

Performance Analysis of FBMC over OFDM for High Data Rate MIMO Configurations

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Abstract: The burgeoning demand of high data rate in next generation wireless communication, the antecedent of the evolution of new multicarrier modulation technique FBMC (Filter Bank Multicarrier) system is OFDM (Orthogonal Frequency Division Multiplexing). Although OFDM has numerous merits but it consumes higher bandwidth due to its cyclic prefix to eliminate ISI (Inter Symbol Interference) in fading channel and shows large PAPR (Peak to Average Power Ratio) in transmission system. To mitigate these problems, FBMC is more suitable candidate in high speed MIMO (multiple input multiple output) system. At first, in this paper, the responses of OFDM and FBMC system have been analyzed with AWGN and Rayleigh fading channel under theoretical and simulation environment. Besides this, Peak to Average Power Ratio (PAPR) with reduction technique, clipping is applied to know the behavior of these systems. Finally, in the area of MIMO scheme, each system is concatenated with MRC, Alamouti STBC and Generalized STBC to find FBMC as superior contender for 5G. Results show that using 16 QAM modulation, BER performance of FBMC significantly achieves 2dB compared to error rate of OFDM in theoretical and empirical analyses under AWGN and Rayleigh channel. Moreover, the clipping technique enhances the response of FBMC in terms of PAPR compared to OFDM approximately 0.5 dB. In MIMO configurations, MRC-FBMC exhibits the improved performance with 2 dB approximately over MRC-OFDM system. Results also show that in the case of Alamouti STBC, at 30dB and 35dB, FBMC (2×1) and (2×2) configurations achieve BER improvement 5×10^{-4} , 3×10^{-4} respectively than OFDM (2×1) and (2×2) configurations. Generalized STBC investigation reveals that to reach FBMC BER performance, OFDM needs at least 2dB increment at specific error rate. In a nutshell, this paper brings up three distinct types of appealing features of FBMC such as good BER response, reduced PAPR, and suitability in MIMO configuration compared to OFDM. These distinct features make FBMC an ultimate choice in the emerging areas of MIMO networks.

Index Terms: FBMC (Filter Bank Multicarrier), OFDM (Orthogonal Frequency Division Multiplexing), BER (Bit Error Rate), PAPR (Peak to Average Power Ratio), MIMO (Multiple Input Multiple Output).

1. Introduction

The most effectual multi-carrier modulation scheme has been dominated ever which is known as OFDM (Orthogonal Frequency Division Multiplexing), as the leading modulation technique of commercial high speed communication systems of next generation wireless communication over the last few years. Meanwhile, using OFDM LTE- ADVANCED desires to acquire data rate from 100 Mbps to 1Gbps for mobile application. 4G standards Wi-Fi a form of Mobile Internet use OFDM to serve 300Mbps-600Mbps etc. [1]. The guard time and cyclic prefix used to mitigate inter-symbol interference (ISI) and inter-carrier interference (ICI) of OFDM completely. High transmission bitrates, flexibility, easy equalization, spectral efficiency, lower multipath distortion, resiliency of RF interfaces are the main facilities of OFDM [2].

The exciting growth of wireless systems, the future (5G) generation technology will be implemented with frequency 30-300 GHz, peak data rate as capacity 20Gbps, and bandwidth 1000x BW/unit area and reduction of latency time until 1 ms [3]. Furthermore, the two most important market drivers for 5G those are mobile internet and IOT (internet of things). The major impediments of OFDM which make it unsuitable for 5G - sensitivity to frequency and time offset, need Cyclic prefix for removing ISI effect, large out of band emissions (OOBE) cause massive side lobes that mitigate the channel efficiency, large peak to average power ratio (PAPR) reduces the efficiency of high power amplifier and degrades the performance of the system [4]. FBMC (Filter Bank Multi-Carrier) is another promising modulation technique that resolves the demerits of OFDM by applying high quality filters. The FBMC system delivers more robustness to the time and frequency compare to the OFDM by removing the cyclic extension. The basic structure of FBMC is made by a set of synthesis and analysis filter banks in transmitter and receiver respectively [28]. The

significant merits of FBMC for which it outperforms OFDM are more resistant for narrowband noise effects, low out-of-Band (OOB) that makes FBMC suitable to apply in the uplink of multiuser networks, and less inter-carrier interference (ICI) issue which is more reliable than OFDM. Peak to Average Power Ratio (PAPR) is considered one of the main problems of any multicarrier modulation scheme. Unfortunately, both OFDM and FBMC suffer PAPR problem [6]. Clipping is one of the simplest reduction techniques which used to reduce PAPR of both schemes.

Furthermore, MIMO (Multiple Input Multiple Output) is an antenna technology which uses multiple antennas at both transmitter and receiver side and delivers higher capacity (bits/s/Hz) through spatial multiplexing scheme, better transmission quality (Bit Error Rate) through transmit diversity scheme (Space Time Block Coding). This diversified antenna system is more robust against fading in which if one signal from one antenna gets faded away then the other antennas will overcome the signal loss. The increasing requirements of high data rates in 5G communication are successfully implemented by applying MIMO with FBMC [7]. Moreover, this FBMC with MIMO schemes provide both efficiency and QOS (quality of the service) to the system. The received signals are combined by Maximum Ratio Combiner (MRC) and detect by ML (maximum likelihood) decoder. The main objectives of this research paper are to mitigate the demerits of OFDM using FBMC and analysis the responses of these systems in terms of BER, PAPR and MIMO. Although there are some other techniques like universal filter bank multi-carrier (UFMC) and generalized frequency division multiplex (GFDM) those are perfectly apposite in 5G communication but in this paper discussions are limited to OFDM and FBMC configurations. Moreover, limitations show that implementing FBMC in MIMO is quit complex and due to the long filter length FBMC is inefficient for short burst transmission.

To bring upcoming trend to the attention of the Signal Processing and Communication communities, a system was proposed in [8] where B. Farhang et al. addressed the shortcomings of OFDM and showed Filter Bank Multicarrier (FBMC) could be a more effective solution. Y. H. Yun et al. introduced a new waveform FBMC-QAM that provides superior spectrum confinement and higher spectral efficiency compared to CP-OFDM and have shown the transmission and reception procedures for QAM-OFDM including its similarities and difficulties with conventional CP-OFDM [9]. Here, performance showed that spectral efficiency gain of QAM-FBMC was better than CP-OFDM [9]. Mr. Sivanagaraju. V. et al. in [28] presented a comprehensive analysis about BER and SNR under various channel such as AWGN and Rayleigh channel using different modulation techniques. The Author in [6] proposed a method to reduce PAPR in FBMC system. In [10], O. Kenneth et. al. Addressed the disadvantages of PAPR in OFDM system and have been proposed several techniques to reduce high PAPR. The authors in [11] have shown various methods of designing effective prototype filters. Also this paper brings the feature of FBMC which emerging areas of multiuser and massive MIMO networks. A. Farhang et al. [12] introduced FBMC as a potential candidate of massive MIMO system and points out the advantages FBMC over OFDM. The FBMC system is interfaced with MIMO system with different antenna array sizes and also measured BER against Signal to Noise Ratio (SNR) for each system which depicts that FBMC with MIMO shows a satisfactory improvements [13]. H. Nam et al. shows that FBMC-QAM satisfies orthogonality conditions and can use MIMO scheme as used conventional OFDM [14]. Here, the signal-to-interference power ratio and bit error rate (BER) for the proposed FBMC-QAM system are evaluated [14]. In [26] I. ESTELLA et al. compare OFDM and FBMC and proposed MIMO requires channel state information (CSI) to improve the system throughput. The Authors showed for imperfect CSI consideration, FBMC still suffers ISI and ICI effects where OFDM shows more robust in such scenarios.

The remainder of this paper is embodied in section II- material methods included OFDM and FBMC transmission and reception procedure, PAPR reduction and also the structure of OFDM and FBMC systems Interfaced with MIMO. The BER and CCDF performances of OFDM and FBMC techniques and also their comparison is depicted in section III, based on the simulation results using MATLAB. Lastly, conclusion is narrated in section IV.

2. Material Methods

In this section the basic construction for both multicarrier systems are introduced. In the following subsections we represent PAPR reduction technique, the combining method of OFDM and FBMC with MIMO structure and their mathematics.

2.1. OFDM Transmission and Reception Techniques

The basic concept of OFDM is, the available bandwidth (BW) is divided into multiple overlapping subcarriers and the subcarriers are mathematically orthogonal to each other. For implementing OFDM orthogonal signals, two basic operations such as Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) are need. OFDM signal combined by multiple sinc-shaped subcarriers in frequency domain are modulated by Quadrature Amplitude Modulation (QAM).

In Fig. 1 each OFDM symbol contains N subcarriers. Transmitter maps the signal bit stream into the transmitted symbols as $\{X_l[k]\}_{k=0}^{N-1}$ QAM symbols. The frequency domain symbol $X_l[K]$ modulates the subcarriers with a frequency of $f_k = k/T_{sym}$ for N where $(k = 0, 1, 2, \dots, N-1)$. The symbol $X_l[K]$ has a duration of T_s but when it converted to parallel N symbols, then its length also extended to $T_{sym} = NT_s$. As a result the transmitted OFDM symbol consists of

N parallel symbols which now has a duration of T_{sym} . Let, the transmitted signal is expressed by (1).

$$\Psi_{l,k}(t) = \begin{cases} e^{j2\pi f_k(t-lT_{sym})}, & 0 < t \leq T_{sym} \\ 0, & \text{elsewhere} \end{cases} \quad (1)$$

In Eq. (1), $\Psi_{l,k}(t)$ represents l^{th} OFDM signal with k^{th} subcarriers. The continuous time domain baseband OFDM signal can be expressed as,

$$x_l(t) = \sum_{l=0}^{\infty} \sum_{k=0}^{N-1} X_l[k] e^{j2\pi f_k(t-lT_{sym})} \quad (2)$$

The Eq. (2) sampled at $t = lT_{sym} + nT_s$ where $T_s = T_{sym}/N$ and $f_k = k/T_{sym}$. After, the equation in discrete form becomes

$$x_l[n] = \frac{1}{N} \sum_{k=0}^{N-1} X_l[k] e^{j2\pi kn/N} \quad \text{for } n = 0, 1, \dots, N-1 \quad (3)$$

Eq. (3) represents the N point IDFT of QAM data symbols $\{X_l[k]\}_{k=0}^{N-1}$ and can be computed efficiently by using IFFT algorithm [15].

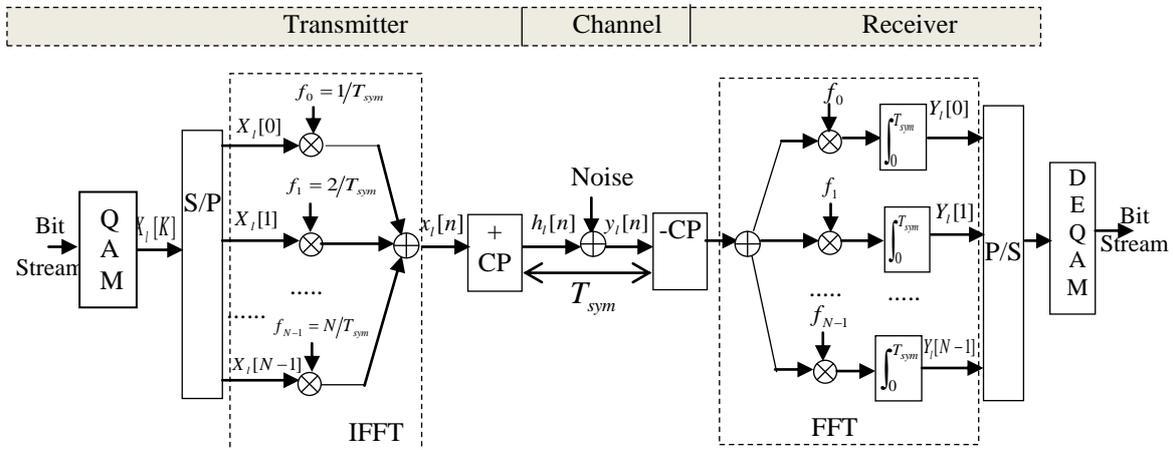


Fig.1. OFDM modulation and demodulation [15].

The cyclic prefix which is denoted by T_{cp} , construction of a copy of the end of the OFDM signal is attached in the front of itself [16]. Then, the modified extended OFDM symbols have the duration of $T_{sym} = T_{sub} + T_{cp}$. If the length of the CP is set longer or equal to the maximum delay of the multipath channel, the ISI effect is denoted in the guard interval so it may not affect the next OFDM symbol (T_{sub}) and the orthogonal properties also maintained.

In wireless communication systems, the presence of multipath scatters (obstacles, vehicles, buildings etc.) causes the transmitted signal to arrive at the receiver through different paths. So, the signals arriving at the receiver would be a superposition of all signals coming with different delays. This channel is known as time-dispersive [4]. An AWGN (Additive White Gaussian Noise) channel is free from inter-symbol interference (ISI). Therefore, the Additive White Gaussian Noise $z_l[n]$, transmitted signal $x_l[n]$, passing the signal through the channel and the received signal $y_l[n]$ becomes

$$y_l[n] = x_l[n] + z_l[n] \quad (4)$$

Rayleigh fading describes radio links between transmitter and receiver in where no direct line-of-sight (LOS) is available. It is one of the mostly used multipath fading models. Taking the samples at $nT_s = nT_{sym}/N$ represented in a discrete time,

$$y_l[n] = x_l[n] * h_l[n] + z_l[n] = \sum_{m=0}^{\infty} h_l[m] x_l[n-m] + z_l[n] \quad (5)$$

Eq. (5) represents $x_l[n]$ = transmitted OFDM symbol, $y_l[n]$ = after passing through the channel, $h_l[n]$ = channel impulse response, $z_l[n]$ = Additive White Gaussian Noise.

In receiver, $\{y_l[n]\}_{k=0}^{N-1}$ are the sample values of the received OFDM symbol at $y_l(t)$ at $t = lT_{sym} + nT_s$. Then the transmitted symbol $X_l[k]$ can be recovered by the orthogonality among the subcarriers including channel and noise,

$$\begin{aligned} Y_l[k] &= \sum_{n=0}^{N-1} y_l[n] e^{-j2\pi kn/N} = \sum_{n=0}^{N-1} \left\{ \frac{1}{N} \sum_{i=0}^{N-1} X_l[i] e^{j2\pi in/N} \right\} e^{-j2\pi kn/N} + z_l[n] \\ &= \frac{1}{N} \sum_{n=0}^{N-1} \sum_{i=0}^{N-1} X_l[i] e^{j2\pi(i-k)n/N} + z_l[n] = X_l[k] + z_l[n] \text{ for } \begin{cases} 1, & \text{for } i = k \\ 0, & \text{for } i \neq k \end{cases} \end{aligned} \quad (6)$$

Eq. (6) represents the N point DFT of QAM data symbols maintained the orthogonal properties and can be computed efficiently by using FFT algorithm. After demodulated the signal by FFT and applied to parallel to serially converter, it is fed into QAM de-mapper. At the end, the original transmitted bit streams can be recovered from the receiver of the system [15].

2.2. Basic construction of FBMC Transmitter and Receiver

FBMC (Filter Bank Multicarrier) highlights the merits of the candidate modulation scheme for 5th generation (5G) communication system. The significant idea of FBMC system is to transmit real symbols (Offset QAM) instead of conventional complex (QAM) symbols as used in OFDM system [17]. At the same time, the Synthesis filter bank (SFB) for the transmitter and the Analysis filter bank (AFB) for the receiver, are the essential parts of the FBMC-OQAM system arranged in Fig. 2 is named as TMUX (Transmultiplexer) configuration [18]. The combination of PHYDYAS prototype filter and extended IFFT in SFB which are responsible for frequency spreading and filtering. The whole configuration delivers not only orthogonality (without using CPs) but also good spectral efficiency, high bandwidth efficiency and channel capacity [19]. The transmission channel is assumed to be ideal for analyzing and designing the TMUX system. To design the system assume the length of the prototype filter $L_p = KM - 1$ where K is the overlapping factor and M is the number of subcarriers in the filter bank.

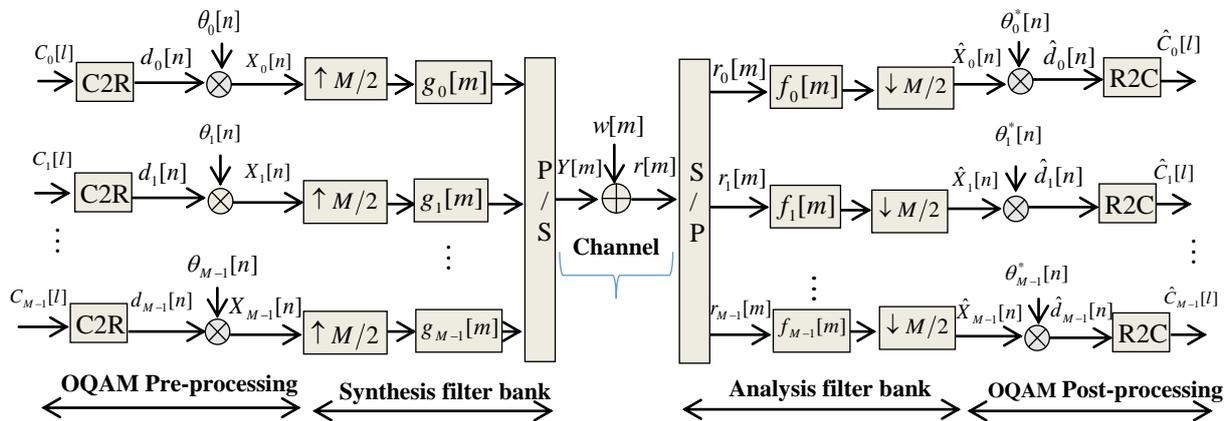


Fig.2. Direct form representation of TMUX configuration [20].

In Fig. 2, the discrete-time baseband signal at the transmitter output from SFB with OQAM pre-processing can be expressed by,

$$Y[m] = \sum_{k=0}^{M-1} X_k[n] g_k[m] \quad (7)$$

For $m = 0, 1, \dots, L_p - 1$, where m is the sample index at SFB output/AFB input and n is the sample index at OQAM Pre-processing output/Post-processing input. $X_k[n]$ is the output of OQAM Pre-processing and $g_k[m]$ is the output of SFB output.

$$X_k[n] = \theta_k[n] \cdot d_k[n] \quad (8)$$

Where, $\theta_k[n] = j^{k+n}$.

In Eq. (8), $d_k[n]$ are the real valued data symbols at subcarriers k (for $k = 0, 1, \dots, M-1$). The input $C_k(l)$ which is complex valued transmitted with the signaling period $T = 1/\Delta f$ ($\Delta f =$ subcarrier spacing), where l is the sample index at OQAM Pre-processing input/Post-processing output. Introducing up-sample by 2, the complex to real conversion is operated. To maintain the orthogonality the phase component $\theta_k[n]$ is multiplied by $d_k[n]$ [20]. The k^{th} SFB output can be represented by the relation shown in Eq. (9).

$$g_k[m] = p[m] \exp\left(j \frac{2\pi k}{M} \left(m - \frac{L_p - 1}{2}\right)\right) \quad (9)$$

Eq. (9) depicts, all sub-channel filters can be generated from a single real valued linear phase FIR low-pass prototype filter $p[m]$.

This paper concentrates on the Frequency sampling method to design the PHYDYAS prototype filter. The frequency coefficients through the interpolation formula for sampled signals

$$H(f) = \sum_{k=-K+1}^{K-1} H_k \frac{\text{Sin}\left(\pi\left(f - \frac{k}{MK}\right)MK\right)}{MK \text{Sin}\left(\pi\left(f - \frac{k}{MK}\right)\right)} \quad (10)$$

Eq. (10) determines the coefficients H_k of the prototype filter and the coefficients are $H_0 = 1$ $H_{\pm 1} = 0.97196$ $H_{\pm 2} = \sqrt{2}/2$ $H_{\pm 3} = 0.235147$.

From frequency sampling method, symmetrical impulse response for even N

$$h(n) = \frac{1}{N} \left[H(0) + 2 \sum_{k=1}^{\frac{N-1}{2}} H(k) \cos\left(\frac{2\pi k \left(n - \frac{N-1}{2}\right)}{N}\right) \right] \quad (11)$$

Eq. (11) helps to determine the impulse response of the prototype filter. The impulse response of the prototype filter is given by inverse Fourier transform of the pulse frequency response that is [19]

$$h(L) = 1 + 2 \sum_{k=1}^{K-1} (-1)^k H_k \cos\left(\frac{2\pi k L}{MK}\right) \quad (12)$$

Where, L is the prototype filter of length $(KM - 1)$. In the case of channel, the same channel properties maintained in FBMC as OFDM used in (4) and (5). So, after passing the channel the input of the receiver is

$$r_k[m] = y_k[m] h_k[m] + w_k[m] \quad (13)$$

In Eq. (13), $h_k[m]$ is a complex valued fading process of k^{th} subcarrier for the m^{th} FBMC symbol and $w_k[m]$ is an Additive White Gaussian noise (AWGN) process.

The inverse operation of real to complex conversion is performed in receiver and results is down-sampled by 2. The k^{th} Analysis filter is simply a time reversed and complex-conjugated symbol as compare as the Synthesis filter bank

$$f_k[m] = g_k^*[L_p - 1 - m] = p[L_p - 1 - m] \exp\left(j \frac{2\pi k}{M} \left(m - \frac{L_p - 1}{2}\right)\right) \quad (14)$$

After processing the received signal $r_k[m]$ in Analysis filter bank the resulting signal becomes

$$\begin{aligned}
 s_k[m] &= [r_k[m] * f_k[m]]_{\downarrow M/2} \\
 &= [y_k[m] h_k[m] * f_k[m]]_{\downarrow M/2} + \eta_k[n] = X_k[n] [g_k[m] \cdot h_k[m] * f_k[m]]_{\downarrow M/2} + \eta_k[n] \\
 &= X_k[n] \cdot h_k[n] + \eta_k[n] = \hat{X}_k[n]
 \end{aligned} \tag{15}$$

Where $\hat{X}_k[n]$ represents the Analysis filter output in (15). $\eta_k[n]$ is a Gaussian noise with variance σ_η^2 . After multiplication by Analysis filter output $\hat{X}_k[n]$ with the inverse phase component $\theta_k^*[n]$ that is followed by the operation of taking the real part. After the operation through Real to Complex block (OQAM post-processing) the successive real valued symbols form a complex valued received signal $\hat{C}_k[l]$ [19].

2.3. Theoretical Analysis of OFDM and FBMC

To map the input bits into the QAM symbols, it is possible to obtain an exact closed-form result for the average bit error probability for arbitrary M [21],

$$p_b(E) \cong 4 \left(\frac{\sqrt{M}-1}{\sqrt{M}} \right) \left(\frac{1}{\log_2 M} \right) Q \left(\sqrt{\frac{3E_b \log_2 M}{N_0(M-1)}} \right) \tag{16}$$

Eq. (16) gives the concept about Q factor. Then, the noise power N_0 for both QAM and OQAM demodulators are derived in [22]. So, as a result, single error equation will be using both QAM and OQAM systems in OFDM and FBMC respectively. Under AWGN channel BER expression of 16 QAM is the same for both multicarrier systems shown in Equation 17

$$p_b(E) \cong \left(\frac{\sqrt{M}-1}{\sqrt{M}} \right) \left(\frac{1}{\log_2 \sqrt{M}} \right) \operatorname{erfc} \left(\sqrt{\frac{3 \log_2 M}{2(M-1)} \frac{E_b}{N_0}} \right) \tag{17}$$

And the expression of BER of 16 QAM for OFDM and FBMC system under Rayleigh channel is [22],

$$p_b(E) \cong \left(\frac{2}{\log_2 M} \right) \left(\frac{\sqrt{M}-1}{\sqrt{M}} \right) \left[1 - \sqrt{\frac{1.5\gamma_s}{(M-1)+1.5\gamma_s}} \right] - \left(\frac{\sqrt{M}-1}{\sqrt{M}} \right)^2 \left[1 - \sqrt{\frac{1.5\gamma_s}{(M-1)+1.5\gamma_s}} \right] \left(\frac{4}{\pi} \tan^{-1} \sqrt{\frac{M-1+1.5\gamma_s}{(1.5\gamma_s)}} \right) \tag{18}$$

Where $\gamma_s = \gamma \log_2 M$ denotes the average SNR per symbol.

2.4. PAPR Reduction with Clipping Technique

The PAPR (Peak to Average Power Ratio) is a critical issue in any multicarrier transmission scheme due to their fluctuated envelop. This PAPR caused after IFFT operation where data symbols across sum up to produce high peak value. At this point of view, multicarrier schemes such as OFDM and FBMC are known to be having high PAPRs which is responsible to degrade the performance [10]. The PAPR can be defined for the continuous time signal as

$$\text{PAPR} = \chi = \frac{P_{peak}}{P_{average}} = \frac{\max |x(t)|^2}{E|x(t)|^2} \tag{19}$$

Eq. (19) presents P_{peak} as peak value and $P_{average}$ as average output power. E denotes the expected value. PAPR increases when the subcarriers of a system increase. To find out the PAPR value, is to execute the probability that PAPR exceeds a certain threshold χ_0 . Complementary Cumulative Distribution Function (CCDF) of χ for N subcarriers follow Exponential distribution is given by [10],

$$\text{CCDF}(\chi) = \text{prob}(\chi' > \chi_0) = 1 - 1(1 - e^{-\chi_0})^N \tag{20}$$

One of the simplest technique known as clipping which is used to clip the parts of the signals that have high peak outside of the selected value. The calculation for clipping is given below

$$Y(t) = \begin{cases} -L & \text{if } x(t) < -L \\ x(t) & \text{if } -L \leq x(t) \leq L \\ L & \text{if } x(t) > L \end{cases} \quad (21)$$

Where $Y(t)$ represents the pass-band clipped signal, L is pre-defined level to clip and $x(t)$ is the pass-band signal.

2.5. Architecture of OFDM and FBMC Systems in MIMO

In wireless communication system, multiple fading effect could be resolvable by using space or antenna diversity where multiple antennas used in transmitter and receiver also [23]. Diversity allows struggling with fading by sending same data across the independent channel. This could reduce the amount of fade suffered by every data copy by sending multiple copies of a data on independently fading channels. This procedure will enhance the chance to get the approximately same data as transmitted.

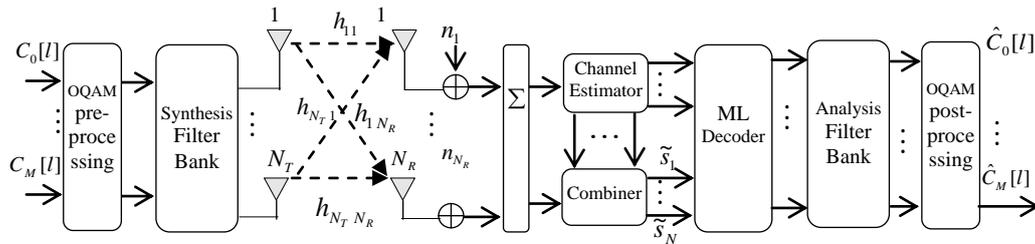


Fig.3. MIMO architecture for the MIMO-FBMC/MIMO-OFDM system [13, 27].

For MIMO-OFDM system the structure of Fig. 3 is analogous of MIMO-FBMC but replacing the OQAM preprocessing and Synthesis Filter Banks block by a combination of an IFFT and CP addition blocks. In the receiver, the reverse environment is created for MIMO-OFDM that means a concatenation of an FFT and removes CP blocks [13, 24].

Multi-Input Multi-Output (MIMO) combined fairly with FBMC and OFDM. Particularly, the signals coming from the transmitter section are synchronized with frequency and time. Each antenna is connected to transmitter output section and each output is fed to the MIMO decoder. MIMO system with k subcarriers consists of N_T antennas at the transmitter and N_R antennas at the receiver. The transmitter consists of parallel stream at each carrier k . All outputs for the same antenna are added and connected to the corresponding antenna. Transmit and Receive space or antenna diversity has been familiar in microwave wireless communications.

In receive diversity, multiple antennas are used in receiver side. Receive diversity is generalized by the number of independent fading branches and the branches is as same as the receive antennas [23]. Maximal Ratio Combining (MRC) system is one of the example of receive diversity. Consider a receive diversity system using N_R receiver antennas. For, single input multiple output (SIMO) the channel is

$$h = [h_1 \ h_2 \ \dots \ h_{N_R}]^T \quad (22)$$

Where $1, 2, \dots, N_R$ are independent Rayleigh fading channel. Let, the transmitted signal is expressed as $Y[m]$ from (7). Then the received signal $r[m]$ is,

$$r[m] = \sqrt{\frac{E_x}{N_0}} h Y[m] + z[m] \quad (23)$$

Where $z[m]$ represents the noise. N_R branches are accumulated by the following weighted sum and the combined signal [25],

$$y_{MRC} = \sum_{k=1}^{N_R} r_k[m] w_k^{(MRC)} = w_{MRC}^T \left(\sqrt{\frac{E_x}{N_0}} h Y[m] + z[m] \right) \quad (24)$$

Where w_{MRC} is the weight vector.

Diversity gain can also be accomplished by space-time coding (STC) at the transmitter side, for decoding in the receiver side need only simple linear processing. Transmit diversity is applicable to channels with multiple transmit antennas and it is equivalent to the number of the transmit antennas, especially if the transmit antennas are placed

sufficiently apart from each other. Information is processed at the transmitter and after that it spread across the multiple antennas

2.5.1 Implementing OFDM in Alamouti Coding Scheme

Alamouti scheme is the fundamental part of the Space-time block code (STBC). Here the mathematical part for two transmitting antenna and one receiving antenna is implemented and it can be generalized by using receiver side antenna size M to make the diversity $2M$. Considering for OFDM, 600 subcarriers and 100 symbols, after 16QAM modulation the complex data streams transmitted in 2 parallel paths. First 6 rows and last 5 rows include zero padding and 1 row in middle includes Pilot data make 612 rows. After IFFT operation and adding 16 cyclic data, the transmitter sends x_1 from antenna one and x_2 from antenna two at first time slot. At 2nd time slot, it transmits $-x_2^*$ and x_1^* from one and two antennas respectively. Assuming the fading is constant for two consecutive symbols duration where α_i , θ_i amplitude gain and phase rotation respectively, n_0 and n_1 are the additive noise at time t and $(t+T)$. The received signals are at time t and $(t+T)$ are,

$$\begin{aligned} r_1 &= r(t) = x_1 h_1 + x_2 h_2 + n_1 \\ r_2 &= r(t+T) = -x_2^* h_1 + x_1^* h_2 + n_2 \end{aligned} \quad (25)$$

r_1 and r_2 are the received signals and the channel gains $h_i(t) = \alpha_i e^{j\theta_i}$ are defined by (25). When the channel coefficients are estimated perfectly at the receiver then decoder uses them as channel state information. The signal combiner at the receiver side combines the received signal as

$$\begin{aligned} \tilde{s}_1 &= h_1^* r_1 + h_2 r_2^* = (\alpha_1^2 + \alpha_2^2) x_1 + h_1^* n_1 + h_2 n_2^* \\ \tilde{s}_2 &= h_2^* r_1 - h_1 r_2^* = (\alpha_1^2 + \alpha_2^2) x_2 - h_1 n_2^* + h_2^* n_1 \end{aligned} \quad (26)$$

Where \tilde{s}_1 and \tilde{s}_2 are two decisions statistics which are constructed by combining the received signal with coefficients derived from the channel state information.

$$d^2(r_1, h_1 x_1 + h_2 x_2) + d^2(r_2, -h_1 x_2^* + h_2 x_1^*) = |r_1 - h_1 x_1 - h_2 x_2|^2 + |r_2 + h_1 x_2^* - h_2 x_1^*|^2 \quad (27)$$

Using Equation 24 ML decides the signals (\hat{s}_1 and \hat{s}_2) from the signal modulation constellation that minimizes the decision metric [25]. Then the noisy signals are sent to the Maximum Likelihood (ML) detector and detecting rule can be separated two decoding signals

$$\hat{s}_1 = \arg \min_{(\tilde{s}_1 \in S)} d^2(\tilde{s}_1, x_1) \text{ and } \hat{s}_2 = \arg \min_{(\tilde{s}_2 \in S)} d^2(\tilde{s}_2, x_2) \quad (28)$$

Determine the minimum distance from the modulation constellation points to the received signal and create the matrix through (28). Then received signal is reversely demodulated by OFDM demodulator where discard the CP and pilot data and converted to frequency domain by FFT operation. Finally demodulated bit stream is compared to the input bit streams and find out BER with respect to input data.

2.5.2 Implementing FBMC in Generalized STBC Scheme

When $N_T \geq 3$ For 3 and 4 orthogonal designs, there are 3 and 4 transmission antennas and 8 time slots are required to transmit [26]

$$X_{4, \text{complex}} = \begin{bmatrix} x_1 & -x_2 & -x_3 & -x_4 & x_1^* & -x_2^* & -x_3^* & -x_4^* \\ x_2 & x_1 & x_4 & -x_3 & x_2^* & x_1^* & x_4^* & -x_3^* \\ x_3 & -x_4 & x_1 & x_2 & x_3^* & -x_4^* & x_1^* & x_2^* \\ x_4 & x_3 & -x_2 & x_1 & x_4^* & x_3^* & -x_2^* & x_1^* \end{bmatrix} \quad (29)$$

In Fig. 4 FBMC transmitter transmits the signal as described in equation 7 for 100 symbols. Next, to segregate the symbols as matrix $[T_{x_1} \ T_{x_2} \ T_{x_3} \ T_{x_4}]$ and then pass it through transmit antenna. After that one receive antenna which use

eight different time slots to receive the signals. $[n_1 n_2 \dots n_8]$ are Additive White Gaussian noise added in the received signals.

$$\begin{aligned}
 r_1 &= \sum_{k=1}^4 h_k x_k + n_1 & r_2 &= -h_1 x_2 + h_2 x_1 - h_3 x_4 + h_4 x_3 + n_2 \\
 r_3 &= -h_1 x_3 + h_2 x_4 + h_3 x_1 - h_4 x_2 + n_3 & r_4 &= -h_1 x_4 - h_2 x_3 + h_3 x_2 + h_4 x_1 + n_4 \\
 r_5 &= \sum_{k=1}^4 h_k x_k^* + n_5 & r_6 &= -h_1 x_2^* + h_2 x_1^* - h_3 x_4^* + h_4 x_3^* + n_6 \\
 r_7 &= -h_1 x_3^* + h_2 x_4^* + h_3 x_1^* - h_4 x_2^* + n_7 & r_8 &= -h_1 x_4^* - h_2 x_3^* + h_3 x_2^* + h_4 x_1^* + n_8
 \end{aligned} \tag{30}$$

Where the channel coefficients are h_1, h_2, h_3 and h_4 respectively. Estimating and combining the signals, the output becomes $\tilde{s}_1, \tilde{s}_2, \tilde{s}_3, \tilde{s}_4$ which are the inputs of the ML detector. ML detector produce $[X_d]$ for $[T_{x_1} T_{x_2} T_{x_3} T_{x_4}]$.

The combining output becomes,

$$\begin{aligned}
 \tilde{s}_1 &= \sum_{m=1}^M \{r_{1,m} h_{1,m}^* + r_{2,m} h_{2,m}^* + r_{3,m} h_{3,m}^* + r_{4,m} h_{4,m}^* + r_{5,m}^* h_{1,m} + r_{6,m}^* h_{2,m} + r_{7,m}^* h_{3,m} + r_{8,m}^* h_{4,m}\} \\
 \tilde{s}_2 &= \sum_{m=1}^M \{r_{1,m} h_{2,m}^* - r_{2,m} h_{1,m}^* + r_{4,m} h_{3,m}^* - r_{3,m} h_{4,m}^* + r_{5,m}^* h_{2,m} - r_{6,m}^* h_{1,m} + r_{8,m}^* h_{3,m} - r_{7,m}^* h_{4,m}\} \\
 \tilde{s}_3 &= \sum_{m=1}^M \{r_{1,m} h_{3,m}^* - r_{3,m} h_{1,m}^* - r_{4,m} h_{2,m}^* + r_{2,m} h_{4,m}^* + r_{5,m}^* h_{3,m} - r_{7,m}^* h_{1,m} - r_{8,m}^* h_{2,m} + r_{6,m}^* h_{4,m}\} \\
 \tilde{s}_4 &= \sum_{m=1}^M \{-r_{1,m} h_{4,m}^* - r_{2,m} h_{3,m}^* + r_{3,m} h_{2,m}^* - r_{4,m} h_{1,m}^* - r_{5,m}^* h_{4,m} - r_{6,m}^* h_{3,m} + r_{7,m}^* h_{2,m} - r_{8,m}^* h_{1,m}\}
 \end{aligned} \tag{31}$$

Where M indicates the receiving antennas which use MRC scheme for receiving diversity. ML decoder used as channel estimator whose output $[X_d]$ to create the matrix which is the input of FBMC receiver.

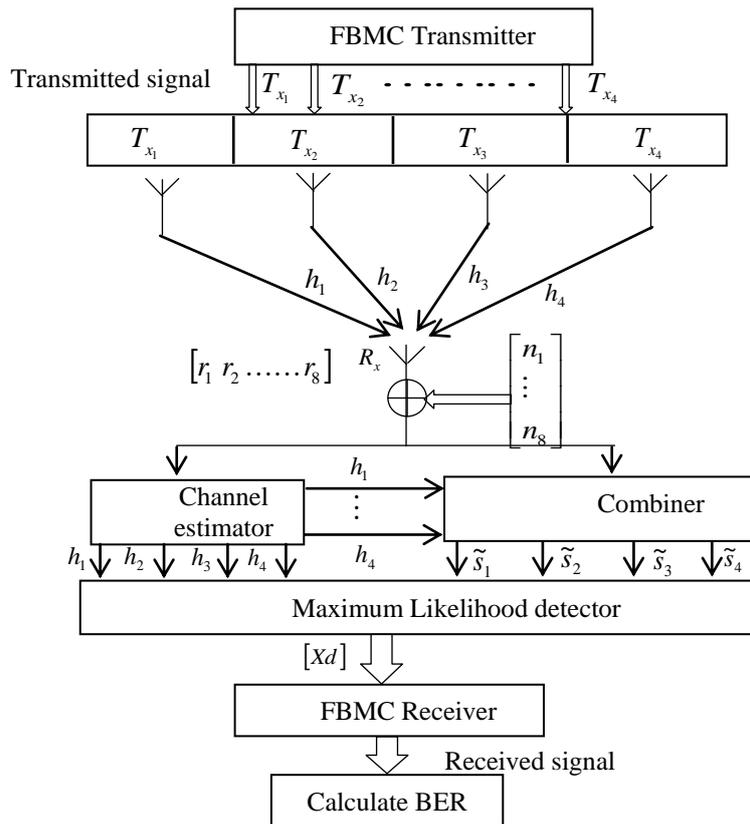


Fig.4. Architecture of STBC-FBMC.

As a result, FBMC receiver demodulated the signal which is known as the received signal and calculate BER with respect to the transmitted signal. But for $N_T = 3$ orthogonal design, (30) and (31) are same only the channel coefficient $h_4 = 0$ and (29) will have only 3 rows for 3 transmitters.

3. Simulation Results

The system analyzed that has been simulated in MATLAB using the version MATLAB R2018a. At first, the simulation is shown to compare the theoretical and empirical results of OFDM and FBMC over AWGN and Rayleigh channels in terms of BER response. Secondly, the response of PAPR reduction technique using clipping is shown for both systems. After that the BER results under different diversity schemes are portrayed. To create an empirical environment using software, the basic parameters are declared as per table 1.

Table 1. parameters for both OFDM and FBMC

PARAMETERS	OFDM/FBMC
No. of symbols	1000
Data subcarriers	600
Modulation type	16QAM
SNR range	0-30
Channel	AWGN, Rayleigh fading
Cyclic Prefix and Pilot data	for OFDM (16 and 12)
Overlapping factor	for FBMC ($K = 4$)
DIVERSITY SCHEME	
No. of symbols	100
MRC	$[1 \times 2, 1 \times 4, 1 \times 8]$
ALAMOUTI	$[2 \times 1, 2 \times 2]$
STBC	$[3 \times 1, 3 \times 4, 4 \times 4]$

Fig. 5 portrays the simulation results of OFDM and FBMC under both AWGN and Rayleigh fading channel which is compared in terms of BER performance. It is clear from Fig. 5(a) that at 12 dB under AWGN channel, BER performance of FBMC shows the best response compared to OFDM technique. In this case, simulations are done using 16 QAM modulation technique with theoretical BER equation and simulation environment for both systems. Here, the performance degradation is 2dB for OFDM because of using CP to maintain the subcarriers orthogonality. Fig. 5(b) depicts the same perspective for OFDM and FBMC over Rayleigh channel scenario. It is narrated from the performance of Figure 5(b) that BER values of $\sim 2 \times 10^{-4}$, 5×10^{-4} and $\sim 6 \times 10^{-4}$ are achieved for FBMC, OFDM in simulation and 16 QAM in theoretical environment under Rayleigh fading channel at the SNR value of nearby 30 dB respectively. The overall performance over Rayleigh fading channel is lower than over AWGN channel because the signals are affected by multipath scattering which present in transmission medium.

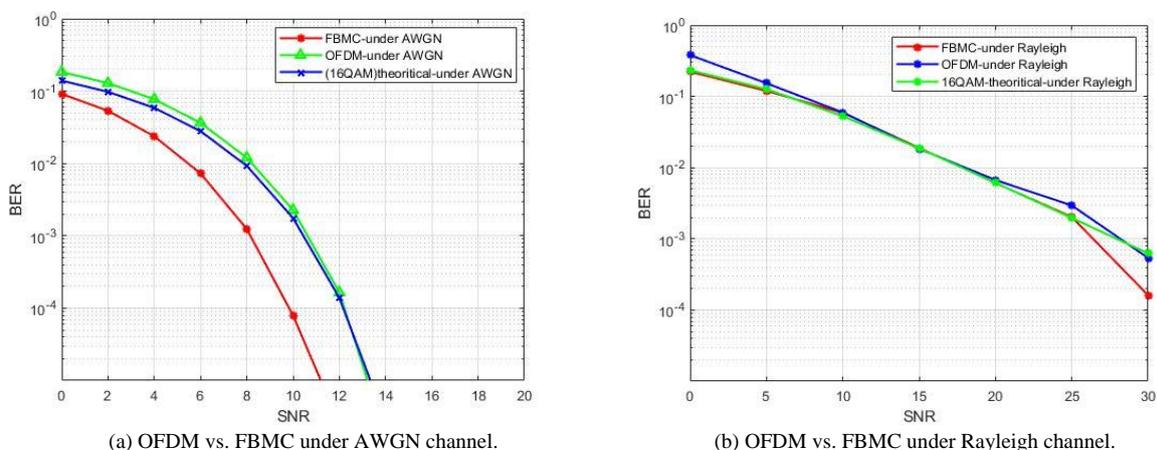


Fig.5. BER under AWGN and Rayleigh channel

Fig. 6 illustrates PAPR performance comparison of OFDM and FBMC in terms of CCDF before and after applying clipping and filtering technique. The curves are evidently decline for OFDM and FBMC signals after clipping. From the outcomes, it is clear that reduction in PAPR performance is achievable by applying clipping ratio as 0.4 and same IFFT points. The PAPR is 11 dB for the clipped OFDM signal at CCDF of 0.2 whereas FBMC signal shows approximately 10.5 dB after applying this algorithm for the same values of CCDF. Aspect all values of FBMC leads OFDM PAPR performance with and without applying clipping technique.

Fig. 7 represents BER vs. SNR curves are plotted using MRC diversity schemes where transmit antenna $N_T = 1$ and receive antennas N_R are 2, 4 and 8 respectively. The simulation environment is created with the help of 16 QAM modulation under AWGN channel for 100 symbols and 600 subcarriers for both OFDM and FBMC systems. It can be visualized from Fig. 7 that BER keeps on decreasing trend when the number of receiving antennas is increased. Consequently, for FBMC it is depicted that to maintain BER at 10^{-3} , MRC (1×2), MRC (1×4) and MRC (1×8) configurations should have to keep SNR values approximately at 34.5dB, 31dB and 28.8dB respectively whereas OFDM need 39.8dB, 35.5dB and 32dB. For this comparison it is clearly said that OFDM system discloses worse results compare to FBMC system.

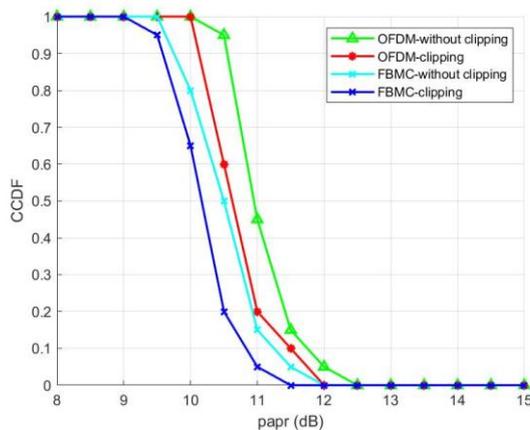


Fig.6. Comparison of PAPR reduction technique.

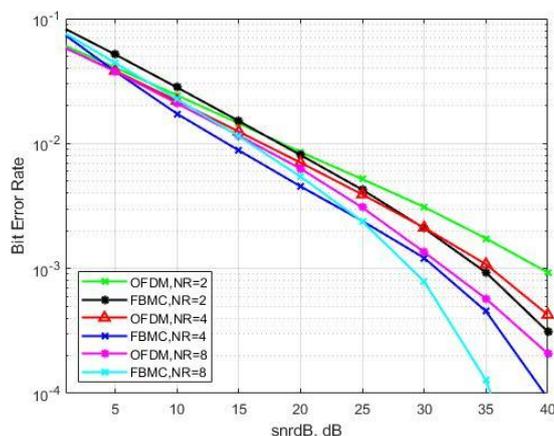


Fig.7. MRC for both OFDM and FBMC.

In Fig. 8 simulations have been accomplished in terms of BER versus SNR for SNR for Alamouti’s scheme with $N_T = 2$ and $N_R = 1, 2$ under the same parameters for OFDM and FBMC as mentioned in MRC. As a result, the BER performance of (2×2) Alamouti’s scheme of diversity order 4, is much better than (2×1) of diversity order 3 for both FBMC and OFDM systems. From Fig. 8 it can be clearly observed that FBMC system for (2×2) antennas shows the best performance which has minimum BER - 10^{-4} at 36dB, at the same time OFDM system for (2×1) antennas discloses the worst performance. For instance, it is pointed out from simulation results that FBMC (2×1) configuration shows a BER improvement of 5×10^{-4} and 2×10^{-4} compare to OFDM (2×1) and OFDM (2×2) configurations respectively.

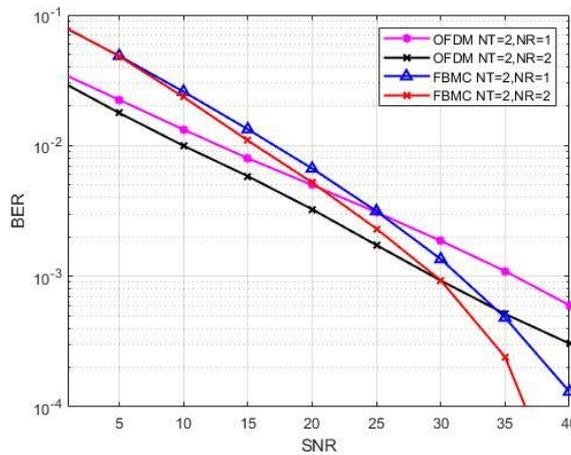


Fig.8. Alamouti for OFDM and FBMC.

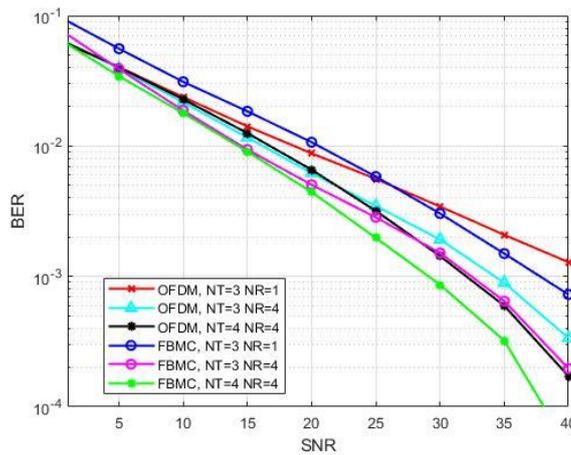


Fig.9. Generalized STBC for OFDM and FBMC.

The BER vs. SNR with (3×4) antenna arrangements for both OFDM and FBMC systems are shown in Fig. 9. It is clearly found from the results that any system performs best in (4×4) antenna configuration among in (3×1) and (3×4) MIMO system. So, it can be noticed that the slope goes on gradually deescalating with enhancing number of transmit antennas for STBC. Using the simulated data, to achieve in low SNR values to have BER performance of 10^{-4} , need to increase the number of antennas not only in transmitter section but also in receiver section considerably. At 10 dB, if FBMC system (3×1) requires BER of 0.0179 there need to add extra one transmitter and 3 receiver antennas. OFDM BER is observed to drop almost 3×10^{-4} for (3×4) and 2×10^{-4} for (4×4) whereas FBMC leads OFDM in order of BER at 8×10^{-4} , 10^{-4} and 2×10^{-4} respectively for all antenna configurations.

4. Conclusion

This paper presents a comprehensive resolution of new multicarrier modulation technique FBMC which evolved from OFDM system. The various kinds of simulations are performed where FBMC using the filter banks instead of cyclic prefix, outclasses OFDM in terms of every investigation. 16 QAM analytical BER expressions under AWGN and Rayleigh fading channel are derived and show OFDM performance nearby theoretical analysis than FBMC performance. The more remarkable characteristics of any multicarrier system, is PAPR and its reduction technique results show OFDM's degradation attitude than satisfactory results of FBMC's performance. Furthermore, this paper also reveals expansive analysis of OFDM and FBMC systems with MIMO under AWGN channel using different antenna configurations and diversity schemes (such as MRC, Alamouti and STBC). The goal of this paper was to find out optimum waveform candidate for 5G wireless communication and it is clear that MIMO-FBMC system provides SNR improvement with minimum BER as compare to MIMO-OFDM. Thanks to save CP which makes it an auspicious candidate for 5G wireless communication. As it is mentioned earlier that due to the multiple limitations of FBMC, there

are other upgraded techniques such as UFMC, GFDM those are suitable for 5G communications. Authors have left these comparisons between FBMC, UFMC and GFDM in their future works.

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