OFDM-CPM Performance and FOBP under IEEE802.16 Scenario

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Abstract

The application of orthogonal frequency domain modulation-Continuous Phase Modulation (OFDM-CPM) in multipath Stanford University Interim (SUI) channels is presented in this paper. OFDM-CPM is proposed for IEEE 802.16 standards as an alternative technique of orthogonal frequency division multiplexing (OFDM) in physical layer. It is shown that, in addition to 0dB Peak to Average Power Ratio (PAPR) and power efficiency, un-coded OFDM-CPM exploits the frequency diversity of multipath channel. Taking into account the Input Power Back off (IBO), OFDM-CPM is shown to outperform OFDM at high bit energy-to-noise density ratios (Eb/N0). However, at low Signal to Noise Ratio (SNR), the OFDM-CPM phase demodulator receiver suffers from a threshold effect. In addition, this paper compares the spectral fractional out of band power of OFDM-CPM for different modulation indices.

Keywords: OFDM-CPM, PAPR, SUI Multipath Channel Model, IEEE802.16, Fractional out of band power (FOBP).

1. INTRODUCTION

The future wireless communication networks will provide broadband services such as wireless Internet access to subscribers. Those broadband services require reliable and high-rate communications over time-dispersive (frequency-selective) channels with limited spectrum and inter-symbol interference (ISI) caused by multi-path fading. Orthogonal frequency division multiplex (OFDM) is one of the most promising solutions for a number of reasons. OFDM has high spectral efficiency since subcarriers overlap in frequency and adaptive coding and modulation can be employed across subcarriers. Its implementation is simplified because the base band modulator and demodulator are simply IFFT/FFT. Other advantages of OFDM include simple receiver (since only one tap equalizer is required) and excellent robustness in multi-path environment. Several variations of OFDM have been proposed as effective anti multipath techniques [1]. OFDM primarily offers a favourable trade-off between performance in severe multipath channels and signal processing complexity. OFDM is considered as physical layer transmission techniques for broadband wireless communication system. It has been adopted by HiperLAN/2, digital video broadcasting (DVB), digital audio broadcasting (DAB), IEEE 802.11a wireless local area network (WLAN) standard, IEEE 802.16 wireless metropolitan area network (WMAN) standard[8]. Despite all the attractive advantages, OFDM has its disadvantages. OFDM has two primary drawbacks. The first is sensitivity to imperfect frequency synchronization. The second problem with OFDM is that the signal has large amplitude fluctuations caused by the summation of the complex sinusoids. PAPR of OFDM signals increases as the number of subcarriers increases. When high PAPR signals are transmitted through non-linear power amplifier, severe signal distortion will occur. Therefore, highly linear power amplifier with power back off is required for OFDM systems. This results in the low power efficiency and limited battery life of the mobile device. OFDM's high peak to average power ratio (PAPR) requires system components with a large linear range capable of accommodating the signal due to the fact that nonlinear distortion results in a loss of subcarrier orthogonality which degrades performance [6]. Nonlinearities in the transmitter also cause the generation of new frequencies in the transmitted signal. This inter-modulation distortion causes interference among the subcarriers, and a broadening of the overall signal spectrum.

Recently, the idea of constant envelope OFDM with continuous phase modulation (OFDM-CPM) system was introduced [2-5]. The significance of the 0 dB PAPR achieved by using continuous phase modulation (CPM) is that the signal can be amplified with power efficient nonlinear power amplifier. The OFDM-CPM approach described in this paper is based on the phase modulator transform technique. In essence, the OFDM waveform is used to phase modulate the carrier. In [2] and [3], the OFDM-CPM signal-space and performance in AWGN channel was investigated, and a suboptimal phase demodulator receiver was proposed. In [4], a non-coherent receiver was presented for OFDM-CPM in flat fading channels. However, the use of OFDM-CPM has not been evaluated for multipath Stanford University Interim (SUI) channels and under IEEE 802.16 scenario.

SUI multi-path channels are widely used for evaluation of the broadband wireless metropolitan area network (WMAN) systems. WMAN systems are being developed by the IEEE 802.16 working group and also by the European Telecommunications Standards Institute (ETSI) Broadband Radio Access Network (BRAN) High-Performance MAN (Hiper-MAN) group. In this study, these channels are employed to investigate multipath effects on OFDM-CPM under IEEE 802.16 Scenario. This work is going to open a window to use OFDM-CPM in WMANs.

In this paper, the application of OFDM-CPM in multipath SUI channel and under IEEE 802.16 scenario is studied. In this study, performance of the frequency domain equalizer (FDE) using both zero-forcing (ZF) and minimum mean-squared error (MMSE) definitions is evaluated over SUI multipath fading channel models. OFDM-CPM is then compared with conventional 16PSK OFDM in the presence of nonlinear power amplification at 0dB input power back off (IBO). In addition, the effect of the modulation index on the BER performance and spectrum broadening is investigated. For this purpose, simulation results are provided to study the fractional out of band power of OFDM-CPM signals for different modulation indices. Finally, simulation results are provided to investigate the effectiveness of OFDM-CPM phase demodulator receiver for multipath diversity as well as threshold effect at low SNR.

2. OFDM-CPM signal Description

The OFDM-CPM is a modulation format that can be viewed as a mapping of the OFDM signal onto the unit circle. The resulting signal has a constant envelope leading to a 0 dB PAPR. The OFDM signal is transformed through continuous phase modulator to a low-PAPR signal prior to the PA and, at the receiver, the inverse transform by a phase demodulator is performed prior to OFDM demodulation as shown in Fig. 1.

The base band of the OFDM-CPM waveform is represented by:

$$S(t) = e^{j\phi(t)}, \tag{1}$$

where the phase signal during the *n*th block is written as

$$\phi(t) = \theta_n + 2\pi h C_N \sum_{k=1}^{N} I_{n,k} q_k (t - nT_B), \tag{2}$$

for $nT_B \le t < (n+1)T_B$, which is the OFDM waveform plus memory term θ_n. Here h refers to modulation index; N is the number of sub-carriers; $\{I_{n,k}\}$ represents M-PAM data symbols; T_B is the block interval, and $\{q_k(t)\}$ represents the set of subcarrier waveforms. The subcarriers must also be real-valued and $\{q_k(t)\}$ may be expressed as

$$q_k(t)=\begin{cases}\cos(2\pi kt/T_B) & ,0\le t<T_B, K\le N/2\\ \sin(2\pi(k-N/2)/T_B) & ,0\le t<T_B, K>N/2\\ 0 & ,othrewise\end{cases} \quad (3)$$

The normalizing constant is set to $C_N=(2/N\sigma_I^2)^{-0.5}$, where σ_I^2 is the variance of the data symbols, and consequently the variance of the phase signal will be $\sigma_\phi^2=(2\pi h)^2$. Assuming that the data is independent and identically distributed, it follows that $\sigma_I^2=(M^2-1)/3$.

To reduce adjacent channel interference, the OFDM-CPM signal is made phase-continuous with the introduction of memory. The benefit of continuous phase OFDM-CPM is a more compact signal spectrum. The phase signal, as defined by (1), has phase jumps at each signalling interval boundary without $\{\theta_n\}$. By including memory terms, these jumps are eliminated. The memory term θ_n, is a function of all data symbols during and prior to the *n*th signalling interval.

The phase demodulator receiver is a practical implementation of the OFDM-CPM receiver and is therefore of practical interest. However, it isn't necessarily optimum, since the optimum receiver is a bank of M^N matched filters, one for each potentially transmitted signal.

The phase demodulator receiver essentially consists of a phase demodulator followed by a conventional OFDM demodulator. The received signal is first passed through a front-end band pass filter, which limits the bandwidth of the additive noise. [2], [5]

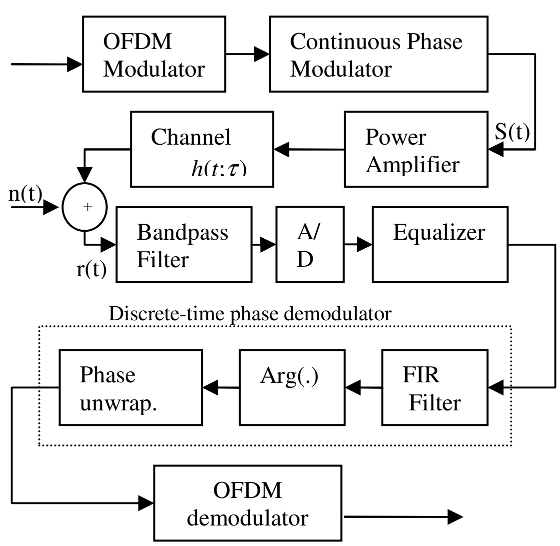

FIGURE 1: OFDM-CPM block diagram.

3. OFDM-CPM in Mulipath Channels

In this section, the performance of OFDM-CPM in multipath channels is analysed. In this case, the received signal takes the following form:

$$r(t) = \int_0^{\tau_{\max}} h(t,\tau)S(t-\tau)d\tau + n(t) \quad (3)$$

where $h(t,\tau)$ is the channel impulse response having a maximum propagation delay $\tau_{\max}$ and $n(t)$ is complex Gaussian noise. Channel is assumed to be wide-sense stationary uncorrelated scattering (WSSUS), and comprises of L discrete paths. For the proposed system, a cyclic prefix guard interval is transmitted. At the receiver, r(t) is sampled, the guard time samples are discarded and the block time samples are processed. Then frequency domain equalizer is applied. Equalizer correction terms, could be based on ZF or MMSE criterion.

As long as the duration of the guard interval is greater than or equal to the channel's maximum propagation delay, that is, $T_g >> \tau_{\max}$, and a cyclic prefix is transmitted during the guard interval, the performance of un-coded OFDM in a time-dispersive channel is equivalent to flat fading performance. In other words, the multipath fading performance is the same as single path fading performance. It can be said that OFDM lacks frequency diversity as well. In OFDM the wideband frequency-selective fading channel is converted into N contiguous frequency non-selective fading channels. Therefore any multipath diversity inherent to the channel is not exploited by the OFDM receiver. Note that OFDM systems typically employ channel coding and frequency-domain interleaving, which offers diversity.

Here, Taylor expansion is applied to consider OFDM-CPM behaviour in multipath channels. The OFDM-CPM signal, with $\theta_n = 0$, can be written as

$$S(t) = e^{j\phi(t)} = e^{j\sigma_\phi m(t)} = \sum_{i=0}^{\infty} [(j\sigma_\phi)^i / i!] m^i(t), \quad (4)$$

where m(t) is the normalized OFDM message signal. This can be seen by viewing the OFDM-CPM waveform by the Taylor series expansion

$$S(t) = [1 + j\sigma_\phi m(t) - \frac{\sigma_\phi^2}{2} m^2(t) - j\frac{\sigma_\phi^3}{6} m^3(t) + \ldots], \quad (5)$$

for $0 \le t \le T_B$, the higher-order terms $m^n(t)$, n >1, results in a frequency spreading of the data symbols. In general, it can be said that the N data symbols that constitute the OFDM-CPM signal are not simply confined to N frequency bins, as is the case with conventional OFDM. The phase modulator mixes and spreads, in a nonlinear and exceedingly complicated manner, the data symbols in frequency, which gives the OFDM-CPM system the potential to exploit the frequency diversity in the channel. These results indicate that the OFDM-CPM receiver exploits the multipath diversity of the channel. The fact that OFDM-CPM exploits multipath diversity is an interesting result since conventional OFDM doesn't. This isn't necessarily the case, however. For small values of modulation index, where only the first two terms in (5) contribute, that is,

$$S(t) = [1 + j\sigma_\phi m(t)], \quad (6)$$

the OFDM-CPM signal doesn't have the frequency spreading given by the higher-order terms. In this case, the OFDM-CPM signal is essentially equivalent to a conventional OFDM signal, m(t), and therefore doesn't have the ability to exploit the frequency diversity of the channel. Simply put, OFDM-CPM has frequency diversity when the modulation index is large and doesn't have frequency diversity when the modulation index is small.

4. Simulation Result

The BER performance of OFDM-CPM is evaluated using computer simulation. In this study, the channel is assumed to be known perfectly at the receiver. The parameters of the representative OFDM-CPM system used for this study are demonstrated in Table 1. These parameters are derived from IEEE802.16 standard [8].

The 256point OFDM based air interface specification seems to be favored by the IEEE 802.16 wireless metropolitan area network (WMAN) standard. The size of the FFT point determines the number of subcarriers. Of these 256 subcarriers, 192 are used for user data, 56 are nulled for guard band and 8 are used as pilot subcarriers for various estimation purposes. The physical layer allows accepting variable CP length of 8, 16, 32 or 64 depending on the expected channel delay spread. The channel bandwidth can be an integer multiple of 1.25 MHz, 1.5 MHz, 1.75 MHz, 2MHz and 2.75 MHz with a maximum of 20 MHz. But the IEEE 802.16 wireless metropolitan area network (WMAN) standard has initially narrowed down the large choice of possible bandwidth to a few possibilities to ensure interoperability between different vendor's products [8].

Here we use SUI channels [7]. The parametric view of the SUI channels is summarized in the Table 2. For each simulation trial, the set of L path gains are generated randomly. Each gain is complex valued, with zero mean and variance $\sigma_{a_l}^2$ .Both the real and imaginary parts of the path gains are Gaussian distributed, thus the envelope is Rayleigh distributed. Also, the channels are normalized.

Fig. 2 illustrates OFDM-CPM BER performance over SUI 1-6 channel models for M=4 and $2\pi h = 1$. Results on this figure confirm the analysis described in section 3. In addition, this figure compares the SUI 1-6 channels with the AWGN and Rayleigh channels results. As shown in this figure, the performance of the SUI 1-6 channels using MMSE equalizer outperforms the Rayleigh channel performance. For example, in Fig. 2, performance at BER=10^{-4}, over SUI6 is 15 dB better than single path Rayleigh channel.

The results presented in Fig. 2 show that multipath diversity is exploited by the OFDM-CPM phase demodulator receiver as expected from the aforementioned analysis. The multipath diversity depends not only on the number of independent paths but also on the way in which the power is distributed over the paths. It is worth noting that the frequency non-selective channel models considered have L = 1 path of which 100% of the channel gain depends, and thus these channels have no multipath diversity. This is the reason that multipath channels outperform Rayleigh channel.

In Fig. 3, the performance of OFDM-CPM with the ZF equalizer and MMSE equalizer over SUI1 and SUI3 is compared. These results show the significant performance improvement provided by using the MMSE equalizer for SUI channels over single path Rayleigh channel. However, these results reveal that for the case of using ZF equalizer, performance in multi path channels could be worse than single path (Rayleigh) channel. At the bit error rate 10^{-4}, for example, MMSE outperforms ZF by 10 dB for Channel SUI1.

In addition, as stated in section 3, OFDM-CPM has frequency diversity when the modulation index is large and doesn't have frequency diversity when the modulation index is small. This property is demonstrated in Fig. 4. It shows the results obtained from simulation of the system over the single path Rayleigh flat fading channel as well as the SUI6 Channel for $M = 4$, $2\pi h = 0.1$ and $2\pi h = 1.1$. As shown in this figure, OFDM-CPM with a small modulation index lacks frequency diversity. Notice that for $2\pi h = 0.1$ the single path and multipath performance is essentially the same. By contrast, for the large modulation index e.g. $2\pi h = 1.1$, the multi-path performance is significantly better than the single-path performance.

On the other hand, the OFDM-CPM power density spectrum $\Phi_s(f)$ can be estimated by the Welch method of periodogram averaging. This estimation can be used to calculate the fractional out-of-band power as follows:

$$FOBP(f) = \frac{\int_o^f \Phi_S(x)dx}{\int_{-\infty}^{+\infty} \Phi_S(f)df}. \tag{7}$$

Fig. 5 compares the estimated fractional out-of-band power curves over a large range of modulation index. As it can be seen in this figure, large amount of modulation index causes spectrum broadening and adjacent channel interference even thought it results better BER performance.

Moreover, In power amplifiers (PA), the most efficient operating point is at the PA's saturation point, but for signals with large PAPR the operating point must shift to the left keeping the amplification linear. The average input power is reduced and consequently this technique is called input power back-off (IBO). At large back-off the efficiency of a power amplifier is very low. Such efficiency is detrimental to mobile battery-powered devices which have limited power resources. Here we assume that we need $IBO = 0dB$.

Considering the power amplifier nonlinearities, in Fig. 6, the performance of OFDM-CPM is compared with the conventional 16PSK-OFDM over SUI4 channel. In this case $2\pi h = 1$ and M=16. In addition, the solid state power amplifier (SSPA) model is employed at 0dB input power back-off level. Here, the advantage of the OFDM-CPM systems is that it operates with $IBO = 0dB$. As shown in Fig. 6, over the region $0dB \le E_b / N_0 \le 10dB$, the OFDM system performs better than the OFDM-CPM system. Under this 10dB threshold, nonlinear and non-Gaussian noise is injected into the OFDM demodulator (following the phase demodulator) and causes performance degradation.

As a result, this figure reveals that although OFDM-CPM exploits the frequency diversity inherent to the channel, however, OFDM-CPM exhibits a poor performance at low SNR due to the threshold effect.

5. CONSLUSION

In this paper, application of OFDM-CPM for SUI multipath channels is analyzed. The results obtained show that OFDM-CPM exploits the frequency diversity of the multipath channel. This diversity comes from spreading of the data symbol energy in frequency-domain for large modulation index. For small modulation index, however, OFDM-CPM does not achieve diversity gains. This phenomenon is explained by viewing the OFDM-CPM signal in its Taylor expanded form. On the other hand, large amount of modulation index causes spectrum broadening and adjacent channel interference even thought it results better BER performance. In addition, OFDM-CPM is compared with conventional 16PSK OFDM in the presence of nonlinear power amplification at 0dB input power back-off (IBO). Taking into account the IBO, OFDM-CPM is shown to outperform OFDM at high bit energy to-noise density ratios (Eb/N0). However, at low SNR the OFDM-CPM phase demodulator receiver suffers from a threshold effect.

TABLE 1: System and Signal parameters

T_B			Block Interval	$114\mu s$		
T_g			Guard Interval	$32\mu s$		
T_F			Frame Interval	$146\mu s$		
J			Oversamplig Factor	8		
$F_{sa} = JN_B / T_B$			Sampling Frequency	$14Mega$ $(samp./\sec)$		
N_B	N_g	N_F	Num. of Carriers	200	56	256
$BW = N / T_B$			Bandwidth	$1.75MHz$		
η_t			Transmission efficiency	$114/146 = \%78$		
$1/T_B$			Subcarrier Spacing	$8750Hz$		

TABLE 2: SUI Channel Parameters

Model	Delay	L (Num of Taps) = 3			Delay spread
	Gain	Tap1	Tap2	Tap3	(τ_{rms})
SUI 1		$0\mu s$	$0.4\mu s$	$0.8\mu s$	0.111µs
		$0dB$	$-15dB$	$-20dB$	
SUI 2		$0\mu s$	$0.5\mu s$	$1\mu s$	0.202µs
		$0dB$	$-12dB$	$-15dB$	
SUI 3		$0\mu s$	$0.5\mu s$	$1\mu s$	0.264µs
		$0dB$	$-5dB$	$-10dB$	
SUI 4		$0\mu s$	$2\mu s$	$4\mu s$	1.257µs
		$0dB$	$-4dB$	$-8dB$	
SUI 5		$0\mu s$	$5\mu s$	$10\mu s$	2.842µs
		$0dB$	$-5dB$	$-10dB$	
SUI 6		$0\mu s$	$14\mu s$	$20\mu s$	5.240µs
		$0dB$	$-10dB$	$-14dB$	

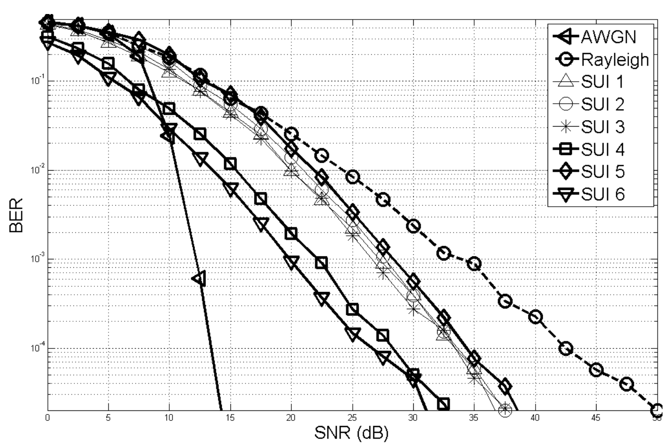

FIGURE 2: OFDM-CPM Performance Simulation (M=4, N=256, MMSE)

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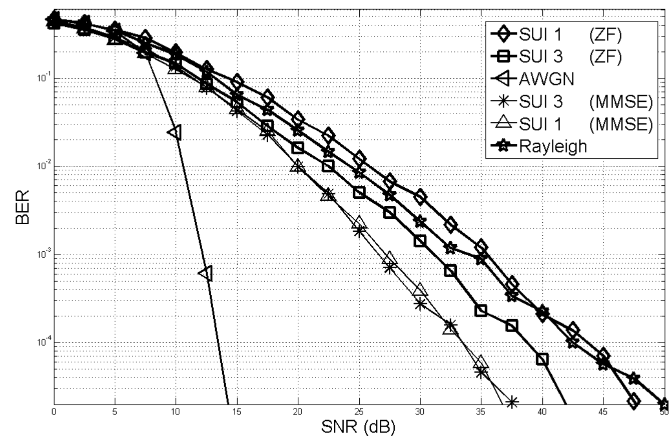

FIGURE 3: Performance Simulation (ZF and MMSE)

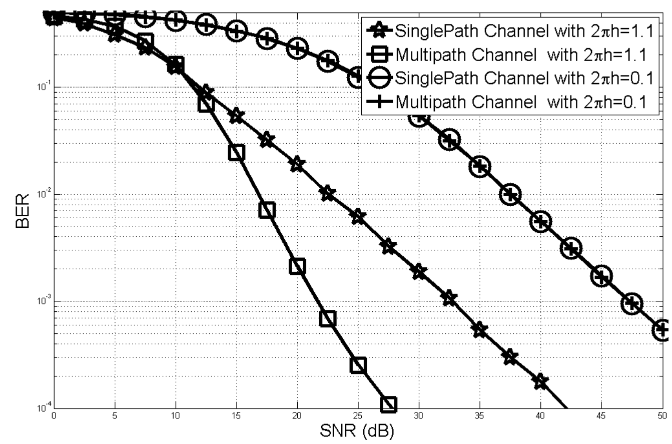

FIGURE 4: Performance Simulation (Modulation index effect)

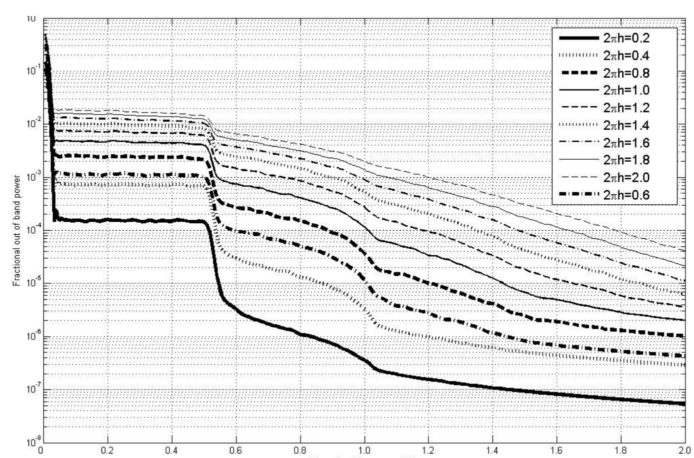

FIGURE 5: Fractional out of band power Simulation (Modulation index effect)

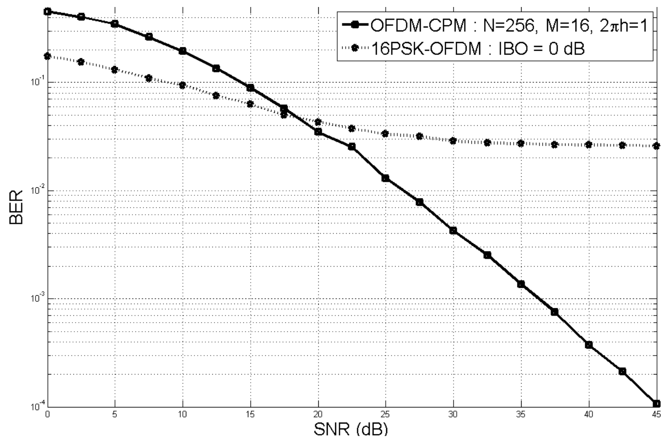

FIGURE 6: Performance Simulation (OFDM-CPM and 16PSK-OFDM)

REFERENCES

1. Z. Wang, Xiaoli Ma, and G. B. Giannakis. *“OFDM or Single-Carrier Block Transmissions?”* IEEE Transaction on Communications, 25(3):36-44, 2004
2. S. C. Thompson, J. G. Proakis, and J. R. Zeidler. *“Constant envelope binary OFDM phase modulation”*. In Proceedings of the 23rd Military Communication Conference. Baltimore, MD, USA, 2003
3. S. C. Thompson, A. U. Ahmed, J. G. Proakis, and J. R. Zeidler. *“Constant envelope OFDM phase modulation: spectral containment, signal space properties and performance”*. In Proceedings of the 23rd Military Communication Conference. Baltimore, MD, USA, 2004
4. Tsai, G. Zhang, and J. L. Pan. *“Orthogonal frequency division multiplexing with phase modulation and constant envelope design”*. In Proceedings of the 23rd Military Communication Conference. Baltimore, MD, USA, 2005
5. S. C. Thompson, J. G. Proakis, and J. R. Zeidler. *“Noncoherent Reception of Constant Envelope OFDM in Flat Fading Channels”*. In Proceedings of the IEEE 16th International Symposium on PIMRC. Baltimore, MD, USA, 2005
6. S. C. Thompson, J. G. Proakis, and J. R. Zeidler. *“The effectiveness of signal clipping for PAPR and total degradation reduction in OFDM systems”*. In Proceedings of the IEEE 16th GLOBECOM. Baltimore, MD, USA, 2005
7. V. Erceg, K.V.S. Hari, M.S. Smith, D.S. Baum et al, “Channel Models for Fixed Wireless Applications”, IEEE 802.16.3 Task Group Contributions, Feb2003
8. IEEE 802.16 2004,” IEEE Standard for Local and Metropolitan Area Networks Part16: Air Interface for Fixed Broadband Wireless Access Systems”,1 October 2004