A Compensating Method Based on SOM for Nonlinear Distortion in 64 QAM-OFDM System

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1. Introduction

Orthogonal frequency-division multiplexing (OFDM) is a multicarrier transmission scheme, which use frequency-division multiplexing efficiently implemented through inverse fast Fourier transform (IFFT) to transport an input data stream on \( N \) orthogonal subcarriers within the usable frequency band of the channel. This technique is effective in a multipath environment since each subchannel carries a low bit rate, thus, resulting in a symbol period much longer than typical echo delays. In addition, owing to the use of a guard interval (inserted before each modulation period), echo equalization simply reduces to a scalar multiplication of the detected decision variables by a corrective coefficient [1-2].

The major drawback of the OFDM technique is its large signal dynamic caused by the high (several hundreds) number of subcarriers with random phase and amplitude, which are summed in the modulator. It results in that OFDM technique is sensitive to nonlinear distortions caused by high power amplifier (HPA) at the transmitter end [3]. Some analysis results about OFDM performance in presence of nonlinearity are given in [4-6]. References [4-6] show that in the case of a large number of subcarriers, the effect of nonlinear distortions can be taken into account just introducing an equivalent Gaussian “nonlinear noise” added to the received symbol.

The first obvious solution is to use a very linear HPA, but this solution is expensive and consumes too much power for portable systems. Several methods are studied to solve this problem. The peak to average power ratio (PAPR) can be reduced with special coding techniques [7], or the signal can be pre- or post-distorted to compensate for its non-linearity. A post-distortion system uses a compensator in the receiver that corrects the received signal [8].

In this paper, we propose a novel compensator that uses a neural network (SOM algorithm) to correct the non-linearity introduced by the HPA. In the proposed scheme, a two-dimensional SOM topology structure is designed to process the real and imaginary parts concurrently and the Euclidean distance between the signal points and the winning neuron in the ideal 64 QAM signal constellation is used as a stationary radius to define the neighborhood of the winning neuron. Because the SOM is inherently nonlinear, it may thus be viewed as a nonlinear generalization of principal components analysis. Simulation results show the effectiveness of the proposed scheme in 64 QAM-OFDM systems under a nonfading AWGN channel and traveling-wave tube amplifier (TWTA) model.

2. System Model

2.1. OFDM System Architecture

The basic principle of the OFDM technique have been described in detail in [1]. A general architecture of an OFDM system is shown in Fig. 1, where the modulation and demodulation processes are efficiently implemented through the fast Fourier transform (FFT) algorithm.

Let \( f_s = 1/\Delta t \) is the symbol rate of the information signal and \( N \) is the number of subcarriers. The OFDM symbol period is \( T = N \Delta t = N/f_s \) and the complex envelope of the
OFDM signal in the $i$th timeslot can be written as

$$x(t) = \sum_{k=0}^{N-1} a_k(i) \exp(j2\pi f_k t)$$

(1)

where $f_k = k\Delta f = k f_s / N$ is the $k$th carrier frequency, $a_k(i)$ is the data symbol modulating the $k$th carrier in the $i$th OFDM symbol interval. Using an 64 QAM modulation scheme for each carrier, $a_k$ are assumed mutually independent equiprobable symbols belonging to the alphabet $A = a_{kq} = \pm 1, \pm 3, \pm 7$. 

The transmitted signal $x(t)$ is completely specified by the $N$ signal samples $x_n = x(n \Delta t)$ generated by taking the IFFT of the data symbols $a_k(k = 0, 1, \ldots, N - 1)$

$$x_n = \sum_{k=0}^{N-1} a_k \exp(j2\pi n k)$$

(2)

Let $z(t)$ be the received signal. The standard demodulator is based on an N-point FFT of the $\Delta t$ spaced signal samples $z_m = z(m \Delta t)$, providing the following detected values at the input of a decision element

$$Z_k = \frac{1}{N} \sum_{n=0}^{N-1} z_m \exp(-j2\pi n k)$$

(3)

Note that, with an ideal channel, $z(t)$ equals $x(t)$ and the detected value $Z_k$ equals the transmitted data symbol $a_k$.

### 2.2. HPA Model

The complex envelope of the input signal to the HPA is

$$x(t) = \rho(t) e^{j\psi(t)}$$

(4)

and the complex envelope of the output signal can be expressed by

$$\tilde{x}(t) = A[\rho(t)] e^{j[\psi(t) + \Phi[\rho(t)]]}$$

(5)

where $A(\rho)$ and $\Phi(\rho)$ represent the AM/AM (amplitude distortion which depends on the amplitude of the input) and AM/PM (phase distortion which depends on the amplitude of the input) conversion characteristics of the nonlinear amplifier. Two nonlinear HPA models have been adopted:

1. a travelling-wave tube with strong AM/PM conversion;
2. a solid-state amplifier without AM/PM conversion.

The feature of HPA determines the effects on the received signal constellation: cloud-like shape, rotation, attenuation, and warping. The SOM algorithm is effective on solving the rotation of signal constellation, which introduced by nonlinear distortion [11]. In this paper, we consider a travelling-wave tube amplifier (TWTA) with AM/PM conversion.

According to [4], the AM/AM and AM/PM conversion characteristics can be expressed as

$$A[\rho(t)] = \frac{A^2_{sat}}{\rho(t)^2 + A^2_{sat}}$$

(6)

$$\Phi[\rho(t)] = \frac{\pi}{3} \frac{\rho(t)^2}{\rho(t)^2 + A^2_{sat}}$$

(7)

where $A_{sat}$ represents the amplifier input saturation voltage.

The nonlinear distortion induced by an HPA depends on the amplifier operating point. This is usually identified by two parameters known as input backoff (IBO) and output backoff (OBO), defined as

$$\text{IBO}_{dB} = 10 \log_{10} \frac{A^2_{sat}}{P_{IN}}$$

$$\text{OBO}_{dB} = 10 \log_{10} \frac{A^2_{sat}}{P_{OUT}}$$

(8)

where $A_{sat}$ is the amplifier input saturation voltage, $A_0$ is the maximum output amplitude and $P_{IN}$ and $P_{OUT}$ are the mean power of the input and output signal, respectively. According to Eq. (6), $A_0 = A_{sat}/2$.

### 3. The Proposed Scheme

To compensate for the nonlinearities at the receiver, the proposed scheme uses a SOM algorithm before the Demod. The main problem is that the non-linearity from the HPA is in the time domain, whereas the SOM algorithm is in the frequency domain. It can’t be moved before FFT because in this case it would have to do the channel equalizing, which is much more complicated in the time domain. In the frequency domain the non-linearity is a bit more complicated: intermodulations appear between the different carriers, so in fact each received symbol is a nonlinear combination of the $N$ transmitted symbols.

In the proposed scheme, we use the SOM algorithm to adapt to non-linearity. The principal goal of the SOM is to transform an incoming signal pattern of arbitrary dimension into a one- or two-dimensional discrete map, and to perform this transformation adaptively in a topologically ordered fashion. Figure 3 shows the Kohonen’s model [9] of a two-dimensional self-organized feature map. Each neuron in the lattice is fully connected to all the source nodes in the input layer. This network represents a feedforward structure with a single computational layer consisting of neurons arranged in rows and columns.

The SOM algorithm is introduced in the following steps.

Step 1: Initialize the values of the nodes $\omega_j$ by using the values of ideal 64 QAM signal constellations. We design the SOM neurons as the same as the constellation of 64 QAM. That is, the two-dimensional weight coefficients of the neuron equal to in-phase and quadrature components of the point in the 64 QAM constellations.
**Step 2:** Locate the winning node $i$ for the input signal $\hat{I}_k$ by
\[
||\hat{I}(k) - \omega_i|| = \min_i(||\hat{I}(k) - \omega_i||)
\]  \hspace{1cm} (9)
After locating the winning node $i$, we use the Euclidean distance as neighborhood radius to define neighborhoods of the winning node $i$.

**Step 3:** Modify the values of the winning node to the direction of the input data and modify the values of the neighbors of the winning node in the same way. The neighborhood function $h_{j,i}$ is defined by
\[
h_{j,i} = \exp\left(-\frac{d_{j,i}^2}{2\sigma^2}\right)
\]  \hspace{1cm} (10)
where $d_{j,i}$ is the neighborhood radius and the parameter $\sigma$ is the effective width of the topological neighborhood. To satisfy the requirement that the size of the topological neighborhood shrinks with time, we let the width $\sigma$ of the topological neighborhood function $h_{j,i}$ decrease with time.
\[
\sigma(n) = \sigma_0 \exp\left(-\frac{n}{\varphi_1}\right) \quad n = 0, 1, 2, \ldots
\]  \hspace{1cm} (11)
where $\sigma_0$ is the value of $\sigma$ at the initiation of the SOM algorithm, and $\varphi_1$ is a time constant. Correspondingly, the topological neighborhood assumes a time-varying form of its own, as shown by
\[
h_{j,i}(n) = \exp\left(-\frac{d_{j,i}^2}{2\sigma^2(n)}\right) \quad n = 0, 1, 2, \ldots
\]  \hspace{1cm} (12)
Thus, as time (i.e. the number of iterations) increases, the width $\sigma(n)$ decreases at an exponential rate, and the topological neighborhood shrinks in a corresponding manner. Because 2 is the minimum radius for 64-QAM system, we let
\[
\sigma_0 = 2
\]  \hspace{1cm} (13)
\[
\varphi_1 = \frac{1000}{\log \sigma_0}
\]  \hspace{1cm} (14)

**Step 4:** For the input signal $\hat{I}(k)$, the output is defined by the modified weight $\omega_i(k+1)$. And reset the signal constellation by the weight vector $\omega_i(k+1)$.

**Step 2, step 3 and step 4** are repeated once for each input sample, which means that each sample is used once and only once for teaching the map.

4. Simulation and Results Analysis

In this section we provide some results to illustrate the proposed SOM compensator for 64 QAM-OFDM system with $N = 128$ subcarriers, in the presence of the TWTA. The transmission of 1000 OFDM symbols is simulated. The beginning 80 OFDM symbols is used to estimated nonlinear distortion, i.e., the weight coefficients of the proposed SOM compensator become stable after about 1000 symbols.

Figures 3 and 4 show the BER performance versus SNR (dB) for 64-QAM-OFDM system at different IBO values and...
OBO values, respectively. In these two figures, the curves are bounded by the system BER performance without nonlinearity. The proposed scheme represents almost the same BER performance as the traditional receiver without SOM compensator in the absence of nonlinearity. When the nonlinear distortion is severe (IBO=12dB or OBO=5.4dB), without the proposed SOM algorithm, system cannot recover nonlinear distortion even increasing SNR. In Fig. 4, the performance with the proposed scheme at OBO=5.4dB, is almost the same as the performance without SOM algorithm at OBO=7dB. This means the SOM algorithm manages to correct some nonlinear distortion introduced by the TWTA and the whole system acts as if it had a higher quality amplifier. Figures 3 and 4 illustrate that the SOM algorithm brings perceptible gains for 64-QAM-OFDM in the presence of TWTA.

It is useful to look at the necessary SNR to obtain a given BER. For 64-QAM-OFDM system, in Fig. 3, if we want a BER of $10^{-3}$ at IBO=15dB, we need a SNR of 31 dB without the SOM algorithm, whereas 25 dB with the SOM algorithm. This means that with the SOM algorithm we can divide the power of the emitted signal and amplifier saturation by 4 (6dB) and still have the same performance. The emitter will consume less power and it is very interesting for portable systems.

5. Conclusions

A novel nonlinear distortion compensator based on self-organizing map for 64 QAM-OFDM systems has been proposed in this paper. The comparisons of the BER performance of the proposed scheme and the traditional receiver without SOM compensator have been studied when facing with strongly nonlinear distortions, which introduced by TWTA. Simulation results have shown that the proposed scheme adapts better to nonlinear distortion than the traditional receiver without SOM compensator. The adaptation of the proposed scheme is based on the topology-preserving characteristic of the map algorithm, i.e. the map is able to trace the nonlinear distortions tightly.

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References


