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Printed and published by the IEE, Michael Faraday House, Six Hills Way,
Stevenage, Herts SG1 2AY, UK

Abstract

Real-world power amplifiers (PAs) are weakly nonlinear. The nonlinear behavior causes sub-carrier intermodulation in OFDM based transmitters. This paper shows the results of simulations performed on a software HiperLAN/2 system with a nonlinear power amplifier model. We show that HiperLAN/2 is much less sensitive to nonlinearities of the PA when BPSK or QPSK modulated sub-carriers are used compared to QAM16 or QAM64 modulated sub-carriers. Both QAM16 and QAM64 require a PA backoff amount of at least 5 dB while BPSK and QPSK don't require any backoff. This means that BPSK or QPSK modulated OFDM is more power efficient.

THE EFFECTS OF NONLINEAR POWER AMPLIFIERS ON THE PERFORMANCE OF A HIPERLAN/2 SYSTEM

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Keywords: Nonlinear power amplifiers, HiperLAN/2, OFDM, simulation

Abstract

Real-world power amplifiers (PAs) are weakly nonlinear. The nonlinear behavior causes sub-carrier intermodulation in OFDM based transmitters. This paper shows the results of simulations performed on a software HiperLAN/2 system with a nonlinear power amplifier model. We show that HiperLAN/2 is much less sensitive to nonlinearities of the PA when BPSK or QPSK modulated sub-carriers are used compared to QAM16 or QAM64 modulated sub-carriers. Both QAM16 and QAM64 require a PA backoff amount of at least 5 dB while BPSK and QPSK don't require any backoff. This means that BPSK or QPSK modulated OFDM is more power efficient.

1 Introduction

Orthogonal Frequency Division Multiplexing is the modulation technique chosen in several communication systems such as HiperLAN/2 [2]. In such OFDM-based systems the power amplifier (PA) in the transmitter has a large impact on the performance of the system. Real-world power amplifiers are weakly nonlinear. This causes intermodulation between sub-carriers of the OFDM signal.

Some of the intermodulation products appear within the channel and cause in-band interference which raises the bit-error rate. The rest of the intermodulation products form out-of-band interference and appear in neighboring channels. These out-of-band products can be reduced by adding a filter after the PA. For in-band products there is no filter-based solution.

It is always possible to use a filter after the PA to remove the out-of-band interference, but the required specifications of the filter may render such a solution impractical.

The amount of intermodulation caused by the PA depends on the drive level. Lowering the drive level of the amplifier reduces the intermodulation products. The amplifier is operated more in its linear region. Reduction of the drive level is called *backoff*. The amount of backoff is specified in dB referenced to the 1-dB compression point of the PA.

Increasing PA backoff decreases the power efficiency of the PA. In effect there is a design trade-off between harmonic distortion and power efficiency.

Simulations were performed of a nonlinear PA model in combination with the HiperLAN/2 software developed in the SDR project [5]. Before presenting the simulation setup and

the results, we first describe the HiperLAN/2 baseband signal and the power amplifier model.

2 The HiperLAN/2 baseband signal

The HiperLAN/2 baseband signal consists of OFDM symbols with 48 data carriers and 4 pilot carriers. The data carriers are modulated with either BPSK, QPSK, QAM16 or QAM64. The uncoded bit-rate increases with the modulation scheme and is 12, 24, 48 and 72 Mbit/s respectively.

parameter	HiperLAN/2
band	5.15 – 5.725 GHz
channel spacing	20 MHz
sub-carrier mod.	BPSK, QPSK, QAM16 or QAM64
nom. bitrate (no FEC)	12 – 72 Mbit/s
frame duration	2 ms
symbol duration	4 μ s

Table 1. Some physical layer characteristics of HiperLAN/2

The allocated frequencies for HiperLAN/2 are 5.15 – 5.725 GHz and each channel is 20 MHz wide. The most important physical layer characteristics of HiperLAN/2 are shown in Table 1. For more information on the HiperLAN/2 physical layer specification, the reader is referred to [3].

3 Power amplifier model

We incorporated the nonlinear baseband-equivalent PA model from 'example 1' [1] into our HiperLAN/2 software. This model is based on a real class AB power amplifier.

The PA model belongs to the Wiener-Hammerstein [4] class of models which is a combination of a Wiener and a Hammerstein model. Both the Wiener and Hammerstein models consist of a memoryless polynomial and a filter. The Wiener model has the filter in front of the polynomial and the Hammerstein model has the filter after the polynomial, see Figure 1.

The term *memoryless polynomial* refers to the fact that the output of the polynomial only depends on the present input and not on past or future inputs.

The filters $H(z)$ and $G(z)$ of the actual model used in the simulations are described by equation (1).

$$H(z) = \frac{1 + 0.5z^{-2}}{1 - 0.2z^{-1}} \quad G(z) = \frac{1 - 0.1z^{-2}}{1 - 0.4z^{-1}} \quad (1)$$

Fig. 1. Block diagram of Wiener, Hammerstein and Wiener-Hammerstein models

The memoryless polynomial is described by equation (2) where x is the complex time-domain input signal and s is the complex time-domain output.

$$s(t) = \sum_{k=1,3,5} b_k x(t) |x(t)|^{k-1} \quad (2)$$

The coefficients b_1 , b_3 and b_5 for this model are

$$\begin{aligned} b_1 &= 1.0108 + j0.0858 \\ b_3 &= 0.0879 - j0.1583 \\ b_5 &= -1.0992 - j0.8891 \end{aligned} \quad (3)$$

We extended the PA model to include a saturation region. This was needed because the original PA model breaks down beyond a certain input level. In Figure 2 the power characteristics of the original and extended model are shown.

When an actual PA is driven into full saturation, any increase in input power no longer causes an increase in output power. The PA model however, does not show this behavior.

The extension of the model is achieved by clipping the magnitude of the complex input signal when the magnitude is beyond or at the saturation point of the PA. A block diagram of the extended model is shown in Figure 3.

4 Simulation setup

A block diagram of the simulation setup is shown in Figure 4. The simulation consists of a HyperLAN/2 transmitter, receiver and a separate PA model described earlier. The PA model is simulated at four times the rate of the transmitter and receiver to allow for spectral expansion without causing extensive aliasing. The simulation does not include an AWGN channel model or any kind of propagation model.

The HyperLAN/2 transmitter generates a baseband signal with constant average power irrespective of the sub-carrier mod-

Fig. 2. Power characteristic of the PA model.

Fig. 3. Extended PA model

ulation scheme. This baseband signal is then scaled to account for the backoff setting before it enters the PA model.

The output signal of the PA is downsampled to the original baseband rate. Then the signal enters the HyperLAN/2 receiver where it is demodulated. The demodulated bits are compared with the transmitted bits to determine the *channel bit-error rate*. The channel bit-error rate is the raw, uncoded, bit-error rate.

The channel bit-error rate is calculated under different PA input backoff conditions and sub-carrier modulation schemes. The simulated backoff range is from -3 dB to 7 dB using BPSK, QPSK, QAM16 and QAM64 modulated sub-carriers. The number of transmitted bits is $1 \cdot 10^6$ for each condition.

In addition to the bit-error rate, the average spectra of the input and output signal of the PA are determined. These spectra are generated from the oversampled baseband signals. This way, the out-of-band interference generated by the PA is also made visible.

5 Results

A graph showing the channel bit-error rate plotted against PA backoff is shown in Figure 5. It is clear that the channel bit-error rate depends heavily on the sub-carrier modulation scheme. For BPSK and QPSK modulated sub-carriers, the bit-error rate introduced by the in-band interference of the PA is below $1 \cdot 10^{-4}$ for backoff amounts over 0 dB¹. For QAM16, however,

¹The HyperLAN/2 standard requires a BER (after error correction) below $2 \cdot 10^{-4}$ [5]. So if the channel BER (before error correction) is lower than $1 \cdot 10^{-4}$, its influence on the system can be neglected.

Fig. 4. Nonlinear PA simulation setup

the bit-error rate drops below $1 \cdot 10^{-4}$ for backoff amount larger than 5 dB.

Fig. 5. Simulation results of channel BER against PA backoff.

In Figure 6, 7 and 8 the constellation diagrams of carrier 26 are plotted under different modulation and PA backoff conditions.

The figures show well-defined constellations for BPSK and QPSK under all three simulated backoff conditions. This indicates that BPSK and QPSK modulated sub-carriers are quite insensitive to weak PA nonlinearities.

The constellation diagrams for QAM16 and QAM64 modulated sub-carriers show that considerable distortion takes place under low PA backoff conditions. In the QAM64 case, the constellation diagrams show clustering only for a PA backoff of 6 dB, while for QAM16 clustering is already recognizable at a PA backoff of 3 dB. These modulation schemes are clearly more sensitive to weak nonlinearities.

Spectrum plots for 0, 3 and 6 dB backoff conditions can be found in Figures 9, 10 and 11 respectively. The spectra are shown for BPSK, QPSK, QAM16 and QAM64 modulated sub-carriers.

Fig. 6. Constellation diagrams for carrier 26 (PA backoff = 0 dB)

Fig. 7. Constellation diagrams for carrier 26 (PA backoff = 3 dB)

Fig. 8. Constellation diagrams for carrier 26 (PA backoff = 6 dB)

Each sub-figure shows the input and output spectrum of the PA at a certain backoff condition and sub-carrier modulation scheme. The input and output spectra show the same shapes irrespective of the sub-carrier modulation scheme. The shape of the output spectrum depends only on the PA backoff amount.

The amount of PA backoff can be deduced from the magnitude of the input spectra. The output spectra magnitudes drop with increased backoff but because the PA is nonlinear, the drop is not exactly equal to the backoff amount. The PA causes some compression of the output signal. At 0 dB backoff, the amount of compression is 1 dB by definition.

The out-of-band interference reduces nonlinearly with the backoff amount. Table 2 shows the shoulder height with respect to the maximum output power as a function of the PA backoff.

PA backoff	Relative shoulder height
0 dB	-13 dB
3 dB	-15 dB
6 dB	-28 dB

Table 2. PA backoff versus relative shoulder height.

From the above, it is then reasonable to assume that the amount of in-band interference is also independent of the sub-carrier modulation scheme.

6 Conclusions

We have performed simulations in a HiperLAN/2 system with nonlinear power amplifiers in the transmitter. Especially for higher modes i.e. QAM16 and QAM64, we have seen that a nonlinear amplifier has a large impact on the performance of the system. However, by reducing the PA drive level, this impact can be minimized to acceptable levels at the cost of power efficiency which is an important parameter for mobile devices.

Fig. 9. PA input and output spectra at 0 dB backoff.

(a)

(a)

(b)

(b)

(c)

(c)

(d)

(d)

Fig. 10. PA input and output spectra at 3 dB backoff.

Fig. 11. PA input and output spectra at 6 dB backoff.

For QAM64 modulated sub-carriers, the backoff has to be greater than 6 dB. For QAM16 this requirement drops to 5 dB. The PA can operate at 0 dB backoff in case of BPSK or QPSK modulated sub-carriers.

The PA input and output spectra show that their shapes do not depend on the sub-carrier modulation scheme but depend only on the backoff amount. Thus, the height of the shoulders, the out-of-band and in-band interference are all independent of the sub-carrier modulation scheme.

The fact that QAM16 and QAM64 are quite sensitive to nonlinearities in the power amplifier indicates that when PA power efficiency is important, i.e. in low-power radio, it is better to use BPSK or QPSK modulated OFDM. This way, the backoff amount can be reduced resulting in a more power efficient system.

Operating the PA at its 0 dB backoff point produces much out-of-band interference. A filter after the PA can reduce this interference but may turn out to be impractical due to its demanding specifications.

In cases where reduction of the PA drive level is not possible or not desirable, other techniques such as PA pre-distortion can be applied [1]. Pre-distortion inversely distorts the waveform before it enters the amplifier thus cancelling the distortion caused by the amplifier.

7 Further work

In the near future, we intend to test the HiperLAN/2 software in combination with a real nonlinear amplifier to verify our conclusions. In addition, we will test pre-distortion algorithms to see their effect on the channel BER and out-of-band distortion.

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