INTERFERENCE CANCELLATION FOR OFDM SYSTEMS WITH HIERARCHICAL MODULATION OVER NON-LINEAR SATELLITE CHANNELS

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ABSTRACT
This paper presents an efficient technique to eliminate the inter-layer interference (ILI) inherent in hierarchical modulation (HM) schemes operating over nonlinear satellite channels. The HM considered in this work is used in conjunction with an orthogonal frequency division multiplexing (OFDM) system. The proposed technique is based on an enhanced version of the selective mapping (SLM) scheme used for peak-to-average power ratio (PAPR) reduction. The enhanced SLM is constructed by using a new metric, which is more informative than the conventional PAPR metric. Simulation results confirmed that a noticeable bit error rate (BER) and interference reductions can be achieved by using the proposed technique.

Index Terms— Hierarchical Modulation, OFDM, TWTA, distortion, interference, satellite and selective mapping.

1. INTRODUCTION
In the digital video broadcasting-satellite services to hand-held (DVB-SH) standard, hierarchical modulation (HM) is selected as an alternative to conventional modulation schemes such as quadrature phase shift keying (QPSK) and quadrature amplitude modulation (16-QAM) [1]. HM is one of the promising technologies to upgrade existing systems with backward compatibility, i.e., receivers that have been designed to use conventional modulation schemes will remain functional by detecting the data in the high priority constellation points [2]-[4]. Furthermore, the additional complexity and cost for HM-based systems are relatively low [5], [6]. However, HM usually suffers from the interference between the enhancement-layer (EL) and basic-layer (BL) streams, which is denoted as inter-layer interference (ILI) [7], [8].

Orthogonal frequency-division multiplexing (OFDM) is a multi-carrier technique adopted for several communication systems due to its robustness against multipath propagation, high spectral efficiency and low-complexity receivers. However, one of the major drawbacks of OFDM transmission is the high peak-to-average power ratio (PAPR), which introduces distortion when it is processed by nonlinear devices such as the travelling wave tube amplifiers (TWTA). The nonlinearity of the TWTA exhibits AM/AM amplitude and AM/PM phase distortions that leads to loss of orthogonality among the subcarriers, which consequently creates inter-carrier interference (ICI) [9]. The ICI power is proportional to the amplitude of the signal at the amplifier input and it may cause a considerable bit error rate (BER) degradation.

The problem of ICI and ILI reduction for HM schemes has received noticeable attention in the literature. For example, Huang et. al, [7]- [8] proposed to adopt repetition coding schemes to mitigate the ICI and ILI produced by Doppler effects in time-varying Rayleigh fading channels with HM. Although, the proposed schemes managed to improve the BER performance, repetition coding will significantly deteriorate the bandwidth efficiency.

In this paper, we propose a new approach to reduce the distortion power that the TWTA would generate due to its nonlinearity. The proposed approach is based on measuring the distortion introduced by the TWTA at the transmitter side, then use the selective mapping (SLM) to minimize the distortion. The distortion metric adopted is the distortion-to-signal power ratio (DSR). The computational complexity of the proposed technique is considerably lower than the standard SLM because the distortion can be computed without over-sampling the input of the inverse fast Fourier transform (IFFT). Monte Carlo simulation results have confirmed that the BER performance of both the BL and EL has noticeably improved by using the proposed DSR approach.

The remainder of this paper is organized as follow; in Section 2, models of the system channel, HM, OFDM and TWTA amplifier are described. Section 3 introduces the proposed SLM technique based-on DSR metric in conjunction with HM. Numerical results are presented in Section 4, and finally conclusions are given in Section 5.

2. SYSTEM AND CHANNEL MODELS
The considered system model consists of a QPSK/QPSK hierarchical and OFDM modulators/demodulators with SLM to reduce the PAPR. The channel is nonlinear and it also introduces additive white Gaussian noise (AWGN). The HM is designed using two separate data streams, namely the basic and enhancement streams that are combined into a single stream. The basic and enhancement information bits are mapped to 16-QAM symbols similar to the conventional 16-QAM systems. The minimum distance between the BL and EL constellation points is equal to 2d1 and 2d2, respectively. The mapping of both information bits streams is performed using a Karnaugh map Gray mapping approach. The ratio of the minimum distances is defined as \( \lambda = \frac{d_2}{d_1} \) [2], where \( \lambda \) is a factor that determines the performance of the BL and EL layers. In this work, we consider \( \lambda = 0.5 \), therefore, the EL constellation is a uniform 16-QAM.

The OFDM transmitter comprises \( N \) independent HM modulated channels utilized to map the binary random data sequence \( D_m \), to the \( N \) subcarriers. The OFDM symbols are constructed for computational efficiency using the IFFT, which is applied to a block of \( N \) symbols, \( \{X_k\} \in \mathbb{C}^{1 \times N} \), obtained via serial-to-parallel conversion of the modulated data streams. The \( N \)-point IFFT yields a complex-
valued sequence that can be expressed as
\[ x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi kn/N}, \quad n = 0, 1, \ldots, N - 1. \] (1)

After parallel-to-serial conversion and cyclic prefix (CP) addition, the samples of the OFDM symbol \( s_n \) are amplified by the TWTA to generate \( y_n \), which are then perturbed by AWGN to construct the received signal \( z_n = y_n + w_n \), where \( w_n \) represents a zero mean AWGN with \( N_0/2 \) variance. At the receiver side, after removing the cyclic prefix, the received signal samples are serial-to-parallel converted and applied to the FFT to produce the decision variables \( \tilde{X}_k \). Finally, a maximum likelihood demodulator can be used to generate the frequency domain HM symbols. It is worth noting that the demodulation process is performed with the assumption of perfect symbol timing, carrier frequency and phase synchronization.

One of the main drawbacks of OFDM systems is the high PAPR of the transmitted signal due to the coherent sum of \( N \) modulated subcarriers. The PAPR for discrete-time signals can be estimated by zero-padding the vector \( \mathbf{X} \) by a factor \( L \) and computing the IFFT. The PAPR is defined as [10],
\[ PAPR = \max \left\{ \frac{|x_n|^2}{E\{||\mathbf{x}||^2\}} \right\}, \quad n = 0, 1, \ldots, LN - 1, \] (2)

where \( ||\mathbf{x}|| \) is the Euclidean norm of a vector \( \mathbf{x} \), which is defined as \( ||\mathbf{x}|| = \sqrt{\sum |x|^2} \), and \( E\{||\mathbf{x}||^2\} \) is the average power of \( \mathbf{x} \).

The nonlinear behavior of satellites’ TWTA is usually described by either Saleh’s model or the polynomial model. The amplifier output using Saleh’s model can be expressed as [9],
\[ y_n = A(\rho_n) e^{j[\theta_n + \phi(\rho_n)]}, \] (3)

where \( \rho_n \) and \( \theta_n \) represent the AM/AM and AM/PM conversion of the nonlinear amplifier, respectively. Moreover, if the modeled TWTA is memoryless, then the AM/AM and AM/PM profiles can be described by,
\[ A(\rho_n) = A_{sat}^2 \frac{\rho_n}{\rho_n^2 + A_{sat}^2}, \] (4)
\[ \phi(\rho_n) = \frac{\pi}{3} \frac{\rho_n^2}{\rho_n^2 + A_{sat}^2}, \] (5)

where \( A_{sat} \) denotes the amplitude input saturation voltage. The operating point of the amplifier is set by choosing either the input back-off (IBO) or the output back-off (OBO) with respect to \( A_{sat} \). These two parameters can be defined as
\[ IBO = 10 \log_{10} \frac{P_{n,max}}{P}, \] (6)
\[ OBO = 10 \log_{10} \frac{P_{out,max}}{P_{av,out}}, \] (7)

where \( P_{av,out} \) is the average power of the OFDM symbol at the output of the amplifier, \( P_{n,max} \) is the maximum input power due to \( A_{sat} \) and \( P_{out,max} \) is the maximum output power due to the maximum input power.

The output of the TWTA \( y_n \) using the equivalent polynomial model for a nonlinear high power amplifier (HPA) with \( A_{sat} \neq 1 \) can be expressed as [11]
\[ y_n = \sum_{k=1}^{K} a_k s_n \frac{|s_n|^{(k-1)}}{A_{sat}^{(k-1)}}, \] (8)

where \( K \) is the order of nonlinearity and \( a_1, \ldots, a_K \) are the polynomial coefficients. In the polynomial model, odd order nonlinearity produces the maximum intermodulation. Moreover, most of the intermodulation power is produced by orders less or equal to 3. Consequently, representing the nonlinearity model by a third order nonlinearity is sufficiently accurate. Therefore, the TWTA can be expressed as,
\[ y_n = \alpha_1 s_n + \alpha_3 \frac{|s_n|^2}{A_{sat}^2}. \] (9)

In practice, the coefficients that represent nonlinearities which demonstrate both AM/AM and AM/PM characteristics should have complex values [12]. In this work, the complex coefficients used are \( \alpha_1 = 0.09290 + j 0.0340 \) and \( \alpha_3 = -0.9100 + j 0.5755 \). These coefficients were obtained by equating (3) with (9) and invoking the minimax criterion [13].

The 4th subcarrier after cyclic prefix removal and applying the FFT can be expressed as [11],
\[ \tilde{X}_k = X_k \beta + I_k + \eta, \] (10)

where the first term in (10) represents the useful part of the data symbol, \( \beta \) is a complex phase shift given by
\[ \beta = \alpha_1 + \frac{\alpha_3}{N} \sum_{n=0}^{N-1} |s_n|^2 A_{sat}^2, \] (11)
and \( I_k \) is the interference component,
\[ I_k = \frac{\alpha_3}{N} \sum_{l=0}^{N-1} \sum_{\|k\|} X_k \eta \exp(j2\pi(l-k)/N), \] (12)

and \( \eta \) is the FFT of the AWGN. For high SNR, the DSR at the receiver side is defined as [14],
\[ DSR = \frac{E\{||\mathbf{I}||^2\}}{E\{||\mathbf{X}||^2\}}, \] (13)

where \( \mathbf{I} = \{I_0, I_1, \ldots, I_{N-1}\} \). The normalized DSR can be obtained by dividing (13) by \( ||\mathbf{I}||^2 \), which is constant for a given OFDM symbol,
\[ \overline{DSR} = \frac{E\{||\mathbf{X}||^2\}}{||\mathbf{I}||^2}. \] (14)

It is worth noting that accurate evaluation of the PAPR requires oversampling factor \( L \geq 4 \), whereas no oversampling is required for the DSR estimation.

### 3. THE PROPOSED SCHEME USING SLM

The proposed system is based on shifting the DSR computation to the transmitter side and adopting it as a metric for the clipping that is introduced by the TWTA nonlinearity. Hence, it is used to replace
the PAPR metric used in conventional SLM systems as depicted in Fig. 1. The data symbols are copied into $U$ sections, each multiplied by $U$ different phase sequences $B^{(u)} = [B_{u,0}, B_{u,1}, \ldots, B_{u,N-1}]$, $u = 0, 1, \ldots, U-1$, to generate alternative input sequences that can be represented as,

$$X^{(u)} = X \circ B^{(u)} , \quad u = 0, 1, \ldots, U-1,$$  

(15)

where $B^{(0)}$ is set as a unity vector, while $B^{(u)}$, $u = 1, 2, \ldots, U-1$ are selected randomly with phase values $\{\pm 1\}$. The operation $\circ$ denotes the Hadamard product (element-wise product). Subsequently, each of the $U$ branches is applied to an $N$-point IFFT. The resulting sample of the $u$-th sequence can be expressed as

$$x_n^{(u)} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k B_{u,k} e^{j2\pi kn/N}, \quad n = 0, 1, \ldots, N-1. \quad (16)$$

Hence, the $k$th frequency domain symbol after the TWTA and FFT, can be expressed as

$$Y_k^{(u)} = X_k B_{u,k} \beta + I_{k,\text{SLM}}, \quad (17)$$

where $\beta$ is given by (11) and

$$I_{k,\text{SLM}}^{(u)} = \frac{\sigma_w^2}{N} \sum_{l=0}^{N-1} \sum_{k=0}^{N-1} X_l B_{u,k} \left| X_k \right|^2 e^{j2\pi (l-k)/N}. \quad (18)$$

The normalized DSR is computed for the $U$ branches using the set of phase vectors $\{B^{(0)}, \ldots, B^{(U-1)}\}$ and the branch with the minimum DSR is selected for transmission, where,

$$\text{DSR}^{(u)} = \left| I_{\text{SLM}}^{(u)} \right|^2, \quad (19)$$

and $I_{\text{SLM}}^{(u)} = \left[ I_{0,\text{SLM}}^{(u)}, \ldots, I_{N-1,\text{SLM}}^{(u)} \right]$.  

### 4. NUMERICAL RESULTS

Monte Carlo simulation is used to assess the performance of the proposed system and compare it to other well established PAPR reduction techniques. The simulation results are obtained using $10^5$ OFDM blocks generated using $N = 1024$, the data symbols are selected uniformly from a Gray coded QPSK/QPSK symbol constellation. The SLM technique is set to use $U = 4$. For this technique, the possible phase factors are 2 selected uniformly from $B^{(u)} \in \{1, -1\}$, $u = 0, 1, \ldots, U-1$. The TWTA is modelled as described in (9) with $OBO = 7.2$ dB. The phase coefficients are assumed to be known at the receiver side.

In this paper, we estimate the CCDF of DSR which is defined as the probability that the DSR is greater than a reference value denoted as $\text{DSR}_0$. Fig. 2 depicts the CCDF of the DSR for the HM-OFDM system with SLM scheme in the presence of the TWTA. As it can be noted from this figure, the SLM-PAPR and the proposed SLM-DSR can achieve an improvement of about 2.3 dB, respectively, at $10^{-4}$ CCDF as compared to the HM-OFDM case without SLM scheme.

The effective SNR (ESNR) is used to assess the performance of OFDM systems with various schemes,

$$\text{ESNR} = \frac{P}{\sigma_w^2 + \sigma_I^2}, \quad (20)$$

where the variance of the interference is denoted as $\sigma_I^2$. The ESNR for the HM-OFDM case, the SLM-PAPR and the proposed SLM-DSR scheme is depicted in Fig. 3. The difference between the SNR and ESNR indicates the degradation caused by the TWTA nonlinearity. As an example, consider the case of the HM-OFDM without any PAPR reduction, a degradation of about 8.5 dB can be noted at a SNR of 25 dB. Invoking the SLM technique using the DSR metric provided an improvement of about 1 dB compared to the HM-OFDM only case.

The BER performance of the proposed DSR and the other considered schemes is presented in Fig. 4 for HM constellation. It can be noted that the SLM-PAPR can achieve an improvement of about 0.5 and 0.2 dB, respectively, at $10^{-4}$ BER for BL and EL; whereas, the proposed SLM-DSR provides an extra improvement of 0.4 and 0.2 dB, respectively. It is apparent that the proposed SLM-DSR is a more accurate indicator for the interference generated by the TWTA and HM.
5. CONCLUSION

This work presented a new technique for PAPR reduction in HM-OFDM-based satellite systems. The proposed method demonstrated that less-direct PAPR indicators may provide better performance when combined with distortionless techniques such as the SLM. The proposed technique is based on using the distortion level to indicate the PAPR, and hence, select the optimal system parameters. Measuring the distortion is less complex than the PAPR as it does not require oversampling. Moreover, designing the system to minimize the ICI and hence MIL provided better BER performance when compared to other techniques, which are optimized to reduce the PAPR.

6. REFERENCES


