CFO ESTIMATION USING ADPATIVE MODULATION TECHNIQUES

[1]Ankita Vyas, [2]Brajlata Chourasiya
[1]Research Scholar, [2]Assistant Professor
[1]Communication Systems, GGITS, Jabalpur, [2]Dept. of ECE, GGITS, Jabalpur

ABSTRACT: Orthogonal Frequency Division Multiplexing (OFDM) suffers from severe performance degradation in the presence of carrier frequency offset (CFO). Specifically, frequency offset leads to common phase error (CPE) & become cause of inter carrier interference (ICI), results reduction in the signal to noise ratio (SNR). In OFDM technique, some of the subcarriers undergo a deep fading. Adaptive technique can be used to mitigate the deep fading effect if the channel state information (CSI) is available at the transmitter. Generally, CSI is estimated from the average signal to noise ratio. The performance of adaptive modulation technique relies on the perfect estimation of CSI. But in general the CFO makes the estimated CSI to deviate from the actual CSI. In this paper the effects of CFO, CFO estimation & correction techniques are analyzed. Various adaptive modulation techniques to improve the spectral efficiency are also analyzed. In this paper a CFO correction technique for adaptive modulation has been proposed. In this proposed method CFO is estimated using Maximum Likelihood Estimation (MLE) & it is compensated. It shows that the proposed adaptive modulation scheme maximizes the average spectral efficiency up to 6 bps/Hz for the target BER of 10-3 & up to 8 bps/Hz for the target BER of 10-5. Thus the proposed method maximizes the spectral efficiency with an acceptable BER than direct estimation of CSI.

Keywords: Orthogonal Frequency Division Multiplexing, Carrier Frequency Offset, Inter Carrier Interference, Channel State Information, Bit Error Rate, Maximum likelihood Estimation.

1. Introduction

An important advantage of the Orthogonal Frequency Division Multiplexing (OFDM) communication scheme is that, due to the Inverse Fast Fourier Transform (IFFT) at the transmitter and the Fast Fourier Transform (FFT) at the receiver, the frequency selective fading channel is converted into flat fading channels [1]. However the OFDM approach can suffer from carrier frequency offset. There are two deleterious effects caused by frequency offset, one is degradation of SNR and the second is introducing Inter Carrier Interference (ICI) [2]. The effects of carrier frequency offset has been analyzed quite extensively [3]-[5]. In [4]-[5] symbol error rate (SER) was derived and in [6] the signal to noise ratio degradation due to the CFO have been derived. Because of carrier frequency offset, the orthogonality among OFDM subcarriers are destroyed, it causes the leakage of Discrete Fourier Transform (DFT), and eventually leads to CPE and ICI among subcarriers.

The performance of communication system with one bit per subcarrier CSI feedback is analyzed. The coded transmission case is considered, and the raw bit error rate (BER) is used as the criterion to evaluate the system performance. Assuming that the feedback channel is perfect, adaptive modulation selection (AMS) is used to exploit the CSI feedback and compared the results with non-adaptive modulation (fixed modulations) systems [8]-[10]. Adaptive technique can be applied to mitigate the deep fading effect if the channel state information (CSI) is available at the transmitter. To achieve the performance advantages of adaptive modulation, however, accurate receiver CSI is required at the transmitter. But in wireless communications, the channel is noisy and affected by CFO, the estimated CSI may be invalid. This is the fact behind the need for CFO correction in adaptive modulation.

This paper proposed the adaptive modulation with CFO correction for the OFDM systems. We analyzed the impact of CFO on the performance of AMS for OFDM systems. Although AMS scheme has better performance when the CFO is very low, it behaves worse when the CFO is large. In this proposed method, the CFO is estimated using MLE which is followed by correction of CFO and then estimating the CSI for adaptive modulation selection.

This paper is organized as follows. In section 2, we consider the perfect feedback channel case and present our analysis of the AMS schemes applied to OFDM systems. Section 3 presents the OFDM system model with carrier frequency offset correction. The CFO estimation and correction method is also analyzed. In section 4, we analyzed the spectral efficiency of non-adaptive modulation schemes, adaptive modulation scheme without CFO and adaptive modulation scheme with CFO. Also the expression for the average spectral efficiency of the adaptive modulation with CFO correction has been derived. Section 5 presents the simulation results where the performances of the various AMS schemes are compared for the performance metrics of the average spectral efficiency. Section 6 concludes this paper.

2. Adaptive Modulation Selection

Adaptive modulation is a powerful technique for maximizing the data throughput of subcarriers allocated to a user. Adaptive modulation involves measuring the SNR of each subcarrier in the transmission, then selecting a modulation scheme that will maximize the spectral efficiency, while maintaining an acceptable BER [7]-[10].

The AMS scheme is based on the following idea. When a certain subcarrier is corrupted by fading channels, a constellation with smaller dimension and higher transmitted power can be assigned to this particular carrier, while constellation of large dimensions and less transmitted power can be assigned to the subcarriers whose channel gain is high. A low rate one bit per subcarrier feedback can be used to divide the subcarriers into two groups that use different constellations and transmitted powers. This adaptive modulation has well performed than conventional non-adaptive modulation techniques. The modulation scheme was chosen from the set of Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16-level Quadrature Amplitude Modulation (16-QAM), 64-level Quadrature Amplitude Modulation (64-QAM), as well as "No Transmission," for which no signal was transmitted. Each scheme provides a tradeoff between spectral efficiency and the bit error rate.

The spectral efficiency can be maximized by choosing the highest modulation scheme that will give an acceptable Bit Error Rate (BER). In systems that use a fixed modulation scheme the subcarrier modulation must be designed to provide an acceptable BER under the worst channel conditions. This results in most systems using BPSK or QPSK. However these modulation schemes give a poor spectral efficiency (1-2 b/s/Hz) and results in an excess link margin most of the time. Using adaptive modulation, the remote stations can use a much higher modulation scheme when the radio channel is good. Thus as a remote station approaches the base station, the modulation can be increased from 1 b/s/Hz (BPSK) up to 4-8 b/s/Hz (16-QAM – 256-QAM), significantly increasing the spectral efficiency of the overall system. Using adaptive modulation can effectively control the BER of the transmission, as subcarriers that have a poor SNR can be allocated a low modulation scheme such as BPSK or none at all, rather than causing large amounts of errors with a fixed modulation scheme. This significantly reduces the need for Forward Error Correction.

In order to keep the system complexity low, the modulation scheme is not varied on a subcarrier-by subcarrier basis, but instead the total OFDM bandwidth of total subcarriers is split into blocks of adjacent subcarriers, referred to as subbands, and the same modulation scheme is employed for all subcarriers of the same subband. This substantially simplifies the task of modem mode signaling.

Frequency errors in the transmission due to synchronization errors and Doppler shift result in a loss of orthogonality between the subcarriers. A frequency offset of only 1-2% of the subcarrier spacing results in the effective SNR being limited to 20 dB.

3. OFDM System Model with Carrier Frequency Offset Estimation and Correction

OFDM partitions the incoming data stream into N low rate parallel sub streams, as is shown in the baseband equivalent model of fig.1, which modulate a set of subcarriers using Inverse Discrete Fourier Transform (IDFT) so as to obtain the time domain signals. A cyclic prefix is then added to the time domain signal to eliminate inter symbol interference (ISI) caused by channel multipath fading and enables simple channel equalization at the receiver. The inverse fast Fourier transform (IFFT) is performed on the transmit symbol $X_m(k)$, $k = 0, 1 \ldots, N-1$, to produce the time domain samples $x_m(n)$ of the m-th OFDM symbol [7]:

$$x_m(n) = \begin{cases} \dfrac{1}{N}\sum_{k=0}^{N-1} X_m(k) e^{j2\pi k(n-N_g)/N}, & for\ 0 \le n \le N+N_g-1 \\ 0 & otherwise \end{cases} \quad (1)$$

where N and N_g are the number of data samples and cyclic prefix samples, respectively.

The OFDM symbol $x_m(n)$ is passed through a channel $h_m(n)$ and is affected by Additive white Gaussian noise $W(n)$. When the oscillator of the receiver is perfectly matched to the carrier of the received signal, a carrier frequency offset and a phase offset will not appear. Then the received signal can be represented as follows:

$$\tilde{y}_m[n] = h_m[n] * x_m[n] + w(n) \quad (2)$$

where * is the convolution operator.

The insertion of guard intervals renders the received carriers orthogonal on the N point symbol interval. However the demodulation process, which is implemented with a DFT, is affected by carrier frequency offset. The CFO will appear when the oscillator of the receiver is not perfectly matched to the carrier of the received signal. After removing the cyclic prefix and taking the N point DFT at the receiver, $(k + r)^{th}$ subcarrier signal of the m^{th} symbol can be expressed as [2]

$$\begin{aligned} Y_m(k+r) &= X_m(k)H_m(k)C_m(0) \\ &+ \sum_{\substack{l=1 \\ l\neq 0}}^{N-1} X_m(k-l)H_m(k-l)C_m(l) + Z_m(k+r) \end{aligned} \quad (3)$$

Where

$$C_m(l) = \left\{ \frac{\sin \pi\varepsilon}{N\sin(\pi(l-r+\varepsilon)/N)} \right\} e^{j\pi\varepsilon(N-1)/N} e^{-j\pi(l-r)/N}$$

From equation (3), it can be seen that the received signal is attenuated by the factor $C_m(0) = \dfrac{\sin \pi\varepsilon}{N\sin(\pi\varepsilon/N)}$, where is normalized frequency offset which is defined as = *fNT*. In equation (3) the second term is the ICI caused by the frequency offset. Third term $Z_m(k+r)$ denotes the AWGN noise with zero mean and variance σ^2.

One of the ways of canceling the effect of ICI in OFDM systems is statistically estimating the frequency offset and canceling this offset at the receiver. In this technique, an OFDM symbol stream of N symbols is replicated. These symbols are then modulated using a 2N-point inverse discrete Fourier transform (IDFT). At the receiver, to get the sequence Y_{1k} the first set of N symbols are demodulated using an N-point discrete Fourier transform (DFT), and the second set is demodulated with another N-point DFT to yield the sequence Y_{2k}. The frequency offset is the phase difference between Y_{1k} and Y_{2k}, that is, $Y_{2k} = Y_{1k} e^{j2\pi\varepsilon}$. The maximum likelihood estimate of the normalized frequency offset is given by:

$$\hat{\varepsilon} = (1/2\pi)\tan^{-1}\{(\sum_{k=-K}^{K} \mathrm{Im}[Y_{2k}Y_{1k}^{*}])/(\sum_{k=-K}^{K} \mathrm{Re}[Y_{2k}Y_{1k}^{*}])\} \tag{4}$$

This maximum likelihood estimate is a conditionally unbiased estimate of the frequency offset and will be computed using the received data [2].

Once the frequency offset is known, the ICI distortion in the data symbols can be reduced by multiplying received symbols with a complex conjugate of the frequency shift.

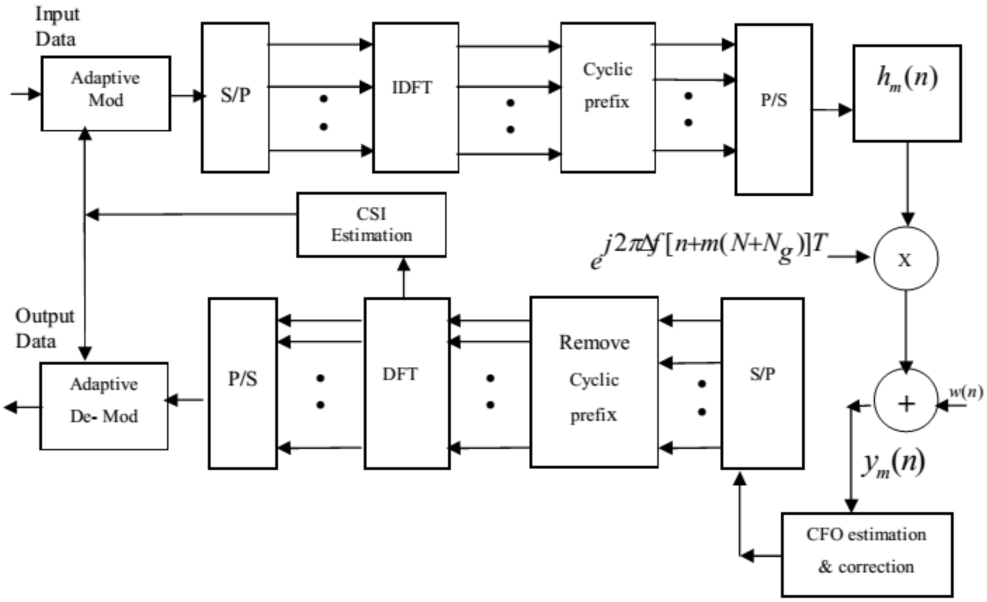


Figure 1: Block diagram of Proposed System Model for CFO correction by Adaptive Modulation

4. Spectral efficiency of Adaptive OFDM

The spectral efficiency is defined as the average data rate per unit bandwidth. When we send $k() = \log_2 [M()]$ (bits/symbol), the instantaneous data rate is $k() / T_S$ (bps), where T_s is the symbol period. Assuming Nyquist data pulse $B = 1/T_s$, for the discrete rate adaptation the spectral efficiency is given by [9]

$$\frac{R}{B} = \sum_{i=0}^{N-1} k_i \int_{\gamma_i}^{\gamma_i+1} p(\gamma)d\gamma \qquad (b/s/Hz)$$

For the Discrete Rate case, the rate region boundaries $\{\gamma_i\}_{i=0}^{N-1}$ define the range of values over which different constellations are transmitted. More clearly, the different constellation sizes correspond to a set of discrete rates $\{k_i\}_{i=0}^{N-1}$ which are allocated respectively to each fading region $[\gamma_i, \gamma_{i+1}]$ $(0 \le i \le N-1)$. When the instantaneous SNR falls within a given fading region, the associated signal constellation is transmitted.

Assume M-QAM is employed for each sub channel, and $[n, k]$ bits/symbol are sent for the kth tone in the nth block. We investigate the spectral efficiency under a constrained average BER requirement. According to [9], given the channel frequency response $H[n, k]$, the instantaneous BER for the k th tone in the n th block can be approximated by

$$P_e[n,k] = 0.2 \exp\left\{-\frac{1.6\,\frac{E_S}{N_O}\,|H[n\,.\,k]|^2}{2^{\beta[n\,.\,k]}-1}\right\} \tag{6}$$

Where E_S is the symbol energy at the transmitter, and $N_0/2$ is the variance of the real/imaginary part of the Gaussian noise $W[n, k]$.

4.1 Non Adaptive Modulation

Consider first the case of non adaptive modulation, where [*n*, *k*] = is a constant for all *n* and *k*. Since *H*[*n*, *k*] is a complex Gaussian random variable and all *H*[*n*, *k*] have identical distributions, the overall average BER become

$$\overline{P_e} = E_{H[n.k]}\left\{P_e[n.k]\right\} = \frac{1.6}{\dfrac{0.2\,{}^{E_s}\!/_{N_0}}{2^{\beta}-1}+1} \qquad (7)$$

Assume *P* target is the target average BER. Then by inverting, the maximum number of bits that can be transmitted given the average BER constraint is

$$\beta = \log_2\left[\frac{1.6\dfrac{E_s}{N_0}}{\dfrac{0.2}{P_{target}}-1}+1\right] \qquad (8)$$

The spectral efficiency (number of bits per second per Hz) is equal to β, under the assumption that the symbol interval is the reciprocal of the sub channel and bandwidth.

4.2 Ideal adaptive OFDM

For adaptive OFDM, different modulation schemes are used for different subchannels. In this section we assume that perfect knowledge of the receiver information channel is available at the transmitter. To achieve the acceptable target BER (P_{target}), the number of bits transmitted in each sub channel can be derived from (6) as

$$\beta[n,k] = \log_2\left[\frac{1.6\dfrac{E_s}{N_0}\left|H[n,k]\right|^2}{\ln\dfrac{0.2}{P_{target}}}+1\right] \qquad (9)$$

Therefore, the average spectral efficiency *R* is

$$R = E_{H[n.k]}\left\{\beta[n.k]\right\} \qquad (10)$$

The average spectral efficiency of adaptive OFDM for target BER of 10^{-3} is obtained through a Monte Carlo simulation is shown in Fig 3. Inter carrier interference and the overhead due to the Guard interval is not considered. The result indicate that a significant improvement in spectral efficiency or bit rate than the non adaptive modulation techniques.

4.3 Adaptive Modulation with CFO Correction

The spectral efficiency of the proposed adaptive modulation with CFO has been derived theoretically and it is expressed as follows.

$$\beta[n,k] = \log_2\left[\frac{1.6\gamma(\varepsilon)\left|H[n,k]\right|^2}{\ln\dfrac{0.2}{P_{target}}}+1\right] \qquad (11)$$

Therefore, the average spectral efficiency R is;

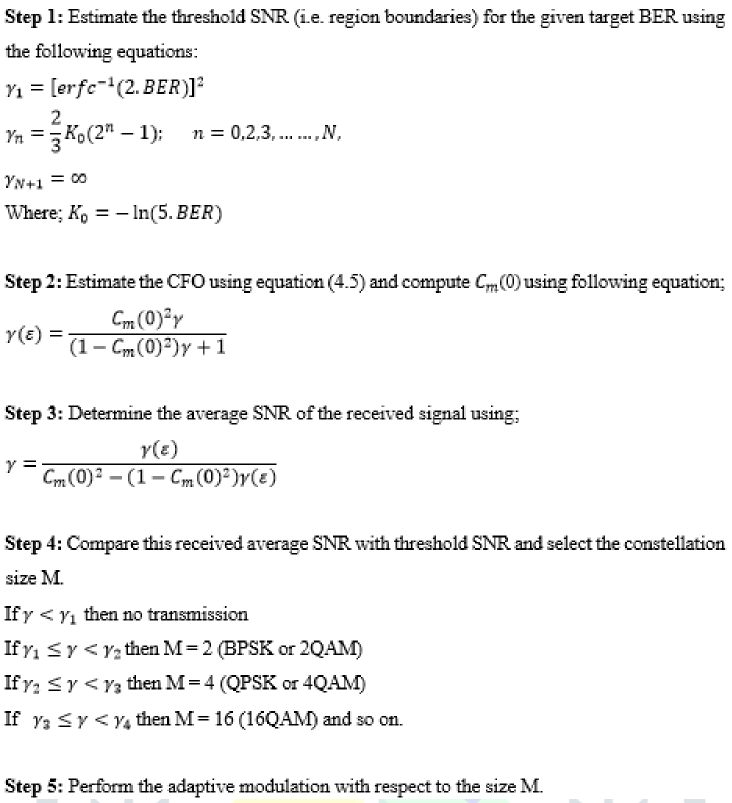
$$R = E_{H[n.k]}\left\{\beta[n.k]\right\} \qquad (12)$$

The average SNR in the presence of CFO for AWGN channel is

$$\gamma(\varepsilon) = \frac{C_m(0)^2\gamma}{(1-C_m(0)^2)\gamma+1} \qquad (13)$$

where $C_m(0) = \dfrac{\sin \pi\varepsilon}{N \sin(\pi\varepsilon / N)}$ and γ is the average SNRin the absence of CFO for AWGN channel. Thus by introducing the CFO correction in adaptive modulation, the attenuation of SNR is reduced and hence the spectral efficiency is improved.

5. Proposed Algorithm



Step 1: Estimate the threshold SNR (i.e. region boundaries) for the given target BER using the following equations:

$\gamma_1 = [erfc^{-1}(2.BER)]^2$

$\gamma_n = \frac{2}{3}K_0(2^n - 1); \quad n = 0,2,3, \ldots \ldots, N,$

$\gamma_{N+1} = \infty$

Where; $K_0 = -\ln(5.BER)$

Step 2: Estimate the CFO using equation (4.5) and compute $C_m(0)$ using following equation;

$$\gamma(\varepsilon) = \frac{C_m(0)^2 \gamma}{(1 - C_m(0)^2)\gamma + 1}$$

Step 3: Determine the average SNR of the received signal using;

$$\gamma = \frac{\gamma(\varepsilon)}{C_m(0)^2 - (1 - C_m(0)^2)\gamma(\varepsilon)}$$

Step 4: Compare this received average SNR with threshold SNR and select the constellation size M.

If $\gamma < \gamma_1$ then no transmission

If $\gamma_1 \leq \gamma < \gamma_2$ then M = 2 (BPSK or 2QAM)

If $\gamma_2 \leq \gamma < \gamma_3$ then M = 4 (QPSK or 4QAM)

If $\gamma_3 \leq \gamma < \gamma_4$ then M = 16 (16QAM) and so on.

Step 5: Perform the adaptive modulation with respect to the size M.

6. Simulation Results

In this section, Monte Carlo simulation is performed to evaluate the average SNR in the presence of CFO. This paper used the simple MLE to estimate the CFO and employed the direct form to correct CFO. Adaptive modulation OFDM system simulation was successfully

Parameter	Value
Bandwidth for each user	20MHz
Number of subcarriers	64,128,256,512
Cyclic Prefix Length	16
Number of pilots	4
Subcarrier frequency spacing	0.3125 MHz
IFFT/FFT period	3.2 µs
Guard interval duration	0.8 µs
Modulation method	Adaptive modulation (M-PSK, BPSK, QPSK, 16QAM, 64QAM)

Table 1: The Simulation Parameters

6.1 OFDM sub-carriers in time domain

Figure 6.1 shows various OFDM sub-carriers in time domain. This figure shows the relation between Amplitude of sub-carriers and sub-carriers index.

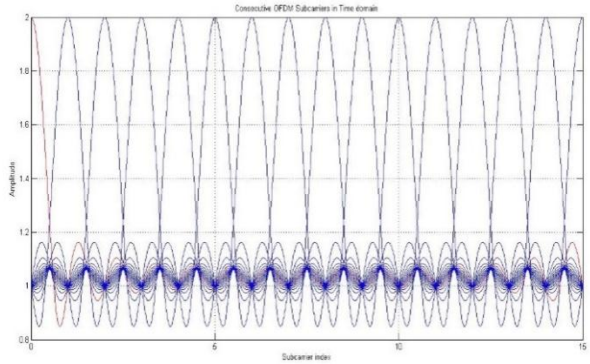


Figure 2: Sensitivity of OFDM subcarriers with Carrier Frequency Offset (CFO)

6.2 Normalized CFO Density in AWGN

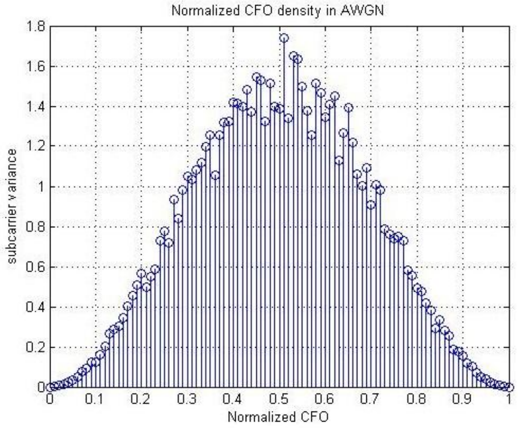


Figure 3: Estimation of ICI density vs CFO in OFDM under AWGN

6.3 ML estimation of time & frequency offset in OFDM systems

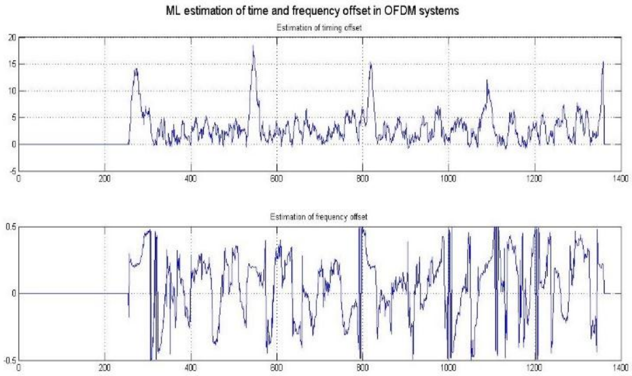


Figure 4: ML estimation of time and frequency offset in OFDM systems

Figure 4 shows relation of joint clock estimation of CFO and SFO. The pulses used here are varying at the peak position.

6.4 BER sensitivity vs CFO under AWGN with proposed technique

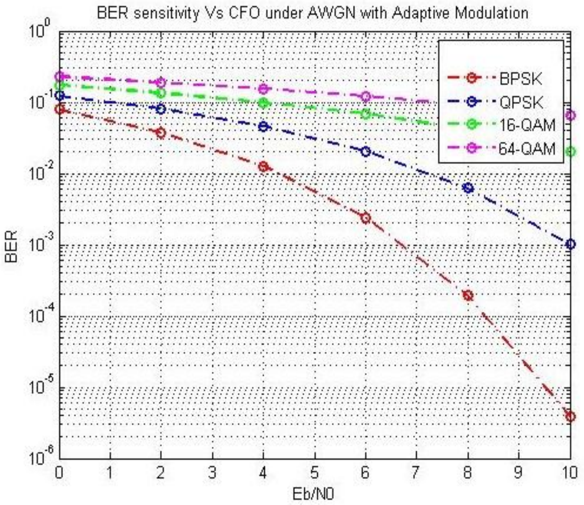


Figure 5: BER sensitivity vs CFO under AWGN with proposed adaptive modulation technique

6.5 BER sensitivity vs snr for different values of CFO under AWGN with proposed BPSK modulation technique

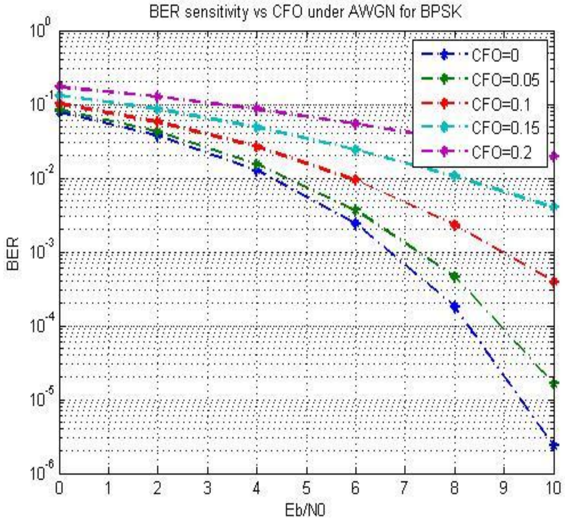


Figure 6: BER sensitivity vs CFO under AWGN with proposed BPSK technique

6.6 Spectral Efficiency vs SNR for BPSK

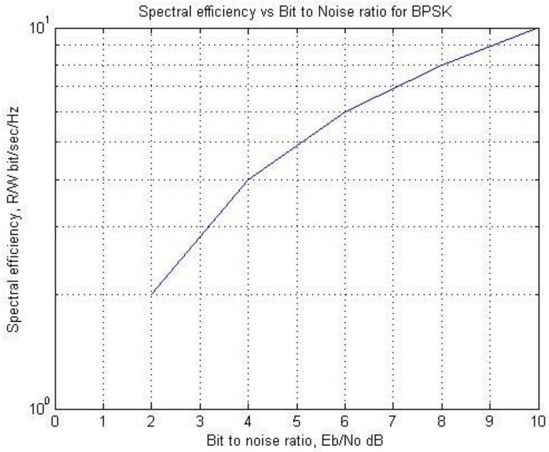


Figure 7: Spectral Efficiency vs Signal to Noise Ratio for BPSK CFO=0.05

6.7 SNR degradation of frequency offset

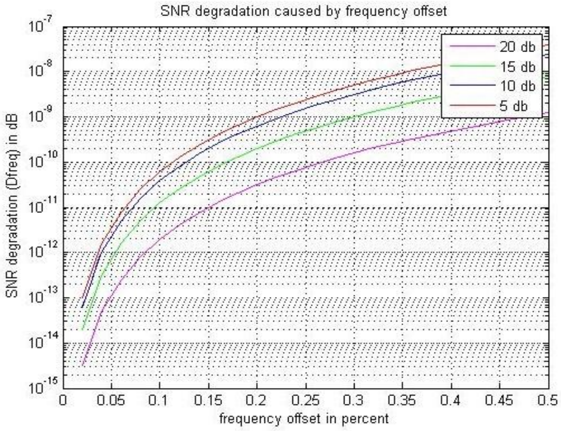


Figure 8: SNR degradation of frequency offset for different values of E_b/N_0

6.8 Simulation results summary

Simulation results are summarized in table 2 for the figure 5 are as:

Target BER	M=2 (BPSK)	M=4 (QPSK)	M=8 (16-QAM)	M=16 (64-QAM)
10^{-2}	4 dB	7 dB	20-21 dB	27 dB
10^{-3}	6-7 dB	10 dB	25 dB	30 dB
10^{-4}	8-9 dB	13-14 dB	28 dB	32 dB
10^{-5}	9 dB	17-18 dB	30 dB	35 dB
10^{-6}	10 dB	18-19 dB	32 dB	37 dB

Table 2: BER vs SNR for Proposed Techniques of Fig.5

It can be seen from table 2 that BPSK modulation shows 3 dB improvement with QPSK and also much better than other two for a target BER of 10^{-3}. Also, QPSK is 15 dB better than 16-QAM for target BER of 10^{-3}.

Target BER	Bit to Noise Ratio (dB) for Different Values of CFO				
	CFO=0	CFO=0.05	CFO=0.1	CFO=0.15	CFO=0.2
10^{-2}	4 dB	4-5 dB	6 dB	8 dB	12 dB
10^{-3}	6-7 dB	7 dB	8 dB	15 dB	20 dB
10^{-4}	8-9 dB	9 dB	12 dB	20 dB	24 dB
10^{-5}	9 dB	10 dB	16 dB	22 dB	28 dB
10^{-6}	10 dB	11-12 dB	18 dB	28 dB	32 dB

Table 3: SNR degradations for different CFO for BPSK of Figure 6.

From table 3 it can be seen that for CFO=0.05 SNR is 7 dB for target BER of 10^{-3}. For this values the average spectral efficiency of 6 bps/Hz, which is better as well good BER performance.

6.9 Results comparisons

Target BER	SNR (E_b/N_0) for QPSK			
	This Work	[3] MMSE	[3] Semi Blind ICA	[3] CAZAC
10^{-2}	7 dB	13-14	16-17	25
10^{-3}	10 dB	23-24	26-27	--
10^{-4}	13-14 dB	31-32	35-36	--
10^{-5}	17-18 dB	--	--	--
10^{-6}	18-19 dB	--	--	--

Table 4: Simulation Results Comparison under no CFO

Target BER	This Work	[5]	[5]
	CFO=0.1	CFO=0.1	CFO=0.1
10^{-2}	6 dB	10-12	15
10^{-3}	8 dB	16-17	22
10^{-4}	12 dB	20-21	27-28
10^{-5}	16 dB	--	--
10^{-6}	18 dB	--	--

Table 5: Simulation Results Comparison for CFO=0.1

7. Conclusion

In this paper we have investigated the influence of the CFO on coded OFDM transmission over AWGN and fading channels. OFDM is quite sensitive to carrier frequency offset, which attenuates the desired signal and causes inter carrier interference, thus reducing the SNR. In this paper we have analyzed the Adaptive modulation with CFO and compared the average spectral efficiency with non-adaptive modulation methods. proposed adaptive modulation with CFO=0.05 achieves average spectral efficiency of that the proposed adaptive modulation scheme maximizes the average spectral efficiency up to 6 bps/Hz for the target BER of 10^{-3}& up to 8 bps/Hz for the target BER of 10^{-5}. The proposed modulation technique is tested by Matlab computer simulations and the simulation results exhibits better performance than the conventional adaptive modulation techniques.

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