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Original Article

Reducing Effect of the Nonlinear Distortion in *M*-QAM OFDM System by Pilot-Based Automatic Phase Shift

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Abstract - *The very high PAPR of M-QAM OFDM systems makes them sensitive to nonlinear distortion caused by HPA, resulting in a steep drop in system performance. There are numerous ways to prevent nonlinear distortion in both the transmitter and the receiver. In OFDM systems, the pilot is used to estimate channels efficiently. It has been found that pilot can be used to help reduce the effect of nonlinear distortion in the system. The use of pilot tones to determine automatically the additional phase shift of subcarriers is presented in this paper. Without relying on the HPA or system specifications, the phase angle is automatically rotated based on the phase mismatch between the transmit and received pilots.*

Keywords - *APS-pilot, HPA, Nonlinear distortion, OFDM.*

1. Introduction

Nonlinear distortion is the signal distortion caused by nonlinear elements of the channel. Nonlinear distortion caused by High Power Amplifier (HPA) in Orthogonal Frequency Division Multiplexing (OFDM) systems is very severe because the Peak-to-Average Power Ratio (PAPR) of the signal is very high [1]. The countermeasures to nonlinear distortion in the transmitter include using linear HPAs, using Back-Off (BO) optimal [2, 3], using pre-distorter [4-7], and reducing PAPR with OFDM systems [8-11], methods to reduce nonlinear distortion in the transmitter are often preferred. However, it does not completely eliminate the effects of nonlinear distortion caused by HPA, especially with amplitude modulation signals, such as M-ary Amplitude Phase Shift Keying (MAPSK) OFDM and M-ary Quadrature Amplitude Modulation (M-QAM) OFDM. Consequently, steps must be taken to compensate for nonlinear distortion at the receiver. Measures to reduce the effects of nonlinear distortion caused by HPA in the receiver include postdistortion, nonlinear equalization [12], iterative detection methods [13], and the Optimum Additional Phase Shift (OAPS) method [14].

With amplitude modulated signals QAM or APSK, under the effect of the nonlinear distortion caused by HPA, the received signal appears as clusters of points on the phase plane rotated counterclockwise and approaching the decision border. Thus, the symbol error rate increases. The OAPS method rotates the received carrier phase counterclockwise. Hence, the decision border also rotates, thereby increasing the distance from the cluster points to the nearest decision border, improving the system's performance. The OAPS approach was employed in earlier research because it may be carried out at the receiver of the M-QAM system with comparatively good performance, particularly for systems that are very sensitive to nonlinear distortions like OFDM [14]. The OAPS method is implemented as follows: If an HPA is given at a certain BO, the dd value (distance degradation, a parameter of nonlinearity [14]) can be calculated from the M-QAM signal constellation, and the optimal additional phase rotation angle will be found by empirical formula between OAPS and dd in the useful BO range; Based on this empirical formula, receiver manufacturers will manually set the OAPS value. However, this method is complicated and inflexible when the HPA, the number of modulation levels M or the number of subcarriers in an OFDM symbol are changed. On the other hand, over time, the parameters of the HPA change due to aging, so the preset value of the phase rotation angle is no longer optimal. These limitations motivate the continued research to improve the OAPS method.

The pilot signal is the signal pattern known in advance to both the transmitter and receiver of amplitude modulation OFDM systems. Pilots are transmitted continuously along with the useful signal source to perform channel estimation in OFDM systems [15-19]. Based on this, the questions are: Is it possible to reduce the impact of nonlinear distortion on OFDM systems by using pilots? Is using phase rotation based on pilots as effective as the OAPS method? By simulating over a long timeframe, the results in the paper showed that the APS-pilot (pilot-based Automatic Phase Shift) method is highly effective in reducing the effect of nonlinear distortion without the need to know in advance the number of subcarriers or the HPA parameters. In other words, neither the empirical formula for calculating OAPS nor the manual preset of OAPS at the receiver is required. Following the introduction, the paper is structured as follows: Section 2 presents the OFDM system model using the APS-pilot approach; Section 3 presents the findings and discussions of the simulation results. Section 4 presents the conclusion.

2. System Model and APS-Pilot Method

2.1. OFDM System Model

Figure 1 displays the simulation model of the OFDM system.

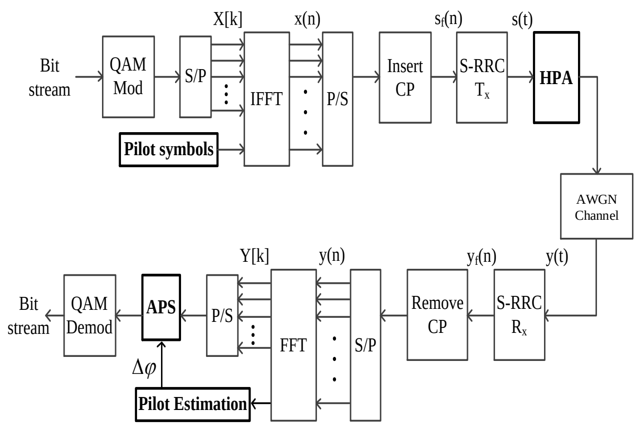


Fig. 1 Surveying model of OFDM system using APS-pilot method

After M-QAM modulation, the Serial/Parallel (S/P) converter splits the symbol stream into several substreams, and the Inverse Fast Fourier Transform (IFFT) converter modulates OFDM. The pilot signals are then inserted into the IFFT to estimate the whole channel effect, including the HPA distortion. In this paper, these pilots are inserted in the frequency domain. After OFDM modulation, the signal is inserted with a Cyclic Prefix (CP) protection interval to prevent Inter Symbol Interference (ISI). It is passed through a square root raised cosine filter for pulse shaping and is then amplified by the HPA and transmitted on the Additive White Gaussian Noise (AWGN) channel.

The receiver carries out the inverse of the transmitter's functions. The pilot estimation and the APS are two blocks that reduce the impact of nonlinear distortion. Since the receiver's channel equalizers are supposed to remove linear distortions from the radio channel, the channel is assumed to be AWGN since we only looked at the impact of nonlinear distortion.

2.2. HPA Model

The HPA is normally described by the AM/AM and AM/PM conversions. Given the input symbol in the form of:

$$s = r \cdot e^{j\theta} \tag{1}$$

Then, the output signal with AM/AM and AM/PM effects has the following form:

$$\hat{s} = A(r) \cdot e^{j\varphi(r)} \cdot e^{j\theta} \tag{2}$$

Where r and θ are the amplitude and phase of the HPA input signal, respectively, $A(r)$ and $\varphi(r)$ are the AM/AM and AM/PM conversions.

$$A(r) = \frac{\alpha_a r}{1+\beta_a r^2}; \quad \varphi(r) = \frac{\alpha_p r^2}{1+\beta_p r^2}, \tag{3}$$

Where α_a, β_a and α_p, β_p are the parameters of the Saleh model [20].

Since literature rarely provides genuine HPA data, traveling-wave-tube amplifiers that Nguyen et al. [14] have employed in earlier research were used in these simulations. These amplifiers, which go by the names of HPA267, HPA1371, and HPA1373, include features provided by manufacturers or by the Saleh model. With different BOs, different nonlinearities can be obtained. The BO values used for OFDM system simulation are the mean BOs (BO_m).

2.3. APS-Pilot Method

Nonlinear distortion affects the signals in the *M*-QAM constellation, causing the received signal points to tend to deviate from the ideal points of the transmitted signal in a counterclockwise direction, as shown in Figure 2 (for symmetry, only a quadrant of the signal constellation is shown).

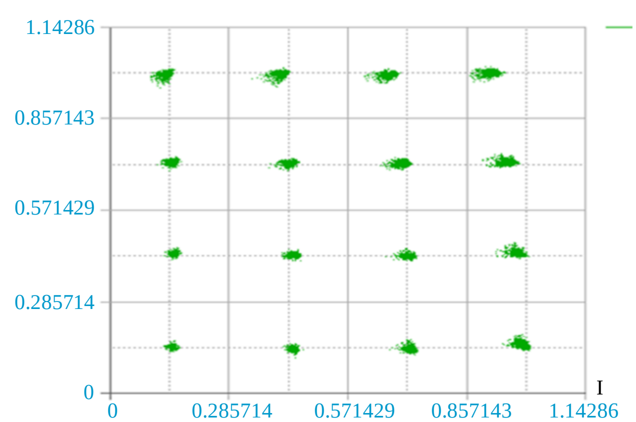


Fig. 2 Effects of nonlinear distortions in the 64-QAM signal constellation on a subcarrier

The APS-pilot method is implemented as follows: In the transmitter, the Transmitted pilot (TX pilot) is inserted during the OFDM modulation process. When the pilot passes through the HPA, information about the nonlinear distortion of the HPA will be carried out. At the receiver, the pilots obtained from the output of the OFDM demodulator enter the pilot estimation block. This block will calculate the average value of the received pilots as RX pilots, then compare it with the TX pilot stored in the reeeiver to calculate the value $\Delta\varphi$. This value is then fed into the APS block to rotate the received signal phase clockwise by an angle $\Delta\varphi$, as shown in the diagram in Figure 3 (instead of rotating the received carrier phase counterclockwise as in the original OAPS method). Based on the phase difference between the transmitted and received pilots, the APS-pilot approach assists the receiver in the automatically rotating phase.

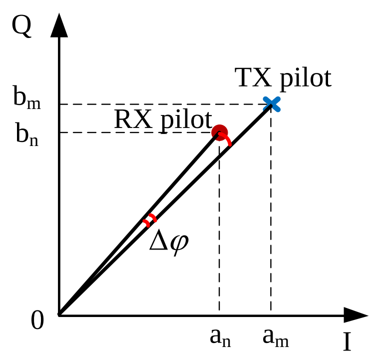


Fig. 3 Determining the angle $\Delta\varphi$ of the pilot estimation block

3. Simulation Results and Discussions

Matlab software was often used to compare the OAPS and APS-pilot methods. The simulation exploits the OFDM system model shown in Figure 1, with the algorithm flow chart given in Figure 4.

The parameters used in the *M*-QAM OFDM system simulation were:

- OFDM modulation: IFFT/FFT size is 256;
- Pilots are inserted in the frequency domain; the pilot signal is inserted with the distance between pilots being Nps=4; the symbol value used in the pilot is 1+1i; the CP guard interval is 1/5 of the integration interval length.
- Number of simulation bits and *M*-QAM modulation: With 16-QAM system, the number of random bits is 153600000 (a sequence of 2000000 consecutive OFDM symbols, each OFDM symbol consists of 768 bits and is modulated in parallel on 192 subcarriers, each subcarrier is 16-QAM baseband modulated, which means each subsymbol period T_u contains 4 bits); With 64-QAM system, the number of random bits is 230400000 (a sequence of 2000000 consecutive OFDM symbols, each OFDM symbol consists of 1152 bits and is modulated in parallel on 192 subcarriers, each subcarrier is 64-QAM baseband modulated, which means each sub-symbol period T_u contains 6 bits). The number of OFDM symbols selected is large to ensure accurate results with less than 0.1 dB dispersion. The number of bits in each OFDM symbol is chosen based on the size of the FFT set and the number of pilots inserted; a large FFT size is intended to have a system with a high PAPR.
- Transmitter and receiver filters are chosen as usual: Square root raised cosine filters: Delay Group = 10, Rolloff factor = 0.35, input sampling rates F_d = 1, output sampling rates F_s = 8.

It has been hoped that the Monte-Carlo simulation will yield highly accurate findings.

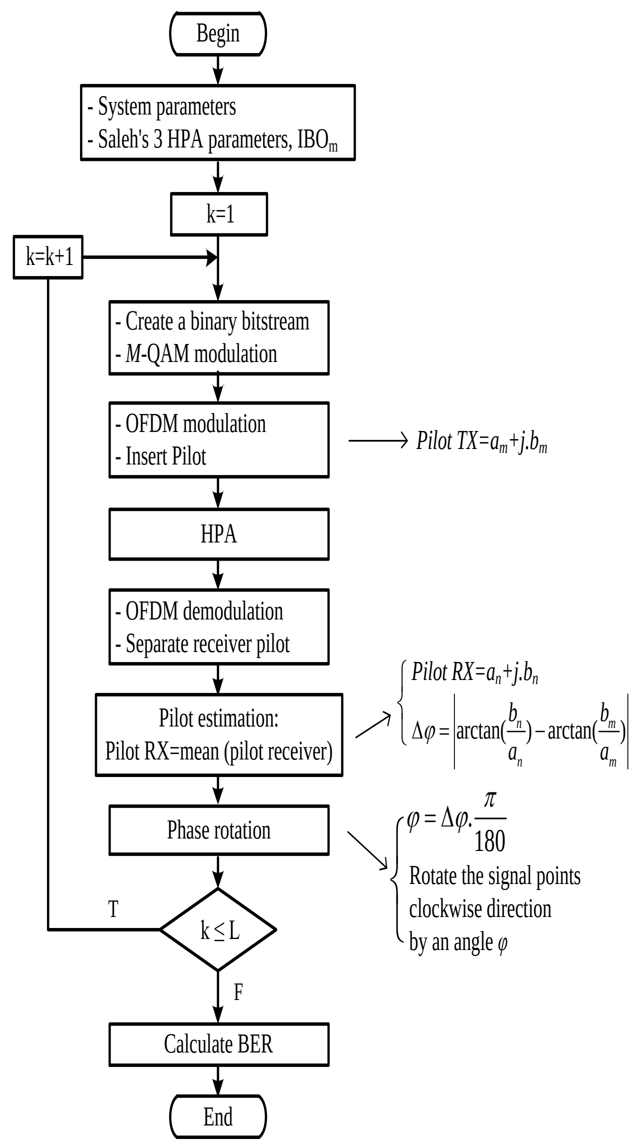


Fig. 4 Algorithmic flow diagram of the APS-pilot method

3.1. Selecting the Symbol Transmitted on the Pilot

There are sixteen values in the 16-QAM signal constellation. The choice of symbol pilot can be one of these sixteen values so that the selected pilot will have the optimal value. Only the symbols in the first quadrant will be considered due to 16-QAM constellation symmetry, which includes four values: 1+1i, 1+3i, 3+1i and 3+3i. Nonlinear distortion affects different signal points in the 16-QAM constellation differently. Signal points with smaller amplitude values will be less affected by nonlinear distortions. If the transmitted signal is 1+1i, a relatively evenly distributed signal cluster is obtained around a point, and this point is deviated counterclockwise by a small angle compared to the transmitted signal. The BER curve of the system using APS-pilot 1+1i is closest to the BER curve for an ideally linear HPA. The BER curve of a linear HPA is the BER curve of the system with completely linear HPA. Vice versa, signal points with larger amplitude values will be affected more by larger nonlinear distortions. If the transmitted signal is 3+3i, the received signal is an unevenly distributed signal cluster that is more deviated from the transmitted signal. Therefore, the BER curve of the system using APS-pilot 3+3i is farthest from the BER curve of the system with linear HPA. APS-pilot with pilot symbol 1+1i will perform better than symbols 1+3i, 3+1i or 3+3i.

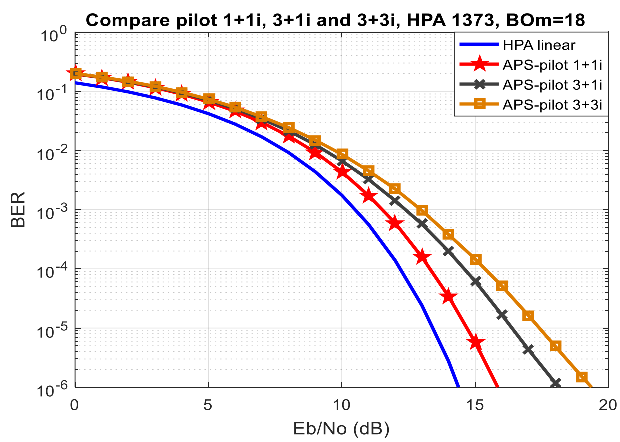
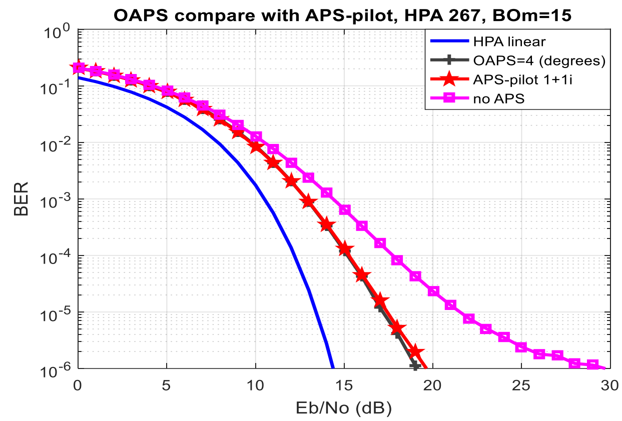
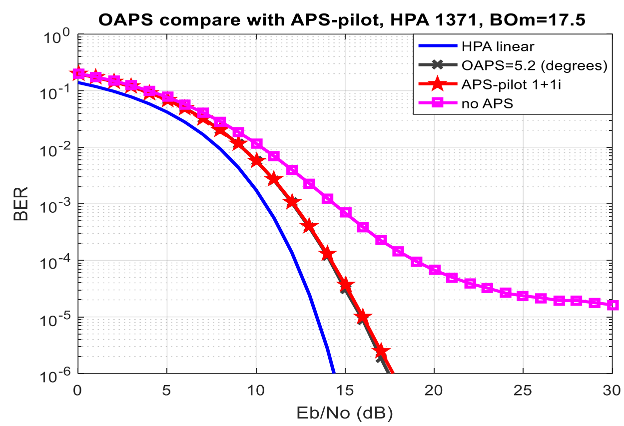


Fig. 5 Comparing the BER curve of the system using APS-pilot with symbols 1+1i, 3+1i, 3+3i

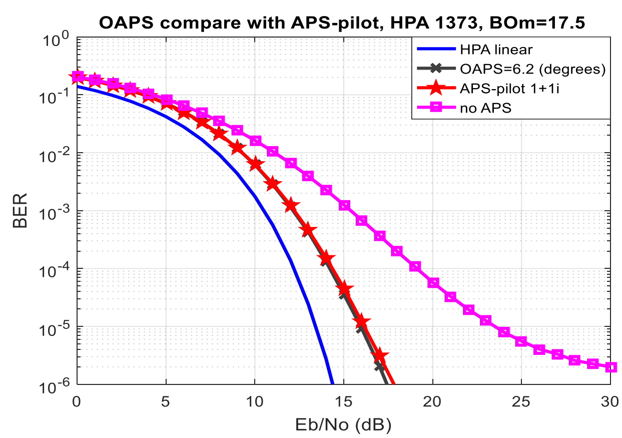
Figure 5 shows the BER curve simulation result for the 16-QAM OFDM system using APS-pilot with symbols 1+1i, 3+1i, 3+3i, HPA1373, BO_m=18 [dB]. A pilot symbol pattern exists with the optimal additional phase shift value, but finding this optimal value is more complicated. As the pilot with the symbol 1+1i gets results that are very close to the optimal value, for simplicity, the symbol pilot 1+1i is chosen for the APS method. In the 16-QAM OFDM systems, the pilot used for channel estimation to compensate for linear distortion often uses the symbol 3+3i = 3*(1+1i). Suppose we insert a pilot with the symbol 1+1i to estimate the channel, and at the receiver's channel estimator, we set the power multiplier to 9 for the equalizers. In that case, it will be equivalent to inserting a pilot with the symbol 3+3i. Therefore, symbol pilot 1+1i is recommended for the 16-QAM OFDM system to simultaneously reduce the nonlinear distortion caused by HPA and the linear distortion caused by the channel. Then, at the receiver's channel estimator, a reasonable power multiplier will be set ($(\sqrt{M}-1)^2$).



(a)16-QAM, HPA267, BO_m=15 [dB]

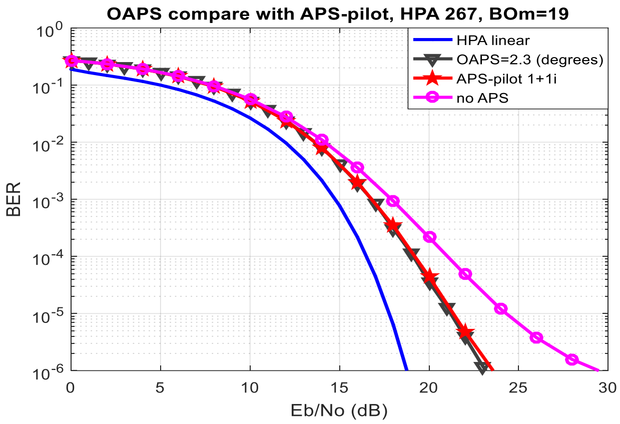


(b) 16-QAM, HPA1371, BO_m=17.5 [dB]

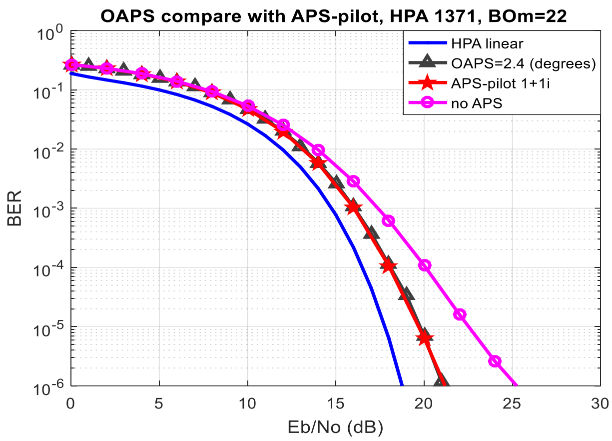


(c) 16-QAM, HPA1373, BO_m=17.5 [dB]

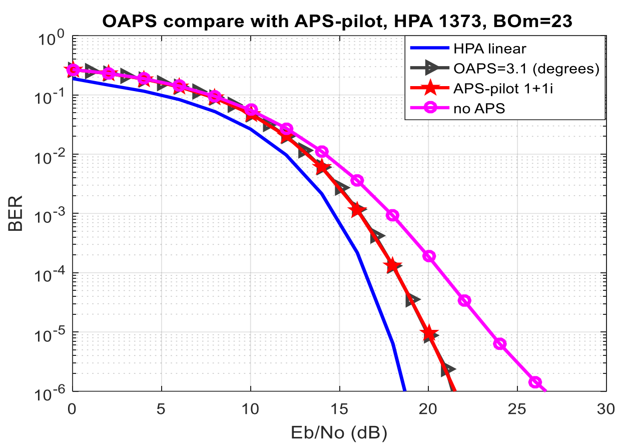
Fig. 6 The BER curve of 16-QAM OFDM system using APS-pilot



(a) 64-QAM, HPA267, BOm=19 [dB]



(b) 64-QAM, HPA1371, BOm=22 [dB]



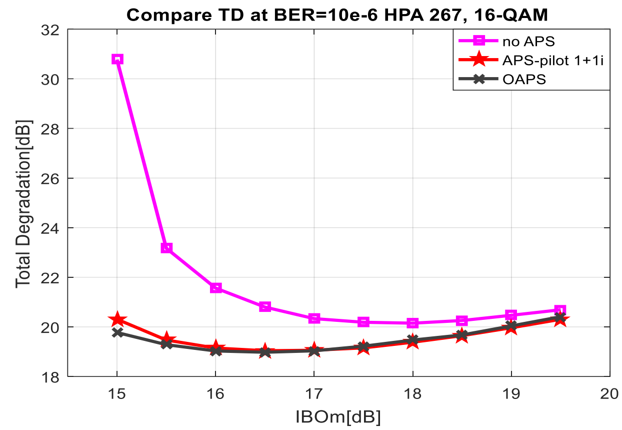
(c) 64-QAM, HPA1373, BO$_m$=23 [dB]

Fig. 7 The BER curve of 64-QAM OFDM system using APS-pilot

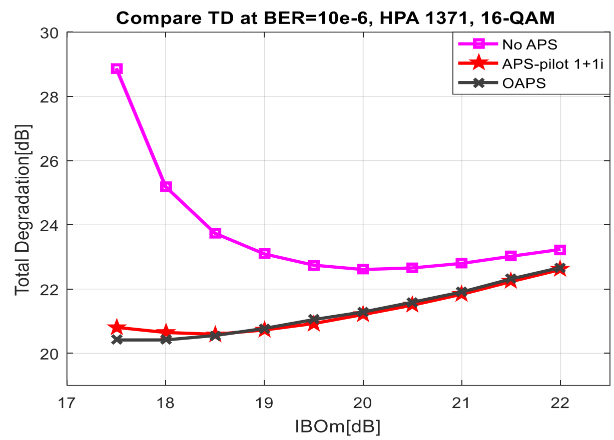
3.2. The BER Curve of the System Using APS-Pilot

The advantages of the APS-pilot method are shown through the BER curves of the system described in Figures 6 and 7. Simulation results in Figures 6 and 7 indicate that:

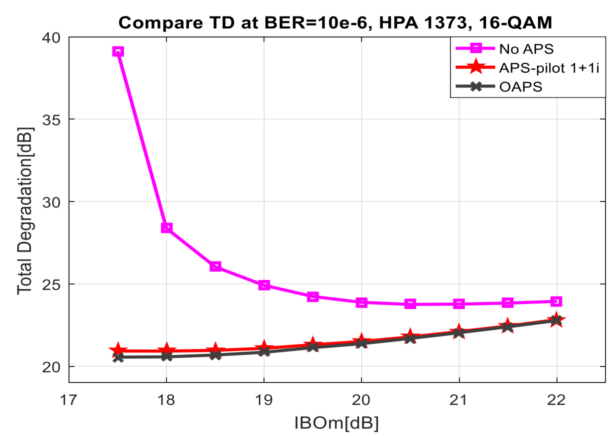
- With the same HPA at a specific BO$_m$ value, the BER curve of the system using APS-pilot 1+1i is close to the BER curve of the system using OAPS. This proves that the effectiveness of the nonlinear distortion reduction of the two methods is almost the same for both 16-QAM OFDM and 64-QAM OFDM systems.
- When the systems do not use APS-pilot or OAPS, the BER curves are very far (to the right) from the BER curve of the systems using APS-pilot. This proves that the APS-pilot method can reduce the effect of nonlinear distortion, resulting in higher performance for the *M*-QAM OFDM system.



(a) 16-QAM, HPA267

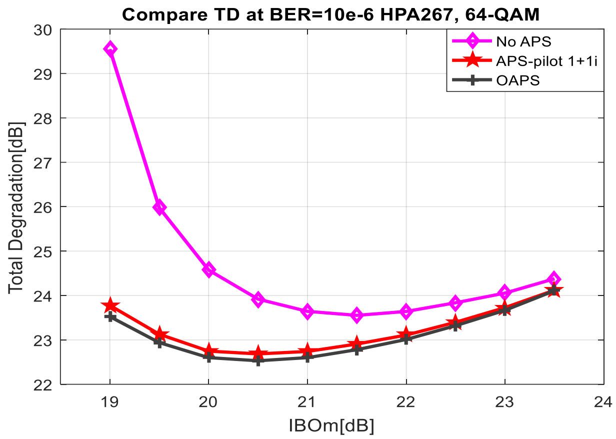


(b) 16-QAM, HPA267

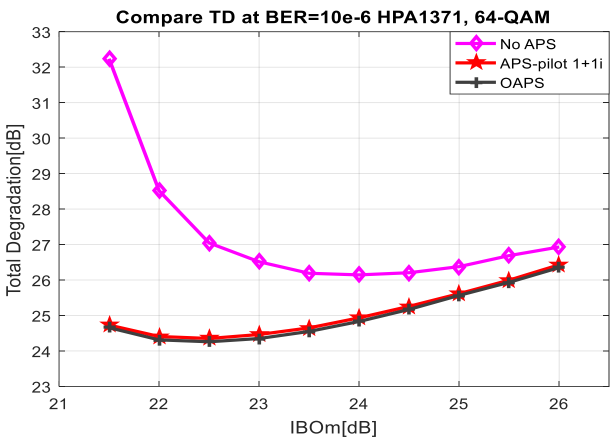


(c) 16-QAM, HPA1373

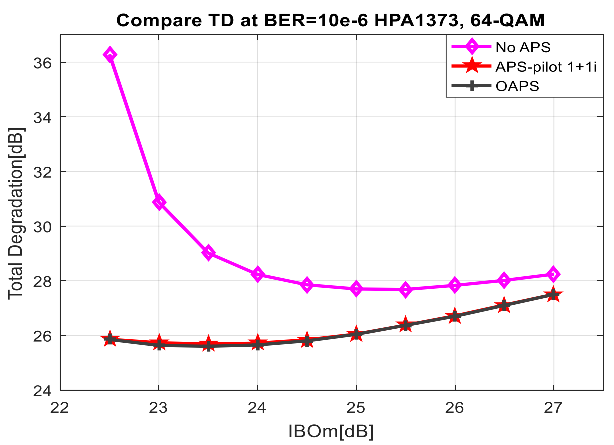
Fig. 8 TD of 16-QAM OFDM system using APS-pilot at BER=10-6



(a) 64-QAM, HPA267



(b) 64-QAM, HPA1371



(c) 64-QAM, HPA1373

Fig. 9 TD of 64-QAM OFDM system using APS-pilot at BER=10-6

3.3. Total Degradation of the OFDM Systems Using APS-Pilot

Total Degradation (TD), a crucial performance parameter, is used to quantify the advantages of phase compensations. It is defined as [21]:

$$TD[dB] = E_b / N_0{}^{NL}[dB] - E_b / N_0{}^{L}[dB] + IBO_m[dB] \qquad (4)$$

Where $E_b/N_0{}^{NL}$ is the E_b/N_0 value required to achieve a given target BER (in this case is 10^{-6}) on the nonlinear channel, $E_b/N_0{}^{L}$ is the same quantity for the linear AWGN channel, and IBO is the input power back-off in OFDM systems using average BO (IBO_m); all quantities are in dB.

Figures 8 and 9 present the change in TD versus IBOm for the system using the APS-pilot and OAPS methods with all 3 HPAs used in simulations. The simulation results in Figures 8 and 9 indicate that Under each HPA's effect, the APS-pilot's TD is always approximately the TD of the system using OAPS. The optimal operating points of HPAs between systems using the two methods are almost the same, as shown in Tables 1 and 2. Thus, in the *M*-QAM OFDM systems, the nonlinear distortion reduction performance of the APS-pilot 1+1i method is approximately the same as in the OAPS method.

Table 1. IBO_{opt} of HPA when 16-QAM OFDM uses OAPS and APS-pilot [dB]

HPA	267		1371		1373	
Method	**IBO_{opt}**	**TD**	**IBO_{opt}**	**TD**	**IBO_{opt}**	**TD**
APS pilot 1+1i	16.5	18.98	18	20.42	18	20.57
OAPS	16.5	18.9	18	20.26	18	20.4
No APS	18	20.15	20	22.61	20.5	23.75

Table 2. IBO_{opt} of HPA when 64-QAM OFDM uses OAPS and APS-pilot [dB]

HPA	267		1371		1373	
Method	**IBO_{opt}**	**TD**	**IBO_{opt}**	**TD**	**IBO_{opt}**	**TD**
APS pilot 1+1i	20.5	22.53	22.5	24.26	23.5	25.6
OAPS	20.5	22.38	22.5	24.20	23.5	25.58
No APS	21.5	23.55	24	26.14	25.5	27.68

The automatic compensation of the phase rotation angle using the pilot will always be optimal for the systems, even if the system parameters change. In fact, this method can be easily implemented at the receiver by inserting pilots when training the system.

However, this method has a small limitation: Small delay due to pilot calculations and estimates and loss of a small portion of bandwidth due to having to insert pilots with large enough quantities to ensure accurate estimation.

4. Conclusion

A pilot-based automatic phase shift is introduced in this paper to improve system performance under the nonlinear distortion effect. When the *M*-QAM OFDM system uses the APS-pilot method, it provides high performance, as shown in Figures 6 to 9. The advantage of the APS-pilot method is that there is no need to know the system and HPA parameters in advance and no need to preset OAPS at the receiver like the OAPS method manually. However, the effectiveness is still nearly the same as that of the OAPS method. This allows HPA to push its operating point closer to saturation while still maintaining the same system performance. In fact, this leads to beneficial consequences such as reducing the size of the equipment, saving power, and increasing the life time of the battery.

The simulation results in Figure 5 show that symbol pilot 1+1i has high performance in reducing nonlinear distortion. Therefore, symbol pilot 1+1i is recommended for the M-QAM OFDM system to simultaneously reduce nonlinear distortion caused by HPA and estimate the transmission channel.

One possible research is to consider using the APS-pilot method to reduce the effect of nonlinear distortion in the MIMO OFDM system.

Acknowledgement

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