CHAPTER 4

COMPENSATION OF NONLINEAR DISTORTION

4.1 NONLINEAR DISTORTION IN OFDM SYSTEMS

OFDM system has been used for high-speed digital communications such as digital audio broadcasting (DAB), digital video broadcasting (DVB), asymmetric digital subscriber line (ADSL) and wireless local area network (WLAN) due to its high bandwidth efficiency, robustness to the narrowband interference and severe multi-path fading. In spite of many advantages, a major drawback of OFDM is a high PAPR problem that causes the nonlinear distortion in HPA and reduces power efficiency. The nonlinear characteristic of HPA is very sensitive to variation in signal amplitudes. So the nonlinear distortion introduced by the HPA is a well known responsive interference in OFDM system due to the large dynamic range of the modulated signal. The disparaging effects of nonlinear distortions are spectral-spreading of the OFDM signal and intermodulation between subcarriers, which are seriously degrade the system performance, investigated by Van den bos et al (2001) & Costa and Pupolin (2002).

4.1.1 Power Amplifiers

Today’s modern wireless communication systems are experiencing explosive growth. The demands for high-speed internet and for the transmission of data, video and multimedia signals stimulate researchers to design devices that provide efficient power amplification with operational linearity. PAs are used to amplify the signal to a desired power level and the
amplified signal is transmitted to a load device, e.g., an antenna. Highly efficient power amplifiers, such as Class C, Class E, Class F, exist, however, they are inherently nonlinear. They introduce distortion in the amplified signal path, especially when non-constant envelope modulation techniques (e.g. BPSK, QPSK, QAM, etc.) are employed, resulting in an undesired effect such as spectral re-growth. Therefore, to exploit their high efficiency, it is desirable to employ linearization techniques to linearize the overall response of these nonlinear amplifiers. The system-level PA model is divided into two types, either with or without a memory effect.

In PA model with memory, the memory effects functioned due to the capacitance and inductance in the circuits and the thermal fluctuation of the PAs, a frequency-domain fluctuation arises in the transfer function of the PA. The memory effects are negligible when the system bandwidth 1MHz - 5MHz. However, the electrical memory effects are severe for the systems using wide-band signal higher than 5MHz and the thermal memory effects are severe for the systems using narrow-band signal lower than 1MHz. A few commonly used PA models with memory effects are Volterra series model, Wiener, Hammerstein, Wiener-Hammerstein models and Memory polynomial model.

In memoryless PA model, the previous PA output signal does not affect the current PA output signal. Amplitude-to-amplitude (AMAM) distortion and amplitude-to-phase (AM-PM) distortion are used for the memoryless model. PM-AM and PM-PM distortions are typically ignored unless they are strong. The commonly used baseband PA models are Saleh model for traveling wave tube amplifier, Ghorbani model for field-effect transistor (FET) amplifier, Rapp model for envelope characteristic of solid state power (especially, class-AB) amplifier with saturation amplitude $V_{sat}$ and smoothness factor $p$ and Soft limiter model for analysis.
The most commonly used power amplifiers for different microwave bandwidths are Travelling Wave Tube Amplifiers (TWTA), and Solid State Power Amplifiers (SSPA).

**Table 4.1 Types of amplifiers for different microwave frequency bands**

<table>
<thead>
<tr>
<th>Name</th>
<th>Frequency Band</th>
<th>Solid State Type</th>
<th>Tube Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-band</td>
<td>10.6 - 10.7 GHz</td>
<td>20 W (GaN device)</td>
<td>3000 W (TWT)</td>
</tr>
<tr>
<td>Ka-band</td>
<td>22 - 36.5 GHz</td>
<td>6 W (0.15 μmPHEMT)</td>
<td>1000 W (klystron)</td>
</tr>
<tr>
<td>Q-band</td>
<td>42.5 - 49.04 GHz</td>
<td>4 W</td>
<td>-</td>
</tr>
<tr>
<td>W-band</td>
<td>86 - 92 GHz</td>
<td>0.5 W (TRW)</td>
<td>1000 W (EIKA)</td>
</tr>
</tbody>
</table>

With respect to modular design of amplifier, SSPA gives more reliable scenario than TWTA. At lower output power, SSPA have the ability of continuous working even a fail occurs in one of its modules. Another important aspect is power supply needed to operate the amplifiers. SSPAs need typically a few volts (between +12 V and +50 V) in contrast with TWTAs, which require supplies of several thousands of volts. From the cost point of view, building a modular TWTA is extremely difficult and expensive because of the complexity of the vacuum tube architecture. Consequently, for the same output power levels, it is possible to build a modular SSPA for the same cost than for an equivalent TWTA.

Even though SSPAs have several advantages on TWTAs, TWTAs are more efficient and less expensive when used at low frequencies. TWTAs have higher linearity than SSPAs. The linearity of power amplifier is measured in-terms of its third-order Intercept Point (IP3) referred to output power level. For a given output IP3, tube amplifiers consume less power than
solid state one. Specific characteristics of each type of amplifiers should be taken on count when choosing one to be used in a specific system.

### Table 4.2 Comparison of TWTAs and SSPAs

<table>
<thead>
<tr>
<th>Specifics</th>
<th>TWTA</th>
<th>SSPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>Simultaneously amplifies all wide range of frequencies.</td>
<td>Physically small.</td>
</tr>
<tr>
<td></td>
<td>Excellent performance in audio and satellite devices.</td>
<td>Amplifies in stages.</td>
</tr>
<tr>
<td></td>
<td>Efficient and less expensive for high power outputs (&gt;10 kW) and high frequencies (&gt;50 MHz).</td>
<td>Can continue working when partial failures occur.</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Difficult to repair. More expensive and complex power supply required. Shorter active life (4 to 6 yrs).</td>
<td>High power consumption.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Instabilities due to failures.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not recommended for low frequencies.</td>
</tr>
<tr>
<td>Applications</td>
<td>High power applications (e.g. remote sensing). Earth stations and communication satellites. Professional audio (e.g. microphones, limiters, equalizers). High-power UHF TV stations. FM broadcast stations. Guitar amplifiers.</td>
<td>Low and medium power applications (e.g. space-flight) AM and FM broadcast transmitters. TV, HF/VHF, lower power UHF, OFDM and HDTV broadcast. Telecommunications. Base station transmitters. Cellular telephone. Radar,</td>
</tr>
</tbody>
</table>
4.1.2 High Power Amplifiers Nonlinearity

Power amplifiers are major source of nonlinearity in communication systems. Generally, a power amplifier is more efficient when it is operated at high power levels. However, this results in distortion at the output of the signal and lost or incomprehensible information at the receiver, examined by Costa et al (1999). Therefore, highly linear power amplifiers are required for efficient wireless communications.

The distortions caused by nonlinearities are classified into two components: the in-band component and out-of-band component. The out-of-band component affects the adjacent bands and causes adjacent channel interference (ACI) but it has no effects on the performance of the actual system, simulated by Santella and Mazzenga (1998). The in-band component affects the performance of the actual system and introduces distortion. The effects of these distortions are: Interference between the in-phase and quadrature (I/Q) components due to AM/PM conversion, Inter-modulation effects on the sub-carriers, Wrapping of the signal constellation in each sub-channel.

The AM-AM characteristic is the conversion between the amplitude modulation present in the input signal and the amplitude modulation present in the distorted output signal. An example of the AM-AM characteristic of a nonlinear amplifier is presented in Figure 4.1(a). Another effect, present in amplifiers is the conversion from Amplitude Modulation to Phase Modulation (AM-PM), illustrated in Figure 4.1(b).

In general, if an amplifier is operated in the linear region, AM-AM and AM-PM characteristics are difficult to measure, since the harmonic components are very small compared to the strong fundamental signal, described by Saleh (1981). The nonlinear characteristics of power amplifier
are represented by AM/AM and AM/PM effects. The AM/AM curve indicates the nonlinear relationship between the output and input envelope (or power). The AM/PM curve shows the output phase shift dependent on the input envelope (or power).

![AM-AM and AM-PM Transfer characteristics for Ideal and Nonlinear amplifier](image)

Figure 4.1 AM-AM and AM-PM Transfer characteristics for Ideal and Nonlinear amplifier

4.1.3 Power Amplifiers Linearization Techniques

There are many techniques to cancel and compensate the nonlinear distortion. According to the different positions they are divided into two classes: transmitter techniques and receiver techniques. Basically, the following linearization techniques are applied at the transmitter to compensate the harmful effects introduced by the nonlinear amplifiers.

- Feedback
- Feed forward
- Linear amplification with nonlinear components (LINC)
- Pre-distortion
Linearization techniques for Narrow-band applications are:

- Cartesian Loop / Polar Loop Feedback
- Analog pre-distortion with nonlinear components
- Envelope Elimination and Restoration (EE&R)
- Linear amplification with nonlinear components (LINC) and
- Combined Analogue Locked Loop Universal Modulator (CALLUM)

Linearization techniques for Wide-band applications are:

- Feedforward
- Adaptive pre-distortion schemes

On the other hand, in receiver technique an algorithm has been designed by reconstructing HPA model at the receiver, to obtain the estimated distortion term and it is eliminated from the received symbols.

The beneficial of amplifier linearization are:

- Reduction of adjacent channel interference (ACI) mainly introduced by the AM/AM nonlinear transfer characteristic in the form of spurious out-of-band spectral components.
- Spectral efficiency and bit-rate improvement.
- Reduction of the in-band distortion introduced by both the AM/AM and AM/PM distortions.
- Increase the power efficiency.
- Linearization allows amplifiers to operate at minimum back-off levels.
4.1.3.1 Cartesian Loop Feedback (CLFB)

In Cartesian loop feedback (CLFB) scheme, the applied input signal is separated into In-phase and Quadrature-phase components, which allows the correction of amplitude gain and phase shift simultaneously, as shown in Figure 4.2. Firstly, the HPA output is sampled and then the low pass feedback components perform an additive pre-distortion of the I-Q components at each input adder. Finally, orthogonal error signals introduced by the nonlinearity were subtracted from the original input. A remarkable advantage of this kind of linearizer is that both the signal modulation and amplification processes are jointly considered in the linearization procedure. That is the non-linear distortions originating in sources external to the HPA are also compensated.

Figure 4.2 Cartesian Loop Feedback
Along with the well known conditional stability, the most remarkable limitation of FB linearizers is their inability to handle wideband signals. Since the time delays are frequency dependent and also associated with the amplifier and other components, it is difficult to make a feedback network respond uniformly to large changes in the frequency of input envelope.

4.1.3.2 Feedforward (FF)

In FF scheme two closed loops are employed for nonlinear distortion cancellation as shown in Figure 4.3. An error signal is generated in the first loop by subtracting the original signal at the HPA input from an attenuated version of the HPA output. Then, in the second loop, the obtained error signal is amplified and subtracted from the aligned RF signal at the output which results distortion-free signal output for transmission.

![Figure 4.3 Feedforward linearizer](image)

Major disadvantages on the exemplified FF technique include power efficiency loss associated to the need of high gain amplification of the error signal, dissipation loss at the final power coupler, complexity of time aligning adjustments and other minor path attenuations. Furthermore, to achieve good linearization, the auxiliary error amplifier must be well designed and set to
operate quite linearly in order to keep the compensation signal free from its own distortion, described by Wilkinson and Kenington (1992). In general, FF can be considered rather complex to implement and hard to incorporate into an existing amplifier structure. Nevertheless, it is easy to find a variety of fixed and adaptive structures, developed by Zozaya et al (2001) based on this principle, starting from the first registered works patent registered by Black (1929 and 1937) and applications for modern single and multicarrier systems, patent registered by Cavers (1996). In practice, FF has been more extensively implemented for SSPAs linearization, given that this type of amplifier presents a low AM/PM distortion level in contrast to TWTAs.

4.1.3.3 Pre-Distortion Model

As previously claimed, along with the feedback and feedforward, pre-distortion is so far one of the most extended linearization techniques. In Pre-distortion (PD), the nonlinear compensation is applied before the signal is presented to the nonlinear HPA input as shown in Figure 4.4.

![Figure 4.4 Block diagram for adaptive digital pre-distortion](image)

**Figure 4.4 Block diagram for adaptive digital pre-distortion**

In the general block PD scheme, the transmitted RF signal from the output of the HPA is down converted and split into discrete quadrature components. The base-band samples are then given to an adaptation algorithm which are basically compares them with the corresponding samples of the
reference input signal, providing information periodically to the adaptation algorithm. The setting parameters of the PD process, which is completely performed in the discrete domain, are updated by searching for the minimum I/O error, in such a way that after a short convergence time the PD block could operate as the exact inverse to the base-band equivalent HPA transfer characteristic.

It is possible to find many different configurations for digital PD processing systems. However, all configurations have the same basic principle. Hence Digital Pre-Distortion has in turn proved to be the most suitable solution for adaptive linearization in wideband communications because of its relative implementation simplicity with low power consumption and its integrability in existing non-linear transmitters, algorithm proposed by Katz (2001) & Zhou and DeBrunner (2007).

Many proposals and implementations based on analog circuitry are open loop second or third-order pre-distorters intended to work either at IF or even higher (near microwave) carrier frequencies, expressed by Cho et al (2002). When the PD output is specified as the new input to the HPA nonlinear function, a one-to-one linear mapping between the input and output of the PD plus HPA combination is produced.

The first suggested and still widely employed digital PD type is mapping PD. This mapping is based on the use of a look-up table and additional DSP techniques for fitting and estimation. By using 2D LUT the complex input signals composed of the I-Q components and it can be mapped to a new constellation of Cartesian components. Usually, RAM space is used to store the additive PD values for the I-Q components. The disadvantages of this method are, a large size of LUTs needed to reach high accuracy and dependence on the sampling rate of the system. A general limitation for all digital PD schemes is its dependence on the system sampling rate.
More memory efficient applications have been developed using Polar PD instead of Cartesian mapping. In this system the adaptation times are minimized using interpolation to accelerate the LUT filling; consequently there is a considerable reduction in the table size, which increases the memory efficiency. The amplifier characteristic on this system depends on only the input modulus. The rectangular to polar conversions involved in this technique introduces an increased computational load, which makes the major limitation on this system. Another drawback of polar PD is, its performance depends on the perfect adjustment of quadrature modulators and demodulators, investigated by Cavers (1997) and Ren and Wolff (1999).

4.2 PRESENT NONLINEAR DISTORTION COMPENSATION TECHNIQUES FOR OFDM SYSTEMS

Different approaches have been carried out to combat the effect of nonlinearities in OFDM systems. They mainly focus on Peak-to-Average Power Ratio (PAPR) reduction and compensation techniques, proposed by Jeon et al (1997) and Behravan and Eriksson (2002). This section provides a brief description of some of these techniques.

4.2.1 Pre-distortion Method

One approach for reducing the effects on nonlinearities is the use of pre-distortion techniques. These techniques aim to compensate the distortions caused by the amplifier before feeding the signal into it. This is, to modify the signal before the amplification process takes place so that the output of the amplifier is closer to the original signal. These modifications can be performed either in a non-adaptive way or in an adaptive way. The most common non-adaptive pre-distortion technique is amplitude clipping.
Figure 4.5 Block diagram of non-adaptive pre-distortion

Figure 4.5 presents block diagram for non-adaptive pre-distortion technique. The input of the pre-distorter $f(t)$ is the wanted signal to transmit, in other words, the output of the IFFT module. The pre-distorter modifies the signal and outputs $x(t)$ which is later fed to the HPA resulting in an output signal $y(t)$. The objective of this technique is to have the following relation between the output of IFFT module $f(t)$ and the output of amplifier $y(t)$.

$$ y(t) = \begin{cases} 
  f(t) & \text{if } |f(t)| \leq V_{sat} \\
  V_{sat} \frac{f(t)}{|f(t)|} & \text{if } |f(t)| > V_{sat} 
\end{cases} \quad (4.1) $$

The output of the pre-distorter can be expressed as:

$$ x(t) = x(t)e^{j\phi(t)} = r(t)e^{j\phi(t)} \quad (4.2) $$

where $r(t)$ depends on the HPA amplifier function. It is possible to see from (4.2) that for all values below the saturation voltage, the pre-distorter should perform the inverse of the HPA operation; as for values exceeding the saturation voltage, it will limit the amplitude to the saturation voltage but keep the phase. Therefore, amplitude clipping adds another source of noise that needs to be considered carefully.

There are techniques that help mitigating the noise caused by amplitude clipping. These techniques are known as Clipping Amplitude Recovery (CAR). A decision aided method and a Bayesian-inference method...

4.2.2 Partial Transmit Sequence (PTS)

Another approach to reduce the effects of nonlinearities in OFDM systems is coding techniques. These techniques require side information, which is to be known both at the receiver and the transmitter. One set of coding techniques within this group is the Partial Transmit Sequence (PTS) techniques. This technique was first introduced by Muller et al (1997). There are several algorithms for implementing these techniques. However, the principle remains the same. The objective is to reduce the PAPR of the transmitted signal. Each data block in the PTS system is partitioned into ‘Ms’ disjoint sets. The weighting factors $b_m$ has to be optimized so that the combination of the clusters, and therefore the PAPR, are minimized:

$$X^{'l} = \sum_{m=1}^{Ms} b_m X_m$$

(4.3)

After IFFT, (4.3) can be written as:

$$x' = \sum_{m=1}^{Ms} b_m x_m$$

(4.4)

It is possible to set one rotation factor $b_m$ to one and remaining can be found with:

$$\hat{b}_m = \arg \min_{b_m} \max_{b_1} \left( b_{1} x_1 + \sum_{m=2}^{Ms} b_m x_m \right), \quad m = 2, \cdots, Ms$$

(4.5)
This technique offers a good improvement in performance with a relatively low increase in complexity of the transmitter.

### 4.2.3 Selective Mapping (SLM)

Selective Mapping (SLM) is the coding technique introduced by Baümi et al (1996). The idea is, the given $M_s$ statistically independent OFDM symbols having the same information, to select the symbol with the lowest PAPR for transmission. These $M_s$ statistically independent OFDM symbols are generated by weighting the OFDM symbols with $M_s$ random sequences of length $N$. This can be performed using Walsh sequences or a random interleaver, investigated by Li and Cimini (1997). This technique, combined with block coding, can provide both error protection and PAPR reduction when only the code-words with small PAPR are selected.

The methods discussed above are objective and easy to realize, but tend to have low power efficiency, and reduced out-of-band emission which is of great importance in mobile systems. However, high computational complexity forbids their uses in small mobile structure.

### 4.3 PROPOSED COMPENSATION METHODOLOGY

In this work, a nonlinear distortion introduced by the HPA at the transmitter is compensated by using a novel based distortion evaluation algorithm. The idea is, the distortion introduced by the HPA is estimated by approximating the attenuation coefficient of HPA model and then it is subtracted from the received symbol at the receiver. By performing several iterations, the estimation of the distortion becomes more accurate, and cancels the nonlinear distortion.
4.3.1 Baseband Equivalent OFDM system Model

Figure 4.6 shows the baseband-equivalent functional block diagram of the OFDM transmission system. The QAM signal generator produces complex symbols with independent, identically distributed random in-phase and quadrature components from the finite alphabet set. The serial-to-parallel block converts the QAM input data stream into a block of $N$ symbols, which in turn modulate the corresponding subcarrier. The Nyquist rate sampled OFDM signal is described as,

$$s_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k e^{\frac{j2\pi kn}{N}}, \quad n = 0, 1, \ldots, N-1,$$

(4.6)

According to central limit theorem, if the number of subcarriers is large the signal can be approximated as a Gaussian distributed random variable. Using Bussgang’s theorem the signal at the output of nonlinearity can be written as the sum of an attenuated input replica and an uncorrelated distortion term, found by Muller et al (1997) & Cimini and Sollenberger (2000).

$$\bar{s}_n = \alpha s_n + d_n$$

(4.7)

where $d_n$ is the distortion term, and ‘$\alpha$’ is the attenuation coefficient,
The transmitter and receiver shaping filters have the frequency response $G_t$ and $G_r$, respectively,

$$\left| G_t(f) \right| = \left| G_r(f) \right| = \sqrt{G(f)} \tag{4.9}$$

where $G(f)$ denotes a raised-cosine Nyquist pulse. The spectrally shaped signal at the output of the transmit filter is fed through the HPA and the channel. The auto-correlation function of the output signal can be written as,

$$R_{\tilde{s}\tilde{s}} = |\alpha|^2 R_{ss} + R_{dd} \tag{4.10}$$

Equation (4.10) can be used to derive the power of distortion for different subcarriers. At the receiver, the output of the FFT block gives a set of decision variables.

$$\tilde{S}_k = \alpha S_k + D_k \tag{4.11}$$

$$S_k = \frac{1}{N} \sum_{n=0}^{N-1} s_n e^{-j \frac{2\pi kn}{N}} \tag{4.12}$$

$$D_k = \frac{1}{N} \sum_{n=0}^{N-1} d_n e^{-j \frac{2\pi kn}{N}} \tag{4.13}$$

$$\tilde{r}_n = \alpha s_n * h(n) + d_n * h(n) + n_k \tag{4.14}$$
where $h(n)$ is the channel response assumed to be perfectly known, and $n_k$ is the channel noise. Therefore the equivalent linear model of the OFDM transmission with nonlinearity consists of a complex attenuation gain $\alpha$, and an uncorrelated additive Gaussian distortion, analyzed by Banelli and Cacopardi (2000) and the concept described by Papoulis (1991).

### 4.3.2 Proposed Nonlinear Distortion Compensation Model

Figure 4.7 shows the block diagram of proposed nonlinear distortion compensation model. The receiver works in an iterative fashion that the attenuation coefficient $\alpha$ of transmitting HPA model is estimated using the training sequence, which gives the imitation of nonlinear distortion components, at last use the replica to cancel the nonlinear distortion components in the received symbols. Based on the proposed system the nonlinear signal can be expressed as the sum of the attenuated linear signal $\alpha s_n$ and the nonlinear distortion $d_n$, defined by

$$d_n = \tilde{s}_n - \alpha s_n$$

(4.15)

**Figure 4.7 Proposed nonlinear distortion compensation model**

The estimated nonlinear distortion term $d_n$ is subtracted from the current channel observation to obtain the refined channel signal. By taking the
advantage of training sequence, it is possible to get more accurate channel response. So the output after nonlinear compensation is,

\[ s_n = r_n - d_n * h(n) \]  \hspace{1cm} (4.16)

A widely accepted HPA model is nonlinear memoryless model, in which transformation carried between the complex envelope of the input and output signals, performance analyzed by Costa and Pupolin (2002).

The output signal of nonlinear HPA is expressed as \( f(t) = A(t) \cdot e^{i \phi(t)} \).

where the function \( A(\cdot) \) and \( \phi(\cdot) \) represents the AM/AM and AM/PM conversion characteristics of nonlinear HPA. For TWTA the AM/AM and AM/PM conversion characteristics, given by Saleh (1981),

\[ A_{\text{out}} = A_{\text{sat}}^2 \frac{A_{\text{in}}}{A_{\text{in}}^2 + A_{\text{sat}}^2} \] \hspace{1cm} (4.17)

\[ \phi\left[ A_{\text{in}} \right] = \frac{\pi}{3} \frac{A_{\text{in}}^2}{A_{\text{in}}^2 + A_{\text{sat}}^2} \] \hspace{1cm} (4.18)

where \( A_{\text{in}} \) and \( A_{\text{out}} \) are the amplitudes at the input and output of the nonlinear amplifier, \( A_{\text{sat}} \) is the saturation amplitude at its input.

For SSPA, the AM/AM and AM/PM conversion characteristics expressed as,

\[ A_{\text{out}} = \frac{A_{\text{in}}}{\left[ 1 + \left( A_{\text{in}} / A_o \right)^2 \right]^{1/2} p} \] \hspace{1cm} (4.19)

\[ \phi[A_{\text{in}}] = 0 \] \hspace{1cm} (4.20)
where $A_{in}$ and $A_{out}$ are the amplitudes at the input and output of the nonlinear amplifier, $A_o$ is the saturated amplitude at its output (For TWTA, $A_o = A_{sat} / 2$ and for SSPA, $A_o = A_{sat} / \sqrt{2}$), and the parameter ‘$p$’ (Rapp’s parameter) controls the smoothness of the transition from linear region to saturation region and decide the nonlinear level that is usually taken by 2, proposed by Costa and Pupolin (2002). A good approximation of AM/AM characteristics of existing amplifier is obtained with the parameter ‘$p$’ in the range of 2 to 3.

The effect of the nonlinear amplifier depends on the operating point, which is usually identified by the backoff parameter. The saturation level is described by the input-backoff (IBO) parameter, which is defined as,

$$IBO = 10 \log_{10} \frac{P_{O, IN}}{P_{IN}}$$

(4.21)

where ‘$P_{IN}$’ is the mean power of the signal at the input of HPA and ‘$P_{O, IN}$’ is the input power corresponding to its maximum output power. Input-backoff (IBO) and output-backoff (OBO) are two common parameters to verify the nonlinear distortion, described by Muller et al (1997).

### 4.3.3 Simulation results

This section presents the various computer simulation results to verify the performance of proposed method compared with the algorithm proposed by Yang et al (2006). Simulations are performed by using 1024 and 512 subcarriers with QAM modulation.

The performances of Yang et al (2006) proposed algorithms are also shown for the purpose of comparison with the proposed method. Two HPA models travelling wave tube amplifier (TWTA) and solid state power amplifier (SSPA) are adopted for simulations.
Table 4.3 Simulation parameters used in the evaluations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation method</td>
<td>16 QAM and 64 QAM</td>
</tr>
<tr>
<td>Demodulation method</td>
<td>Coherent</td>
</tr>
<tr>
<td>OFDM bandwidth</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Number of FFT points</td>
<td>512 and 1024</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>512 and 1024</td>
</tr>
<tr>
<td>Model of nonlinear amplifier</td>
<td>SSPA and TWTA</td>
</tr>
<tr>
<td>Rapp’s parameter</td>
<td>$P = 2$</td>
</tr>
<tr>
<td>Channel model</td>
<td>AWGN</td>
</tr>
</tbody>
</table>

In figure 4.8, the ideal curve shows the BER performance under the ideal AWGN channel without SSPA. With SSPA, the SNR performance of the proposed algorithm can be improved more than 5dB compared with the algorithm proposed by Yang et al (2006) at BER = $5 \times 10^{-3}$.

![Figure 4.8 BER versus SNR for 16QAM when IBO=1dB](image)
Figure 4.9 BER versus SNR for 16QAM when IBO=8dB

In figure 4.9, the ideal curve shows the BER performance under the ideal AWGN channel without TWTA. With TWTA, the SNR performance of the proposed algorithm can be improved more than 6 dB compared with the algorithm proposed by Yang et al (2006) at BER = 5x10^{-3}.

In figure 4.10, it can be observed that the IBO of the compensated signals with SSPA can be improved more than 1 dB compared with the algorithm proposed by Yang et al (2006) at BER = 6x10^{-3}.

In figure 4.11, it can be observed that the IBO of the compensated signals with TWTA can be improved approximately 2 dB compared with the algorithm proposed by Yang et al (2006) at BER = 4x10^{-3}.
Figure 4.10 BER versus IBO for 16QAM when SNR = 20dB

Figure 4.11 BER versus IBO for 16QAM when SNR = 25dB
Figure 4.12 shows the BER performances for 16QAM and 64QAM modulation methods in the HPA non-linearity. In the simulation, the input back-off (IBO) of non-linear amplifier for 16QAM and 64QAM are taken by \(-4\) dB and \(-6\) dB, respectively. From the figure, it can be observed that the proposed method shows much better BER performance than the other compensation methods.

4.3.4 SUMMARY

Nonlinear distortion in OFDM system operating in AWGN channel was deliberated and a new novel based method to combat this distortion was also implemented. Here the novelties corroborate by introducing a HPA in the receiver side and also constructed a new adaptive algorithm to compensate the nonlinearity at the receiver. By performing several iterations, the simulated outputs show better BER performance compared with the previous algorithms proposed.