data volume in comparison with the entire global Internet traffic in 2005 [1], [2]. Moreover next generation wireless networks will be characterized by variety of use cases, such as, enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra-reliable low latency communications (uRLLC) [7]-[9], and [13].

Manuscript received on July 16, 2021.
Revised Manuscript received on July 27, 2021.
Manuscript published on 30 July, 2021.
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This service diversity has become important issues that impose huge challenges on existing 4G waveforms with associated channel coding. Conventional OFDM doesn't meet the requirements of heterogeneous services for its high PAPR and OOB emission. It reserves excess bandwidth for guard band that reduces spectral efficiency. 5G offers mixed numerologies for diverse services instead of uniformly distributed time/frequency resources as in LTE. In LTE, stringent synchronization is maintained through frequent transmission of timing advance signals that is not suitable for services like mMTC that requires asynchronous transmission [4], [13]. F-OFDM supports multi-user asynchronous transmission that uses per-user equipment filtering to suppress the OOB leakage. It uses filtering and windowing to improve spectrum utilization efficiency by reducing OOB emission by limiting guard band. F-OFDM enables spectrum slicing operation that allows efficient coexistence of multiple sub-bands for individual traffic type and corresponding channel conditions to support growing diversity for future services [3], [4]. F-OFDM supports shorter sub-frame and filter lengths that keep overall symbol duration low that is why it is suitable for low latency applications. It uses discrete Fourier transform (DFT) precoding technique to reduce PAPR [6], [10], [11], and [12]. Another way of improving the efficiency of the wireless 5G and beyond networks is to use multi antenna technology either by increasing the number of antennas per site or by adding more APs(access point) and BSs(base station). The number of antenna elements may vary from a relatively small number to many hundreds. F-OFDM is MIMO-friendly [6], and [10]-[12]. In our work we have used 4x4 MIMO. As channel coding technique, Turbo Coding is adopted in many applications such as 3G, 4G, and IEEE 802.16 (WiMAX), but it has long latency and high decoding complexity due to its interleaving and iterative process [3]-[5]. For 5G new radio standard, Low-density parity-check (LDPC) codes have been adopted as the standard codes. Its performances based on the sparse matrix are extremely near to the Shannon limit. Another two coding techniques, Quasi-cyclic (QC) LDPC and Repeat Accumulate (RA) codes have been studied due to its low complexity algorithms. In our study, we have used Repeat Accumulate (RA) codes. It combines aspects of both Turbo and LDPC codes, was introduced by Abbasfar et al. in 2007 [14], [15].

Filter Design Concepts

Achieving a desired balance between time and frequency localization is the main objective of filter design [3, 16]. Among various filter designing methods windowed sync method is recommended that multiplexes a sync function and a finite time domain window which shown in figure 1.

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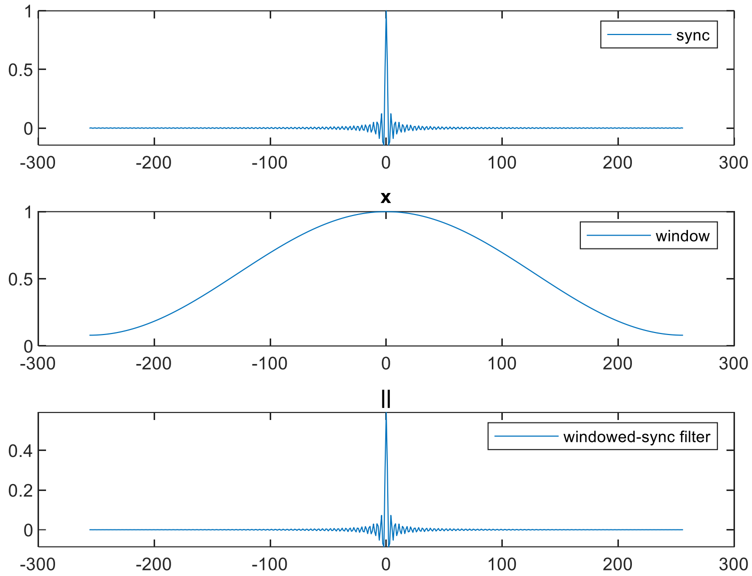

Figure 1: Windowed-sync filter generation

The time domain filter is given by the following equation

$$h(n) = h_{sync}(n) \cdot W(n) \qquad (1)$$

Where $h_{sync}(n)$ represents the time domain Sync response of ideal low pass filter (LPF). $h_{sync}(n)$ can be represented as

$$h_{sync}(n) = \frac{1}{2\pi}\int_{-\omega_c}^{\omega_c} e^{j\omega n}\, d\omega = \frac{\sin(\omega_c n)}{\omega_c n} \qquad (2)$$

ω_c is the cutoff frequency of LPF. $W(n)$ is the time domain window function. In our study, Hanning, Hamming, Blackman and root raised cosine (RRC), windows have been used. Their window functions are given below

- **Hanning window:**
  The equation of Hanning window is given by
  $$W_{hn}(n) = 0.5 + 0.5\cos\left(\frac{2\pi n}{N-1}\right),\ \left(\frac{N-1}{2}\right) \geq n \geq -\left(\frac{N-1}{2}\right) \quad (3)$$
- **Hamming window**
  The Hamming window function is given by
  $$W_{hm}(n) = 0.54 + 0.46\cos\left(\frac{2\pi n}{N-1}\right),\ \left(\frac{N-1}{2}\right) \geq n \geq -\left(\frac{N-1}{2}\right) \quad (4)$$
- **Blackman window**
  In Blackman window there is additional cosine term added which reduces side lobes, hence the main lobe improves [18]. The Blackman window function can be defined by
  $$W_{bl}(n) = 0.42 + 0.5\cos\left(\frac{2\pi n}{N-1}\right) + .08\cos\left(\frac{4\pi n}{N-1}\right), \left(\frac{N-1}{2}\right) \geq n - \left(\frac{N-1}{2}\right) \qquad (5)$$
- **Rooted raised cosine (RRC) window**
  Time domain response of RRC can be defined as
  $$W_{bh}(n) = \left[0.5\left(1-\cos\left(\frac{2\pi n}{N-1}\right)\right)\right]^{\alpha} \quad (6)$$
  Where parameter α is the window shaping parameter that controls shape of the window. In our study its value is 0.6. N defines the filter length for all windows [3, 4].

F-OFDM based System Model

The conceptual block diagram of F-OFDM based 5G enabled 4x4 MIMO systems for downlink is shown in Figure 2. In our proposed system base station and user equipment both equipped with 4 antennas.

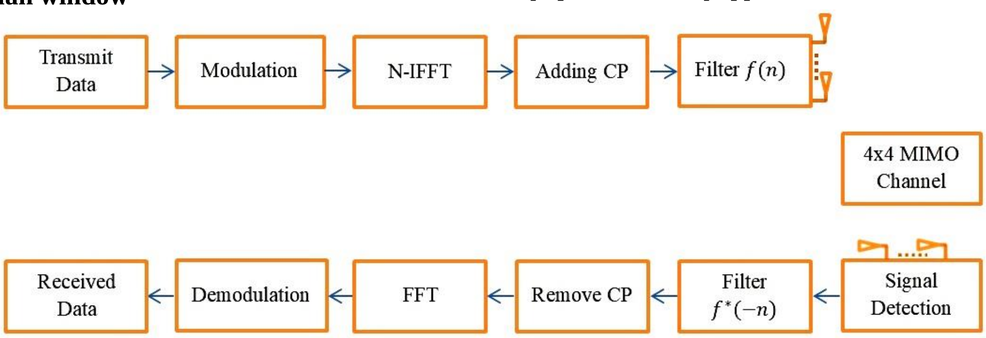

Figure 2: System model of 4×4 MIMO based F-OFDM

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We have taken random bits as transmit data. RA code is used as channel coding technique which is used for detecting and correcting bit errors in communication systems. At the transmit side encoder performs the channel coding action whereas at the receive side, decoder performs channel decoding to retrieve message bits [8]. Modulation is the strategy of combining the low-frequency signal with a very high-frequency radio wave called carrier wave (CW). Here 16-QAM, 16-PSK, 16-DPSK, 64-QAM, 64-PSK, and 64-DPSK modulation schemes have been considered. These modulated symbols are loaded by IFFT to the required OFDM subcarriers. Every sub-band produces its own OFDM symbols. The inverse is made i.e. FFT is done at the receiver section where the symbols are converted back to the frequency domain. In this work 1024 FFT size has been considered. Then the term cyclic prefix refers to the prefixing of a symbol, with a repetition of the end. The receiver is typically configured to discard the cyclic prefix samples, but the cyclic prefix serves two purposes: It provides a guard interval to eliminate inter-symbol interference from the previous symbol. It repeats the end of the symbol so the linear convolution of a frequency-selective multipath channel can be modeled as circular convolution, which in turn may transform to the frequency domain via a discrete Fourier transform. Windowed sync method based sub-band filters have been used. In receiving section, all the transmitted signals are detected with MMSE signal detection scheme.

Table-I: Summary of the simulated model parameters.

Parameters	Types
Matlab Version	2019b
Message Type	binary bits
Bandwidth	10 MHz
DL throughput	46 Mbps
Channel	AWGN and Rayleigh
SNR	0 to 18 dB
Signal Detection Scheme	MMSE (Minimum Mean Square Error)
Windows	Hanning, Hamming, Blackman, RRC
Carrier Spacing	15 kHz
Number of resource blocks	50
Number of subcarriers per resource block	12
Number of subcarriers	600
Configuration of Special sub-frame	7
CP Length	4.67 μS
Filter Order	512
Sampling Frequency	15.36 MHz
Tone offset	5 subcarriers
IFFT / FFT Size	1024
Digital Modulation	16-PSK, 16-QAM, 16-DPSK, 64-QAM, 64-PSK, 64-DPSK
Channel Coding	RA code
Antenna configuration	T4xR4

II. RESULTS AND DISCUSSION

Results of the simulation study presented in terms of BER, OOB, PSD and PAPR have been investigated by computer simulation programs written in MATLAB R2019b.

Figure 3 shows the theoretical probability of symbol error for 16-QAM, 16-PSK, 16-DPSK, 64-QAM, 64-PSK, and 64-DPSK modulations. It shows minimum symbol error rate for the 16-QAM and maximum for 16-DPSK for 16-ordered modulations and minimum symbol error rate for the 64-QAM and maximum for 64-DPSK for 64-ordered modulations.

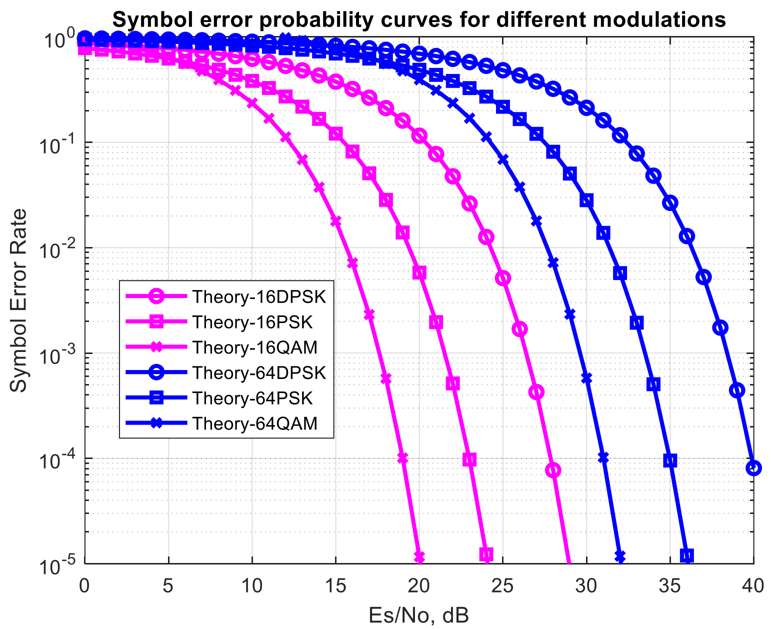

Figure 3: Theoretical probability of symbol error curve for 16-QAM, 16-PSK, 16-DPSK, 64-QAM, 64-PSK, and 64-DPSK modulations.

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Channel capacities for SISO (1×1) and different MIMO configurations are shown in Figure 4. Capacity increases if the numbers of antennas are increased in both BS and UE. For this reason, the channel capacity is maximum for 4×4 MIMO and minimum for SISO (1×1) channels for the same SNR.

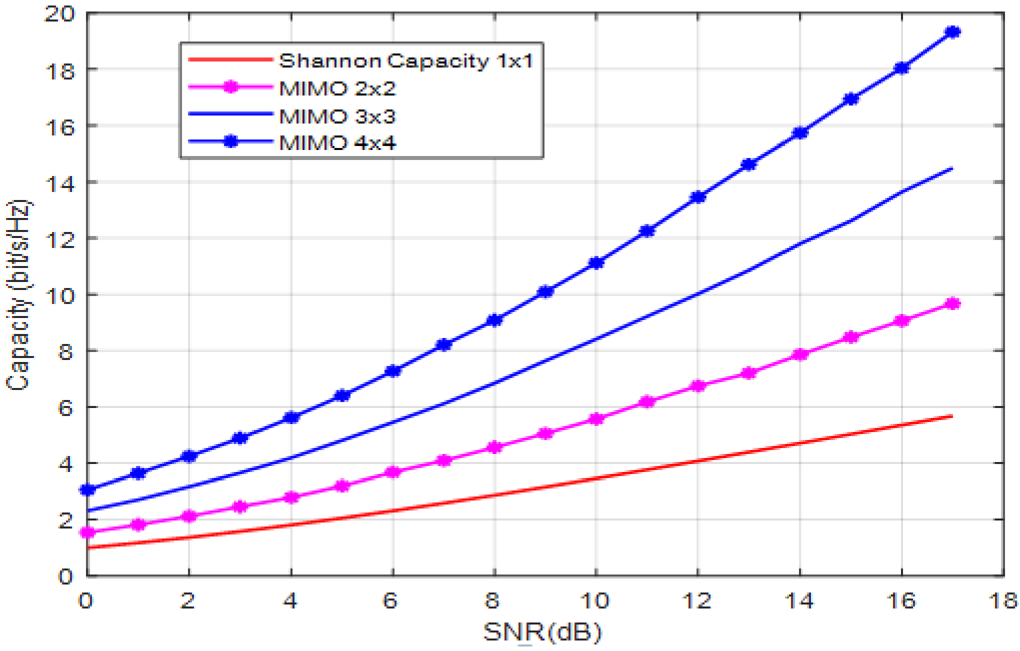

Figure 4: Channel capacity for SISO and different MIMO configurations.

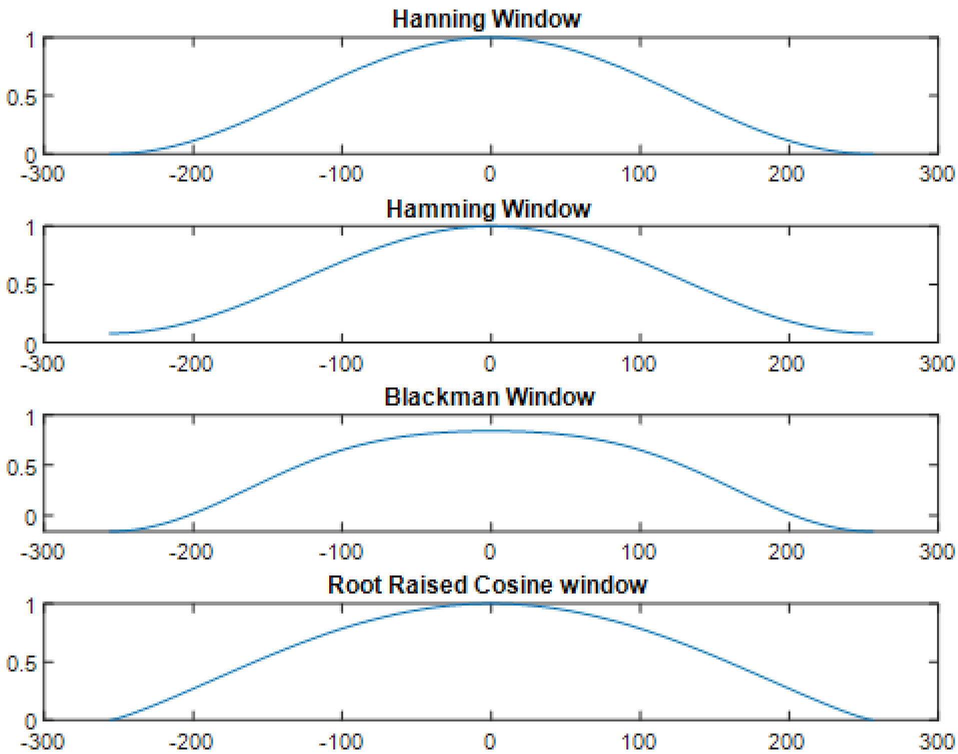

Figure 5: Shape of different windows (Hanning, Hamming, Blackman and RRC)

The shape of different windows (Hanning, Hamming, Blackman, and RRC) is shown in figure 5. Window shaping parameter α in case of RRC plays a significant role. If α is zero, then RRC becomes rectangular window when its value equals to 1, it becomes Hanning window.

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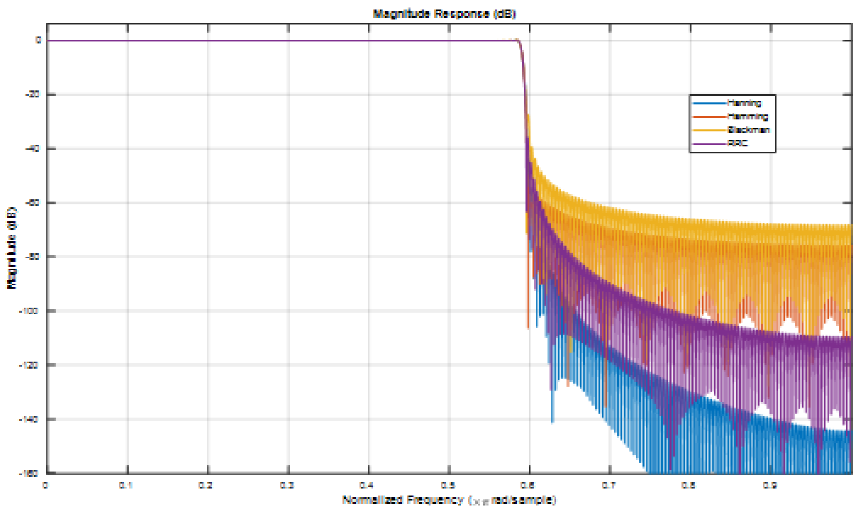

Figure 6: Magnitude responses of different window-based filters having normalized frequency in x axis and magnitude in y axis.

Figure 6 shows the magnitude response of different window (Hanning, Hamming, Blackman, and RRC) based filters. All filters show almost same flat passbands without any attenuation and sharp transition bands that reduce guard bands as well as leads to stop band quickly.

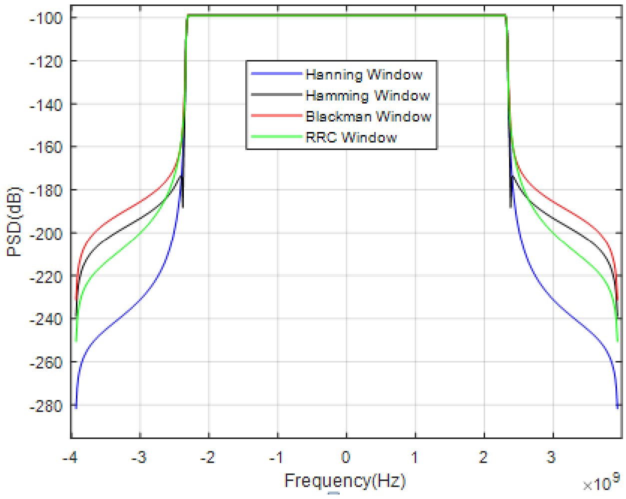

Figure 7: PSDs of different window (Hanning, Hamming, Blackman, and RRC) functions.

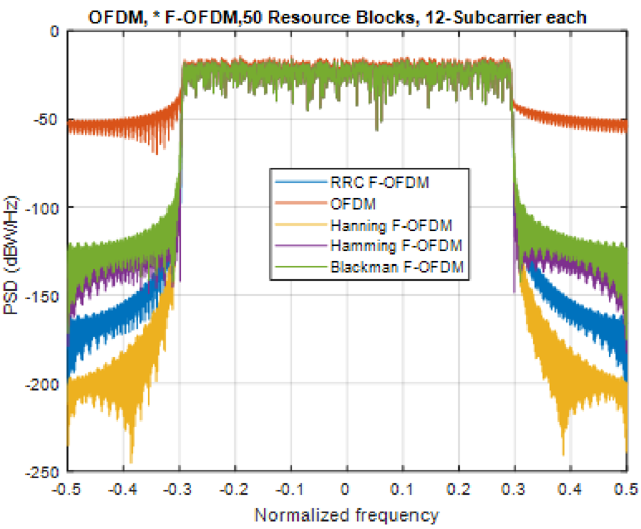

Figure 8: PSDs of different window (Hanning, Hamming, Blackman, and RRC) based F-OFDM and CP-OFDM systems

Figure 7 represents the estimated PSD of Hanning, Hamming, Blackman and RRC window-sync filters. Figure 8 shows the estimated PSD of Hanning, Hamming, Blackman and RRC window based F-OFDM and CP-OFDM systems. From fig. 8, it is quite noticeable that any window based F-OFDM system gives better OOB emission performance than CP-OFDM system. From figures 7 and 8, it is noticeable that the Hanning window-sync filter based system gives the lowest stop-band rejection performance and Blackman window based system provides highest stop-band rejection performance. RRC window based system has a very narrow transition band. The estimated OOB power for Hanning, Hamming, Blackman, and RRC window based filters are -281.819, -238.956, -231.314, and -250.627 dB respectively. So, Hanning window based F-OFDM system provides best OOB performance than others.

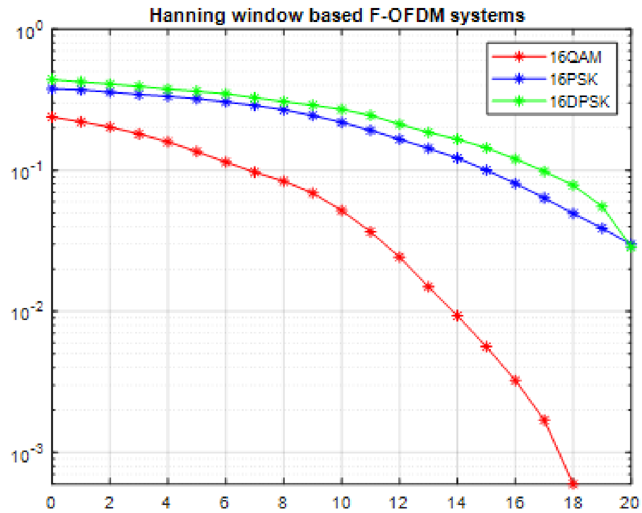

Figure 9: BER performance of 4×4 MIMO F-OFDM System under utilization of 16-QAM, 16-PSK, 16-DPSK and Hanning window based filter.

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The graphical illustration presented in Figure 9 shows 4×4 MIMO F-OFDM based system performance with implementation of MMSE signal detection technique under 16-PSK, 16-QAM, 16-DPSK digital modulations with RA channel coding and Hanning window based filter. System shows best performance for 16-QAM digital modulation and worse for 16-DPSK. The BER values at 3 dB SNR is 0.1811 for 16-QAM, 0.3442dB for 16-PSK and 0.3937 for 16-DPSK. 16-QAM based F-OFDM system shows the lowest BER. The 16-QAM based system shows 2.78 dB gain as compared to 16-PSK as well as 3.37 dB gain as compared to16-DPSK.

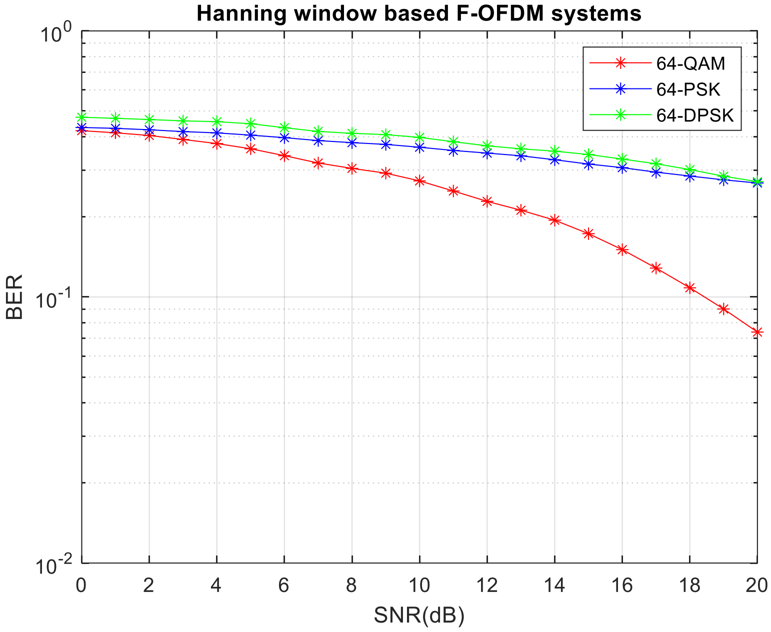

Figure 10: BER performance of 4×4 MIMO F-OFDM System under utilization of 64-QAM, 64-PSK, 64-DPSK and Hanning window based filter.

The graphical illustrations presented in Figure 10 shows system performances of Hanning window based F-OFDM systems for64-PSK, 64-QAM, and 64-DPSK digital modulations with implementation of MMSE signal detection technique and RA channel coding. System shows best performance for 64-QAM digital modulation and worse for 64-DPSK. The BER value at 3 dB SNR is 0.3908 for 64-QAM, 0.4183 for 64-PSK and 0.4590 for 64-DPSK respectively. The 64-QAM based system shows 0.3 dB gains as compared to 64-PSK as well as 0.6 dB gains as compared to16-PSK.

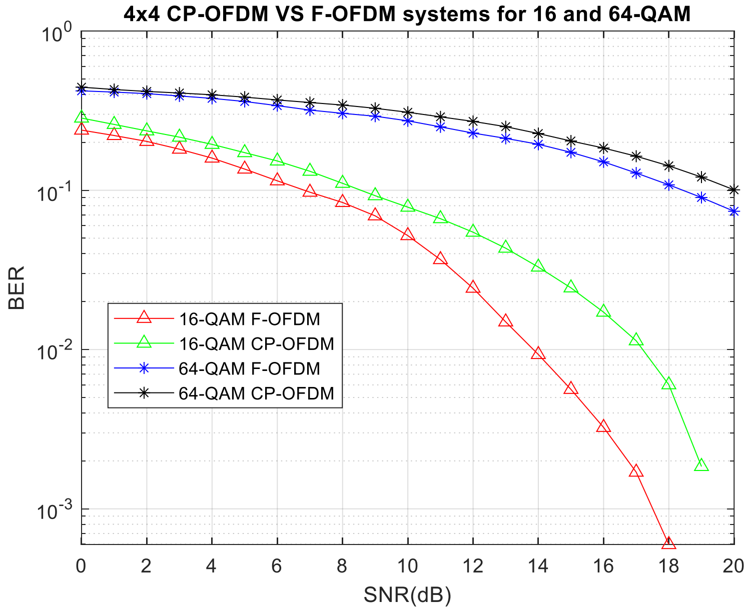

Figure 11: BER performance of 4×4 MIMO CP-OFDM vs Hanning window based F-OFDM Systems under utilization of 16-QAM and 64-QAM.

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Figure 11 shows CP-OFDM and Hanning window based F-OFDM system performances comparison with implementation of MMSE signal detection technique scheme under 16-QAM and 64-QAM digital modulations with RA channel coding. F-OFDM based system shows best performance for both 16-QAM and 64-QAM digital modulations in comparison with CP-OFDM based systems. The BER value at 3 dB SNR is 0.1811 for 16-QAM based F-OFDM system, 0.2155 for 16-QAM based CP-OFDM systems. The F-OFDM based system shows 0.76 dB gain as compared to CP-OFDM systems. The BER value at 3 dB SNR is 0.3909 for 64-QAM based F-OFDM system, 0.4085 for 64-QAM based CP-OFDM systems. The F-OFDM based system shows 0.2 dB gain as compared to CP-OFDM systems. In case of PAPR, without implementation of RA channel coding technique to the systems the estimated values are 7.8622 dB, 9.5307 dB, 9.5388 dB, 9.5386 dB, and 9.5287 dB for CP-OFDM, RRC window based F-OFDM, Hanning window based F-OFDM, Hamming window based F-OFDM, and Blackman window based F-OFDM systems respectively. With RA channel coding, the estimated values of PAPR are 20.5883 dB, 22.3631 dB, 22.3623 dB, 22.3626 dB, 22.3617 dB for CP-OFDM, RRC window based F-OFDM, Hanning window based F-OFDM, Hamming window based F-OFDM, and Blackman window based F-OFDM systems respectively. For both cases, difference between PAPR values of CP-OFDM and F-OFDM based systems is approximately 2 dB and CP-OFDM based system shows lower PAPR than F-OFDM.

III. CONCLUSION

In this paper, a comprehensive study has been made to analyze the symbol error probabilities for 16-QAM, 16-PSK, 16-DPSK, 64-QAM, 64-PSK, 64-DPSK modulations, channel capacity of different antenna configurations, magnitude response of different window-sync FIR filters, PSD of different window functions as well as different window based F-OFDM and CP-OFDM systems to observe OOB emission, BER performances and PAPR of CP-OFDM and F-OFDM based systems under implementation of MMSE signal detection scheme. From simulation study, it is observed that F-OFDM systems outperform CP-OFDM systems in all cases except in case of PAPR. Among different windowed-sync based F-OFDM systems, Hanning window-sync filter based system gives best stop-band rejection performance. Hanning windowed filter also gives smoother impulse response compared to other window based filters which leads to better trade-off between time and frequency localization. For BER performance, it is observed that Hanning windowed F-OFDM systems represent minimum BERs for QAM (16 and 64) modulation as compared to PSK (16 and 64) and DPSK (16 and 64) modulations. It also shows afford mention F-OFDM system offers minimum BER than CP-OFDM system. From simulation results it can be concluded that Hanning windowed MIMO W-OFDM system with QAM (16 and 64-order) digital modulation is very much robust and effective in retrieving transmitted signals. It also enhances spectrum efficiency and reduces spectrum leakage over conventional CP-OFDM.

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