

Design and Performance Analysis of Pre-Distorter Including HPA Memory Effect

Dong Geon An · Il-Jin Lee · Heung-Gyoon Ryu

Abstract

OFDM(Orthogonal Frequency Division Multiplexing) signals suffer serious nonlinear distortion in the nonlinear HPA(High Power Amplifier) because of high PAPR(Peak Average Power Ratio). Nonlinear distortion can be improved by a pre-distorter, but this pre-distorter is insufficient when the PAPR is very high in an OPFDM system. In this paper, a DFT(Discrete Fourier Transform) transform technique is introduced for PAPR reduction. It is especially important to consider the memory effect of HPA for more precise predistortion. Therefore, in this paper, we consider two models, the TWTA(Traveling-Wave Tube Amplifier) model of Saleh without a memory effect and the HPA memory polynomial model that has a memory effect. We design a pre-distorter and an adaptive pre-distorter that uses the NLMS(Normalized Least Mean Square) algorithm for the compensation of this nonlinear distortion. Without the consideration of a memory effect, the system performance would be degraded, even if the pre-distorter is used for the compensation of the nonlinear distortion. From the simulation results, we can confirm that the proposed system shows an improvement in performance.

Key words : OFDM, PAPR, HPA, DFT, Pre-Distorter, NLMS, Memory Effect.

I. Introduction

The OFDM(Orthogonal Frequency Division Multiplexing) system has been used in high speed digital communication areas such as DAB(Digital Audio Broadcasting), DVB(Digital Video Broadcasting), and Wireless LAN(local area network), due to robust multi-carrier modulation to multi path fading channels^[1]. However, the OFDM system has serious disadvantages of the high PAPR(Peak Average Power Ratio)^[2]. Therefore, an OFDM signal is more susceptible to nonlinear distortion than is a single carrier signal. Moreover, high PAPR leads to poor power efficiency of a HPA(High Power Amplifier) and causes the degradation of BER(Bit Error Rate) performance.

To overcome this problem, many approaches have been proposed. The simplest method is a back-off that forces the OFDM signal to move into a linear region of amplifier. However, this method does not become a true solution because the power efficiency of the amplifier becomes very low. A second method is that of PAPR reduction. A typical PAPR reduction would involve clipping, which cuts the input signal at a fixed level. This is a very simple and efficient method from the viewpoint of reducing PAPR, but it causes a serious in-band and out-of-band clipping noise^[3]. This in turn causes BER performance degradation and adjacent channel inter-

ference(ACI). Other approaches include SLM(Selective Mapping) and PTS(Partial Transmit Sequence), which belong to the phase rotation method^{[4],[5]}. These methods reduce the PAPR level, but require a prolonged time and a very high complexity. DFT transform is another efficient method for reducing the PAPR level in general, it is considered as very good PAPR reduction method that does not require side information^{[6]-[8]}. One last method is the use of a pre-distorter, which distorts the OFDM signal before it passes through the HPA^{[9],[10]}.

However, use of a pre-distorter is insufficient when PAPR is as high as occurs in an OPFDM system. Therefore, in this paper, the DFT(Discrete Fourier Transform) transform technique is additionally discussed for PAPR reduction. In addition, it is also important to consider the memory effect of HPA for a more precise predistortion. Therefore, we also consider two models, including the TWTA(Traveling-Wave Tube Amplifier) model of Saleh that involves no memory effect and the HPA memory polynomial model that has a memory effect. We design a pre-distorter and an adaptive pre-distorter that uses the NLMS(Normalized Least Mean Square) algorithm for compensation of this nonlinear distortion. In addition, we show the performance variation in the HPA nonlinear characteristics according to a change in IBO(Input Back Off) value when the DFT transform is used for PAPR reduction. Without the consideration of

memory effect, system performance would be degraded even if the predictor is used for the compensation of the nonlinear distortion. In order to evaluate performance, we use TWTA as a nonlinear HPA that has both AM/AM and AM/PM nonlinear characteristics. We also analyze PAPR reduction and BER performance using QPSK modulation and 64 sub-carriers in the AWGN channel. From the simulation of performance analysis, we can confirm that the proposed system shows an improvement in performance.

II. The OFDM Communication System and PAPR

The OFDM symbol can avoid ICI(Inter-Symbol Interference) because it is extended cyclically, since part of the OFDM signal is copied and arranged as in the guard interval.

Fig. 1 is block diagram of the OFDM system in an AWGN(Additive White Gaussian Noise) channel. In general, the output signal of the OFDM is as follows:

$$x(t) = \frac{1}{N} \sum_{l=0}^{N-1} X[l] e^{j2\pi f_l t} = \frac{1}{N} \sum_{l=0}^{N-1} X[l] e^{j2\pi l t / NT_s} \quad (1)$$

where N is the number of sub-carriers, T_s is symbol duration, $f_l = l/NT_s$ is l^{th} sub-carrier frequency. Because $t = nT_s (n=0, \dots, N-1)$, $x(t)$ is:

$$x[n] = x(nT_s) = \frac{1}{N} \sum_{l=0}^{N-1} X[l] e^{j2\pi l n / N} \quad (2)$$

$X[l]$ is modulated data in the mapper. Input data modulated by PSK(Phase Shift Keying) or QAM(Quadrature Amplitude Modulation) complex the data symbol through the mapper. After this complex data symbol passes through S/P(Serial to Parallel) and IFFT(Inverse Fast Fourier Transform) and P/S(Parallel to Serial), an OFDM output signal $x(t)$ is produced. This OFDM signal passes through nonlinear HPA and AWGN channels.

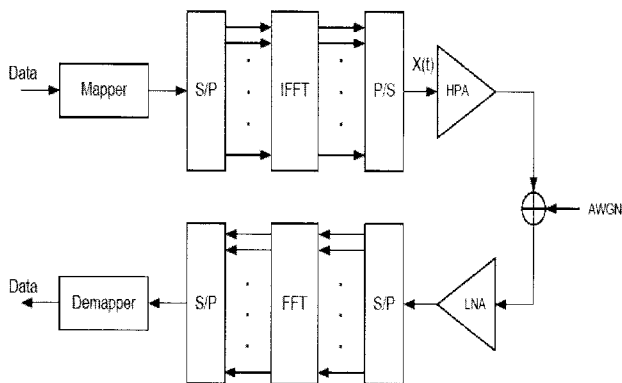


Fig. 1. Block diagram of the OFDM system.

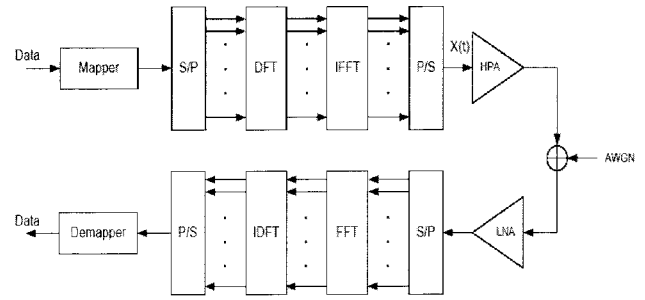


Fig. 2. Block diagram of the DFT method.

The receiver gets back the OFDM information signal through reverse operation of the transmitter.

The PAPR in the OFDM signal is defined as:

$$PAPR \equiv \max_{0 \leq t < T} \frac{|x(t)|^2}{E[|x(t)|^2]} \quad (3)$$

In this case, $E[\cdot]$ means the average.

III. The DFT Spreading Method

The OFDM block diagram of the DFT method is shown in Fig. 3. The overall diagram takes the shape of inserting a DFT block in front of an IFFT block of the ordinary OFDM. This process is effective for the PAPR reduction in the final output signal.

If the row of DFT block input is $y = [y_0, y_1, \dots, y_{M-1}]^T$, the DFT spread signal after passing the DFT block is as follows:

$$Y_k = \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} y_m \cdot e^{-j2\pi mk/M}, \quad (k=0, 1, \dots, M-1) \quad (4)$$

In the sub-carrier allocation block, '0' is added to the row of the DFT spread signal Y . The number of '0' is $N-M$. The number LZ is in front of Y and the number RZ is in back of $Y (LZ+RZ=N-M)$. On this occasion, $X = [0_0, \dots, 0_{LZ-1}, Y_0, Y_1, \dots, Y_{M-1}, 0_0, \dots, 0_{RZ-1}]^T$ is the row of the signal and its size is $[1 \times N]$. After X , the row of the signal of length N that gets through the sub-carrier allocation block, past the IFFT block, is the transmitted signal as follows:

$$\begin{aligned} x(t) &= \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n \cdot e^{j2\pi n \Delta f t} = \frac{1}{\sqrt{N}} \sum_{n=LZ}^{LZ+M-1} Y_{n-LZ} \cdot e^{j2\pi n \Delta f t} \\ &= \frac{1}{\sqrt{N} \cdot M} \sum_{n=LZ}^{LZ+M-1} \sum_{m=0}^{M-1} y_m \cdot e^{-j2\pi m(n-LZ)/M} \cdot e^{j2\pi n \Delta f t}, \quad 0 \leq t \leq NT \end{aligned} \quad (5)$$

IV. HPA and the Pre-Distorter

The sum of the multi user's signals, X_n has a high

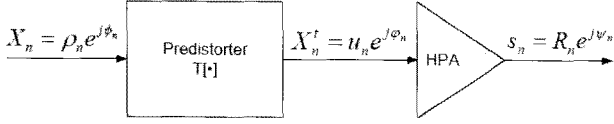


Fig. 3. Block diagram of a basic pre-distorter.

PAPR. To compensate for this, we use a pre-distorter before HPA, as shown in Fig. 3.

Fig. 3 shows the principle of the pre-distorter. A transfer function $T[\cdot]$ is the part that compensates for nonlinearity that is generated when signal is amplified.

In the case of a HPA without a memory effect, the transfer function $T[\cdot]$ is as follows:

In order that the memory effect does not have an effect on the signal, $X_n^r = S_n$ should be matched as in Fig. 3, so that the following condition is satisfied^{[9],[13]}:

$$\begin{cases} \rho_n = A[u_n] \\ \phi_n = \varphi_n + \Phi[u_n] \end{cases} \quad (6)$$

ρ_n and φ_n are the amplitude and phase of the signal before entering the pre-distorter. $A[\cdot]$ and $\Phi[\cdot]$ are the AM/AM and AM/PM of the transfer function. u_n , φ_n are the signals distorted by the pre-distorter. Therefore, the pre-distorter input and output relation is the inverse of equation (6):

$$\begin{cases} u_n = A^{-1}[\rho_n] \\ \varphi_n = \phi_n - \Phi[u_n] \end{cases} \quad (7)$$

In other words, that relation shows the relation of equation(7).

The TWTA has amplitude and phase nonlinear distortion. The AM/AM, AM/PM of TWTA is shown in the following equation. The AM/AM distortion effect is large, but the AM/PM distortion effect is very large. By normalizing the TWTA characteristic, the input and output saturation points are the same as 1.

$$\text{- AM/AM: } A[r(t)] = \frac{2r(t)}{r(t)^2 + A_0^2} \quad (8)$$

$$\text{- AM/PM: } \Phi[r(t)] = \frac{\pi r(t)^2}{3(r(t)^2 + A_0^2)} \quad (9)$$

In the case of TWTA, the AM/AM characteristic is not a one to one correspondence relationship. Therefore, we calculate its inverse function at $p(t) \leq A_0$. If the input amplitude is $p(t) > A_0$, its value is 1 by clipping. Therefore, the AM/AM of the pre-distorter is as follows:

$$\text{- AM/AM: } r(t) = \begin{cases} \frac{1 - \sqrt{1 - \rho(t)^2}}{\rho(t)} & \rho(t) \leq A_0 \\ 1 & \rho(t) > A_0 \end{cases} \quad (10)$$

$$\text{- AM/PM: } \phi[r(t)] = \begin{cases} \frac{(1 - \sqrt{1 - \rho(t)^2}) \cdot \pi}{6} + \phi(t) & \rho(t) \leq A_0 \\ -\frac{\pi}{6} + \phi(t) & \rho(t) > A_0 \end{cases} \quad (11)$$

Using the pre-distorter AM/AM characteristic of TWTA does not have nonlinearity of the input signal before A_0 , but signal distortion is still generated, because the signal after A_0 is clipped. On the other hand, distortion of the AM/PM characteristic disappears completely. In other words, there is the same phase response irrespective of input amplitude.

4-1 Memory Polynomial

$$P_{mem_out}(n) = \sum_{k=1}^K \sum_{q=0}^Q c_{kq} P_{in}(n-q) |P_{in}(n-q)|^{k-1} \quad (12)$$

where P_{mem_out} and P_{in} are output and input of the nonlinear HPA with memory effect.

Odd number polynomial degree PA memory depth is expressed by K and Q . Coefficient c_{kq} is extracted from the Class AB power amplifier^[13].

$$\begin{aligned} c_{10} &= 1.0513 + 0.0904j & c_{30} &= -0.0542 - 0.2900j \\ c_{50} &= -0.9657 - 0.7028j & c_{11} &= -0.0680 - 0.0023j \\ c_{31} &= 0.2234 + 0.2317j & c_{51} &= -0.2451 - 0.3735j \\ c_{12} &= 0.0289 - 0.0054j & c_{32} &= -0.0621 - 0.0932j \\ c_{52} &= 0.1229 + 0.1508j \end{aligned}$$

4-2 NLMS Pre-Distorter

Fig. 4 is a block diagram of a NLMS base-band pre-distorter. The OFDM signal is distorted by passing through a LUT which stores the inverse characteristics of the HPA. This signal is transmitted after it goes through a D/A converter and a nonlinear HPA. The LUT values are updated through feedback and an estimation process of the HPA transformation characteristic by the NLMS algorithm.

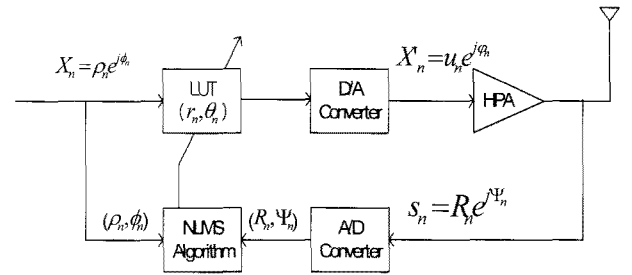


Fig. 4. Block diagram of a NLMS pre-distorter.

The pre-distortion output signal X'_n is the same as amplitude as the baseband OFDM signal X_n .

- Input signal : $X_n = \rho_n e^{j\phi_n}$ (13)

- LUT Output signal : $X'_n = u_n e^{j\varphi_n}$
 $u_n = r_n, \varphi_n = \phi'_n + \theta_n$ (14)

After the D/A converter, this signal is entered at non-linear HPA.

- HPA output signal: $s_n = R_n e^{j\Psi_n}$
 $R_n = A[u_n], \Psi_n = \Phi[u_n] + \varphi_n$ (15)

In this case, $A[\cdot]$ and $\Phi[\cdot]$ are the distortion characteristic functions of AM/AM and AM/PM. This output signal feeds back into the A/D converter and the LUT coefficients are updated regularly through the NLMS algorithm.

- Amplitude and phase error estimation:

$$\begin{cases} e_A = \rho_n - R_n \\ e_P = \phi_n - \Psi_n \end{cases} \quad (16)$$

The NLMS algorithm, which renews the LUT coefficient, is as follows:

$$\begin{cases} r_{n+1} = r_n - \nabla_A e_A \\ \theta_{n+1} = \theta_n - \nabla_P e_P \end{cases} \quad (17)$$

In this case, ∇_A, ∇_P are updated step sizes of amplitude and phase.

V. Simulation Results and Discussion

In this paper, we discuss PAPR reduction and BER performance when DFT spreading for PAPR reduction and pre-distortion and the NLMS algorithm are used for the compensation of the nonlinear HPA with memory effect in an OFDM system. Two types of HPA are considered: HPA without memory effects and HPA with a memory effect. According to the type of HPA, we use a pre-distorter and an adaptive pre-distorter selectively, so as to compensate the nonlinear distortion of HPA.

- Modulation method: QPSK
- Number of subcarrier: N=64
- Oversampling rate: 4
- Channel: AWGN
- HPA: TWTA, Memory polynomial
- Back-off: 0~6 dB

Fig. 5 shows the PAPR characteristics of ordinary OFDM and DFT-OFDM systems. As we can see, the DFT method is good for reducing high PAPR, as PAPR reduc-

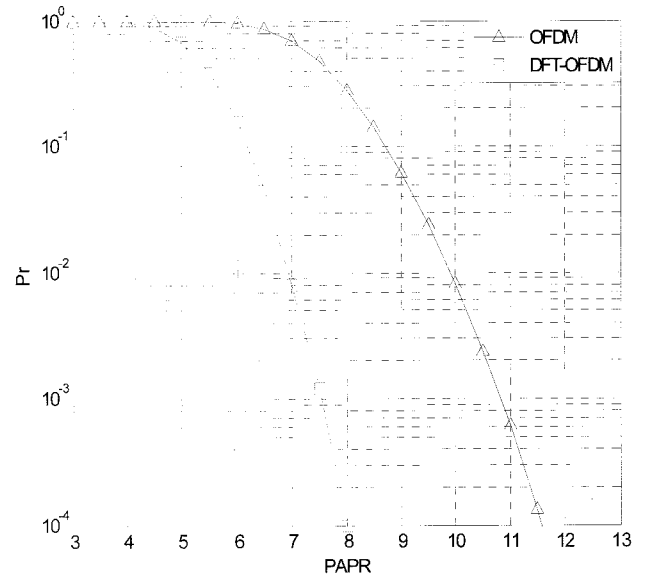


Fig. 5. PAPR reduction effect(QPSK, N=64).

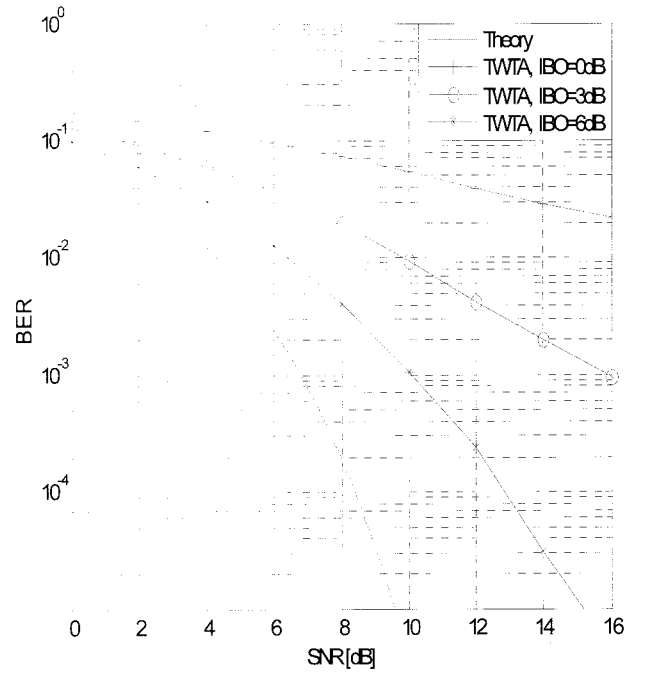


Fig. 6. BER performance of a HPA without a memory effect(TWTA, IBO=0, 3, 6 dB).

tion by DFT spreading is about 3.6 dB in $\Pr(PAPR > PRPR_0) = 10^{-4}$.

Fig. 6 shows BER performance curves in the case when the DFT spreading method is used in the TWTA of a memoryless Saleh HPA, when input back-off is 0, 3, or 6 dB, respectively. Even though the DFT method is used for the PAPR reduction, BER performance is rather poor because of the serious nonlinear distortion. Actually, the TWTA has a very severe nonlinearity. To

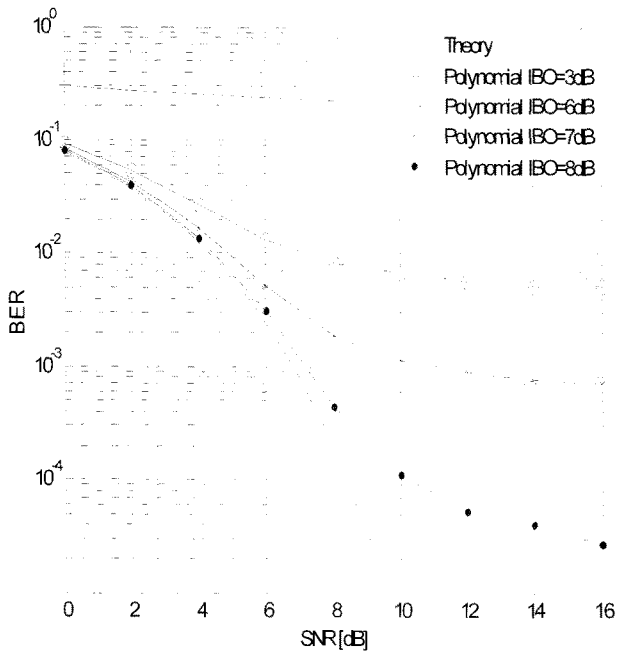


Fig. 7. BER performance of a HPA with a memory effect.

achieve a linear performance, at least 10 dB backoff is necessary.

Fig. 7 shows the BER performance curves when the DFT spreading method is used in the memory polynomial model HPA at the input back-off of 3, 6, 7, or 8 dB. Compared with Fig. 6, the BER curves are much worse because of the memory effect, which results in the previous input signal having an influence on the present signal. Therefore, the BER performance of a HPA with a memory effect is even more degraded than that of a HPA without a memory effect, even if DFT spreading is used for PAPR reduction. At least 13 dB backoff is necessary to obtain a linear performance.

Next, we can consider the effect of a predistorter in reducing the nonlinear distortion. Fig. 8 shows the BER performance curves in the case where the pre-distorter is used, the DFT spreading is used, and the TWTA of a memoryless Saleh HPA is considered. Compared with Fig. 6, the BER performance shown in Fig. 8 is much improved, since the pre-distorter compensates for the nonlinear distortion of the HPA.

Fig. 9 shows the BER performance curves of a HPA with a memory effect when a pre-distorter is used. Even if the predistorter is used, when compared with Fig. 7, the BER performance is not improved in the HPA memory effect situation. Although we used a pre-distorter, the nonlinear distortion is not compensated since the previous signal still exerts a serious influence on the present signal, owing to the memory effect.

Fig. 10 shows the BER performance curve of a polynomial model with a memory effect. It is harder to find

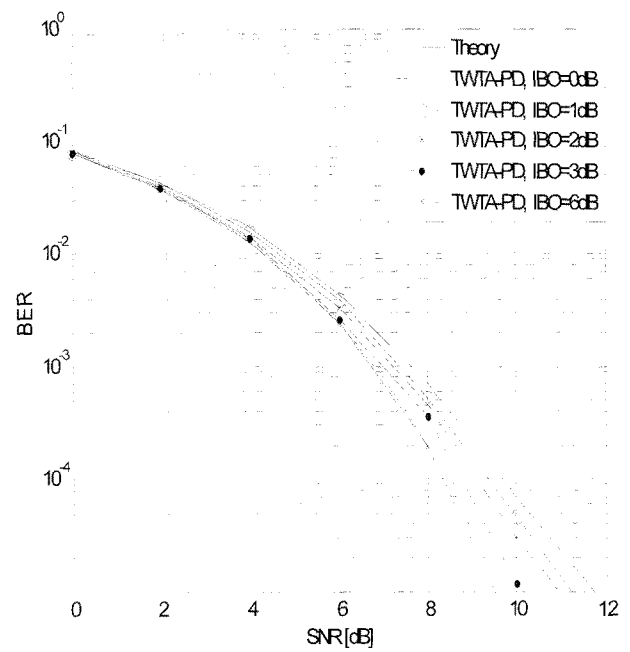


Fig. 8. BER performance without a memory effect (pre-distorter is used).

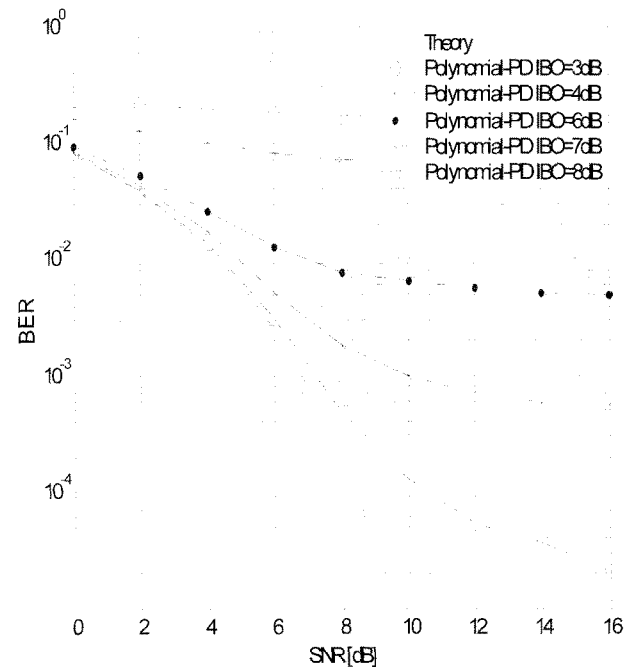


Fig. 9. BER performance with a memory effect (pre-distorter is used).

the inverse function of this memory effect HPA than it is for the memoryless HPA. Even if we find the numerical formula model, the performance is poor because the characteristic is changed by the previous input signal. Consequently, in this paper, we designed an adaptive pre-distorter using the NLMS algorithm, which

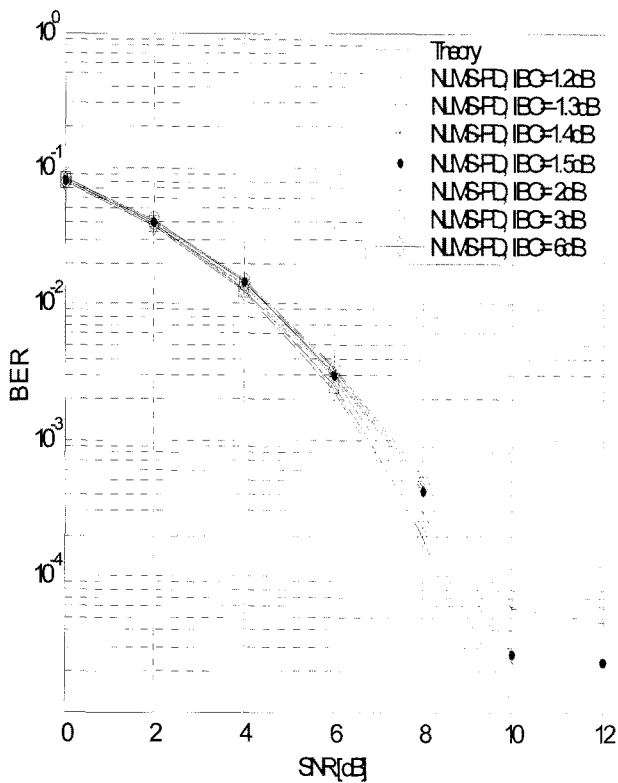


Fig. 10. BER performance of a HPA with a memory effect (NLMS predistorter is used).

worked quite well to compensate nonlinear distortion.

As we can see from Fig. 10, comparing it with Fig. 8, the BER performance is almost the same as that seen for HPA without memory effect except that input back-off is now lower than 3 dB. Therefore, we can make a reasonable compensation for the memory effect HPA with the adaptive pre-distorter using the NLMS algorithm.

VI. Conclusions

In this paper, we have studied the DFT method for PAPR reduction that is combined with an adaptive pre-distorter. The adaptive pre-distorter that uses the NLMS algorithm is a very effective compensation method for HPA nonlinear distortion. We consider two models, the TWTA (Traveling-Wave Tube Amplifier) model of Saleh without a memory effect and the memory polynomial model of HPA with a memory effect. Even without considering a memory effect, system performance would be degraded, if the predictor were to be used for the compensation of the nonlinear distortion. In order to evaluate performance, we used the TWTA as a nonlinear HPA that has both AM/AM and AM/PM nonlinear characteristics, and we analyzed PAPR reduction

and BER performance using QPSK modulation and 64 sub-carriers in an AWGN channel. In a simulation of system performance, PAPR reduction performance of DFT improved by about 3.6 dB over the performance of ordinary OFDM systems at $Pr(PAPR > PRPR_0) = 10^{-4}$. Both HPAs, either with or without memory effects, generated error floors without using any kind of pre-distorter. An error floor was generated even in a HPA with a memory effect using a pre-distorter. However, BER performance was improved when we used a pre-distorter and an adaptive pre-distorter. SNR gain of 10 dB was needed at $BER = 10^{-5}$ in a HPA without a memory effect and at $BER = 10^{-5}$ in a HPA with a memory effect. Therefore, we can compensate well for the memory effect HPA with an adaptive pre-distorter using the NLMS algorithm.

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