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	Sunil Chinnadurai, Poongundran Selvaprabhu, Yong-Chae Jeong, Moon Ho Lee Division of Electronics & Information Engineering, Chonbuk National University, Korea
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	Jung Song Lee1, Soon Cheol Park2,3 1Division of Electronics and Information Engineering, Chonbuk National University, Korea, 2Division of Electronics and Information Engineering, Chonbuk National University, Korea 3Center for Intangible Culture in Chonbuk National University, Korea
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BER Performance of Windows Cyclic Prefix-COQAM scheme for AWGN and Rayleigh Channel

Sunil Chinnadurai, Poongundran Selvaprabhu, Yong-Chae Jeong, Moon Ho Lee*

Division of Electronics & Information Engineering,
Chonbuk National University, 664-14Ga,
Jeonju-si, Jeollabuk-do 561-756, Republic of Korea
Email: sunilkcsss@gmail.com

Abstract— **Filter bank multicarrier - offset quadrature amplitude modulation (FBMC-OQAM) has recently engrossed a lot of research interest and also being considered as an alternative to orthogonal frequency division multiplexing (OFDM) due to its bandwidth and high spectral efficiency. Filter bank multi carrier with circular offset quadrature amplitude modulation (FBMC-COQAM) is a multicarrier modulation scheme with smart features that address the necessities of evolving applications of high speed wireless communication systems like massive MIMO. Multi carrier modulation (MCM) schemes such as FBMC/OQAM and generalized frequency division multiplexing (GFDM) have certain drawbacks such as less robustness against frequency selective fading channels and non-orthogonality respectively. An advanced multicarrier modulation scheme such as windowed cyclic prefix - FBMC/COQAM (WCP-COQAM) scheme was introduced to overcome the above problems. In this paper, we introduce an analytical study of windows cyclic prefix FBMC-COQAM system on the performance of the bit error rate (BER) of various channel equalization schemes to reduce the system receiver complexity. Simulation results exemplifies the efficiency of the various channel equalization schemes of WCP-COQAM system. Simulation results are compared in terms of BER for both the additive white Gaussian noise (AWGN) channel and Rayleigh multipath fading channel.**

Keywords— FBMC; windows - cyclic prefix; OFDM; Bit error rate; FBMC/COQAM; massive MIMO; GFDM; WCP-COQAM; Channel equalization; Rayleigh channel; AWGN channel.

I. INTRODUCTION

OFDM is the physical layer transmission technology embraced in existing broadband communication systems such as wireless local area networks (WLAN), world-wide interoperability for microwave access (WiMAX), long term evolution (LTE), digital video broadcasting (DVB) and digital audio broadcasting (DAB) [1,2]. But in recent times, there is a plenty of research and development on filter bank multi carrier (FBMC) modulation system since it can provide higher data rate, good spectral shaping of the subcarriers and better out of band radiation than the orthogonal frequency division multiplexing (OFDM) system. Both OFDM and FBMC system are implemented using inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) pairs in the modulator and demodulator respectively [13]. FBMC is a multicarrier modulation scheme where the modulated signal on each sub carrier is shaped by a well-designed prototype filter designed using Nyquist pulse shaping principle which can significantly reduce the spectral leakage problem of OFDM [3]. The main aim of FBMC modulation system is to convert a sequence of data symbols at high rate into a number of sub sequences at lower rate [4]. Discrete wavelet multitone, filtered multitone, cosine modulated multitone, modified discrete Fourier transform, exponentially modulated filter bank and FBMC/OQAM are some of the existing filter bank multi carrier structures [13]. FBMC/OQAM is the most prevalent filter bank scheme and it is the combination of filter banks and offset quadrature amplitude modulation. FBMC/OQAM scheme splits the complex data symbols into their real and imaginary parts. Offset quadrature amplitude modulation (OQAM) is used in FBMC to make sure that only real symbols are fed into the filter bank. Moreover, FBMC/OQAM scheme presents the half symbol space delay (offset) between the real and imaginary components of quadrature amplitude modulated (QAM) symbols [6]. The above mentioned multicarrier modulation schemes are very cooperative for the application of massive MIMO networks. Massive MIMO is an emerging technology that helps to increase the capacity of the multiuser networks. The processing gain in massive MIMO can be achieved by placing the massive number of antenna elements at the base station. Spreading gains of different users are determined by the corresponding channel gains between the mobile terminal (MT) antenna and base station (BS) antenna [7]. Massive MIMO reduces the system complexity and noise since it has larger number of antennas than the number of users [8]. In this paper, we mainly consider AWGN and Rayleigh fading multipath channel since these noises and fading cause huge data loss and inter symbol interference to the massive MIMO network. Inter symbol interference (ISI) plays a major role in deciding the error performance of any communication system. Increase of ISI degrades the error performance of the communication system. There are two vital methods to cancel the inter symbol interference. The first method is to design the band limited transmission pulses and the other one is called as equalization which filters the received signal to cancel the ISI [10]. This paper mainly concentrates on the second method to improve the bit error rate performance of the communication system. AWGN channel and Rayleigh multipath channel are used for implementing the efficient channel equalization techniques on windows cyclic prefix - circular offset quadrature amplitude modulation (WCP-COQAM) system.

II. WCP – COQAM scheme:

A combination of FBMC/OQAM scheme and the generalized frequency division multiplexing (GFDM) scheme is called filter bank multi carrier- circular offset quadrature amplitude modulation system. FBMC/COQAM overcomes the drawbacks of previous multicarrier modulation (MCM) schemes while still preserving their advantages [12]. The key idea of FBMC-COQAM is to replace the linear convolution inherited in offset quadrature amplitude modulation (OQAM) with a circular convolution used in the general frequency division multiplexing (GFDM) scheme. The difference between the FBMC/COQAM and WCP-COQAM is explained as follows. A cyclic prefix is introduced to cancel the inter block interference as well as to maintain the perfect orthogonality after the desired signal is transmitted through a multipath channel. Windowing (Hamming) is applied after the insertion of cyclic prefix (CP) in order to prevent a change in the power spectral density which in turn avoids the spectral leakage that occurs due to block processing. Windowing does not ruin orthogonality as well as the spectral efficiency. The transmission system occurred from the result of the above two operations is called as windowed cyclic prefix-FBMC/COQAM (WCP - COQAM). Remaining operations of WCP-COQAM are same as the FBMC/OQAM and GFDM scheme as mentioned in the previous section. The transmitter structure of WCP-COQAM scheme is given in Figure 1.

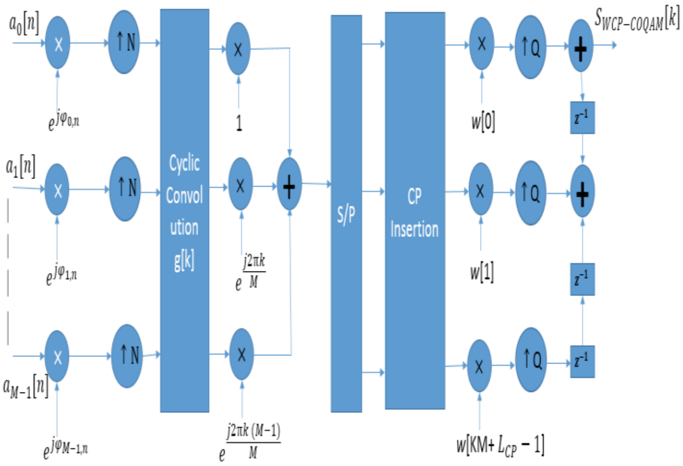

Figure 1: Block Diagram of WCP-COQAM system

The baseband modulated signal of WCP-COQAM is given as

$$S_{WCP-COQAM}[k] = \sum_{r=l-1}^{l+1} S_{COQAM}[mod(k - L_{CP}, KM)] * w\,[\mathrm{k} - \mathrm{r}\,(\mathrm{KM} + L_{GI})] \quad (1)$$

Where k=0,…..,KM + L_{CP} − 1 and S_{COQAM} is the baseband modulated signal for circular offset quadrature amplitude modulation and it is expressed as

$$S_{COQAM}[k] = \sum_{m=0}^{M-1} \sum_{n=0}^{K-1} a_m[n]\tilde{g}[k - nN]e^{\frac{j2\pi}{M}m(k-\frac{D}{2})}\, e^{j\varphi_{m,n}} \quad (2)$$

Equation 1 can be simplified as

$$S_{WCP-COQAM}[k] = \sum_{r=l-1}^{l+1} S_{COQAM}[mod(k - L_{CP}, KM)] * w\,[\mathrm{k} - \mathrm{r\,T}]$$

Where T= KM + L_{GI} (L_{GI} is length of the guard interval). Pulse shaping filter is introduced in WCP-COQAM like GFDM to implement the circular convolution with a prototype filter which is given as $\tilde{g}[k] = g[mod(k, MK)]$ and this prototype filter satisfies the orthogonality condition. Window function w [n] is computed as follows

$$w\,[\mathrm{k}] = \begin{cases} window\ coefficients & k \in [0, L_{RI} - 1] \\ 1 & k \in [L_{RI}, KM + L_{GI} - 1] \\ w[KM + L_{CP} - 1 - k] & otherwise \end{cases} \quad (3)$$

III. CHANNEL EQUALIZATION SCHEMES

The transmit signal x[k] is achieved through the superposition of all subcarriers with complex valued data symbols ($a_m[n]$) is given as

$$x[k] = \sum_{r=l-1}^{l+1} \sum_{m=0}^{M-1} \sum_{n=0}^{K-1} a_m[n]\tilde{g}[(k - L_{CP}) - nN]e^{\frac{j2\pi}{M}m\left(k-\frac{D}{2}\right)}\, e^{j\varphi_{m,n}} * w\,[\mathrm{k} - \mathrm{r\,T}] \quad (4)$$

The data symbols can be reconstructed as

$$\hat{a}_m[n] = (y[n]\, e^{-\frac{j2\pi}{M}m\left(k-\frac{D}{2}\right)}\, e^{-j\varphi_{m,n}} \circledast \tilde{g}\,[n]\,) \quad (5)$$

Where $\circledast$ denotes circular convolution. The data symbols($a_m[n]$) are reshaped by a serial to parallel converter to a matrix (Y) and up sampled (S_N^M) in order to shift the data to the individual subcarrier frequencies which is given in equations 11 and 12 respectively

$$Y = \{a_m[n]\}_{M\,X\,K} \quad (6)$$

$$S_N^M = \{s_{n,m}\}_{MN\,X\,M} \quad (7)$$

Now we apply the pulse shaping filter and also the up conversion of the sub carriers is done by $W = \frac{1}{\sqrt{MN}}\{w^{k,n}\}_{MN\,X\,MN}$. The estimation of the transmitted signal vector is expressed as given below by putting all the above steps together as

$$\hat{X} = \mathrm{A} \,.\, \mathrm{y} \quad (8)$$

Where y is the received data signal vector and A is an $MN\ X\ MN$ complex value modulated matrix which is derived as

$$A = diag(G\, S_N^M\, Y\, W^H) \tag{9}$$

WCP-COQAM system requires different equalization schemes to minimize the Inter symbol interference (ISI) from the neighboring symbols. The various channel equalization schemes are described below.

A. Zero Forcing Equalizer (ZFE):

Zero forcing is the simplest method used for channel equalization in the frequency domain and the main aim is to force the inter symbol interference component at the equalizer to zero. ZFE is good only when the channel is noise free. Assuming the noise is zero, we can estimate the transmitted complex constellation value on the nth subcarrier as follows

$$\hat{X}^{ZF} = \frac{y}{A} \tag{10}$$

But the main drawback of zero forcing equalization is that the noise power gets enhanced where the channel response has very small magnitude. Hence the error performance of the receiver will still be poor.

B. Match Filter Equalizer (MFE):

Zero forcing equalizer removes ISI to certain extent but still does not give the best error performance for the communication system. The major weakness for zero forcing equalizer is its inheritance to the possible noise amplification. Match filter equalizer addresses the above problem and increases the power gain at the desired symbols direction but it does not pay any attention to the existence of further symbols from other directions [11]. Match filter is applied to each subcarrier separately to receive the estimation of the originally transmitted signal of WCP-COQAM system. The estimation of the matched filter is given below as

$$\hat{X}^{MF} = \frac{y}{\hat{A}^{MF}} \tag{11}$$

Where $\hat{A}^{MF} = \frac{1}{A^*}$. Matched filter suffers strong interference from other symbols since it cannot cancel the interference caused by the neighboring symbols. Thus more advanced equalizer is needed.

C. Minimum Mean Square Error (MMSE):

MMSE is based on the mean square error (MSE) criterion. Minimum mean square error minimizes the power associated with the noise and ISI components present in the output. MMSE also reduces the mean square error between the original information symbols and the output of the equalizer. Minimum mean square error confirms that there is an ideal tradeoff between residual inter symbol interference (ISI) and noise enhancement. Channel equalization is performed at the observation window which has to be moved by Δ_n samples and the channel impulse response.

The equalization coefficient for the k^{th} subcarrier is expressed as

$$\frac{1}{\hat{A}^{MMSE}} = \frac{A^*}{|A|^2 + \frac{N_0 + I}{E_s - I}} \; . \tag{12}$$

Where N_0 is noise power and E_s is the signal power. Minimum mean square error (MMSE) estimate of subcarrier is given as

$$\hat{X}^{MMSE} = \frac{Y}{\hat{A}^{MMSE}} \tag{13}$$

Therefore, signal to noise ratio at the output of the MMSE equalizer achieves better than the output of the zero forcing and matched filter equalizer.

D. Improved Minimum Mean Square Error (IMMSE):

Inter symbol interference can still be reduced by taking average of the all complex modulation values belonging to the same sub carrier. This process is called as improved minimum mean square error. Demodulation and MMSE equalization are performed for each Δ_n positions of all the possible L observation windows to minimize the inter symbol interference. ISI can also be considered as a noise and can be eliminated by averaging the minimum mean square error. The improve MMSE estimate of the subcarrier is given as

$$\hat{X}^{AVG} = \frac{1}{L}\sum_{\Delta_n=0}^{L-1} \hat{X}^{MMSE}(\Delta_n) = \frac{1}{L}\sum_{\Delta_n=0}^{L-1} \frac{y(\Delta_n)}{\hat{A}^{MMSE}(\Delta_n)} \tag{14}$$

IV. SIMULATION RESULTS

Bit error rate (BER) performance of the various channel equalization schemes (zero forcing, matched filter, MMSE, improved MMSE) for windows cyclic prefix – circular offset quadrature amplitude modulation (WCP-COQAM) scheme over the Rayleigh fading channel are plotted using the Matlab is shown in Figure 2. In multipath fading environment like Rayleigh channel there is only a marginal difference in the bit error rate performance of the several equalization schemes. Bit error rate reduces with increase in the signal to noise ratio for all the above channel equalizers of WCP-COQAM scheme. It can be observed that matched filter, MMSE and improved MMSE outperforms zero forcing equalization at higher SNR values (SNR > 10 dB) where as there is not much difference in the performance of BER at lower SNR values (SNR< 10 dB). The improved MMSE equalizer produces the lowest error rates (complexity will be higher) when there are more self-interference in a communication system. Simulation results reveal that improved MMSE shows a better BER performance than the other channel equalization schemes since inter symbol interference can be almost eliminated by taking average of MMSE (IMMSE).

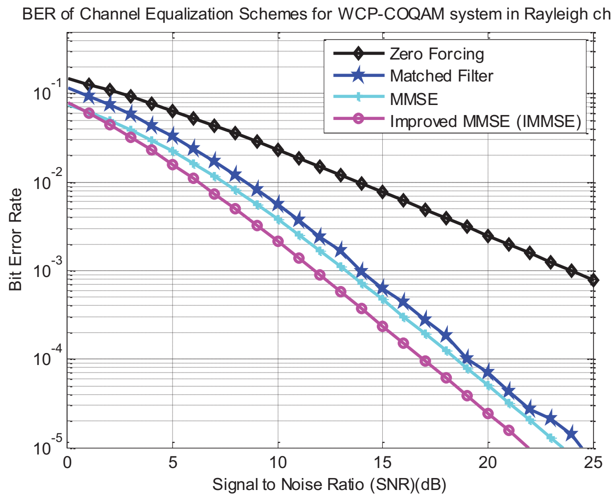

Figure 2: Performance of BER for WCP-COQAM in Rayleigh channel

In the second simulation, the BER results of the four channel equalization schemes for additive white Gaussian noise (AWGN) channel are evaluated for a WCP-COQAM scheme. Simulation results of the second scenario can be seen in figure 3.

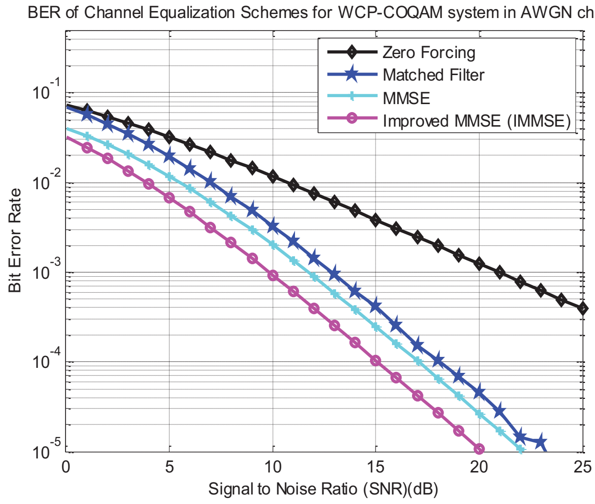

Figure 3: Performance of BER for WCP-COQAM in AWGN channel

V.CONCLUSION

In this paper, simulations have been carried out for both Rayleigh channel and AWGN (additive white Gaussian noise) channel. System performance has been investigated in terms of bit error rate (BER) to reduce the complexity of the receiver system. Simulation results reveals that WCP-COQAM performs better in AWGN channel than Rayleigh fading channel due to the fact that performance of bit error rate in all the equalizers (zero forcing, matched filter, MMSE, IMMSE) using AWGN channel is better than Rayleigh multipath channel. Furthermore, with the help of BER simulation graphs, it is shown that improved minimum mean square error (IMMSE) equalizer gives better performance compared to other three equalizers. IMMSE equalizer can reduce the effect of inter symbol interference in WCP-COQAM scheme. Finally, simulation results also confirms the achievements of WCP-COQAM scheme and further proved its efficiency as a suitable modulation scheme for the application of massive MIMO since it can provide higher data than the other existing multi carrier modulation schemes. In future, the work presented in this paper initiates a new line of research topics such as pilot contamination and carrier frequency offset (CFO) analysis of WCP-COQAM scheme.

ACKNOWLEDGEMENT

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