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EFFECTS OF HPA-NONLINEARITY ON A 4–DPSK/OFDM–SIGNAL FOR A DIGITAL SOUND BROADCASTING SYSTEM

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Abstract

Orthogonal Frequency Division Multiplexing (OFDM) in conjunction with a 4–DPSK modulation format has been proposed for the future digital audio broadcasting system (DAB), that should provide compact disk sound quality in portable, vehicular and fixed receivers. With properly chosen parameters, this system should be appropriate for both terrestrial and satellite transmission. In this paper the influence of the nonlinear distortions introduced by the high power amplifier (HPA) of the transmitter is examined. In particular, the degradations in power efficiency due to intermodulation effects and backoff operating, as well as spectral degradations are investigated. It is shown for three different kinds of limiting amplifier models, that even with an output backoff (OBO) in the region of 5–6 dB, the degradation of, *e.g.*, a 512-carrier 4–DPSK/OFDM system relative to the linear case is below 1.7 dB ($P_b = 10^{-4}$), while the regenerated sidelobes of the transmitted spectrum are kept below −20 dB.

Keywords: Orthogonal Frequency Division Multiplexing (OFDM), Nonlinear High Power Amplifier (HPA), Backoff, Spectral Spreading.

1 Introduction

Recently much work has been done in developping a digital audio broadcasting system particularly for mobile receivers. Such a system should provide nearly ,,compact–disk" sound quality in portable, vehicular and fixed receivers. This claim requires a transmission scheme, allowing high–rate data transmission over a severly time– and frequency selective fading channel. Orthogonal frequency division multiplexing (OFDM) has been proposed to combat the effects of the selective fading channel, by multiplexing a serial data stream into a large number of N orthogonal subchannels, which results in a time– and frequency interleaving of the transmitted data [1]. Combined with additional channel–coding and 4–DPSK modulation in each subchannel, such an OFDM signal can be suitable for a bandwith and power efficient transmission of high quality digital audio signals over the selective fading channel [2].

Due to the large number N of subchannels, the OFDM signal owns a large dynamic signal range (large envelope fluctuations). When considering a system with a real RF transmitting amplifier, the nonlinear distortions introduced by the HPA play an important role. Normally, nonlinear distortions could be avoided by ,,backing off" the amplifier, that means forcing the amplifier to work in its linear region. Unfortunately this would not result in a very power efficient operation of the amplifier, which is especially important in the case of a satellite system, where power is a costly ressource. Therefore, when aiming to a power efficient operation of the HPA with low backoff values, nonlinear distortions and peak–limiting effects will produce intermodulation between the different carriers and introduce additional interference. In this paper, special attention is payed to the influence of such nonlinear high power amplifiers (HPA) on the OFDM signal. This is done by considering only a nonfading AWGN channel and an OFDM–signal without channel–coding.

After a short introduction to the OFDM–signal structure in section 2, the model of the HPA is explained in section 3. The three different kinds of HPA transfer characteristics used in this paper are described by analytical functions. In section 4, the effects of the nonlinear amplifier on the OFDM–signal are discussed. Results in terms of power efficiency and bandwidth expansion for the optimized operation points of the HPA-models are given in section 5.

2 The OFDM–Signal

The principles of the OFDM–modulation for digital audio broadcasting is described in detail in [3, also in [2]]. A brief review concerning the structure of the transmitted signal is followed here. The complex envelope of a N–subchannel OFDM signal can be written as the double sum

$$s'(t) = \sum_{i=-\infty}^{\infty} \sum_{k=0}^{N-1} a_{i,k}\, g(t - iT_s) e^{j2\pi f_k t}, \qquad (1)$$

where $a_{i,k}$ are the complex channel symbols in the i'th time slot of the k'th subchannel with carrier frequency f_k.

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If the N carrier frequencies are separated by the symbol rate $1/T_s$

$$f_k = f_c + \frac{k}{T_s} \quad \text{for} \quad k = 0 \dots N-1, \tag{2}$$

and with the one-symbol-duration rectangular impulse $g(t)$, the elementary signal impulses in the N subchannels can be written as

$$g_k(t) = \begin{cases} e^{j2\pi kt/T_s} & ; \quad 0 \le t < T_s \\ 0 & ; \quad \text{otherwise} \end{cases} \quad (k = 0 \dots N-1) \tag{3}$$

and eq. (1) becomes

$$s'(t) = \sum_{i=-\infty}^{\infty} \sum_{k=0}^{N-1} a_{i,k} g_k(t - iT_s). \tag{4}$$

It is easy to show, that the elementary impulses $g_k(t)$ are forming an orthogonal signal base in time and frequency, and, although the signal spectra of the N subchannels mutually overlap, the transmitted channel symbols $a_{i,j}$ can be detected in the noiseless case without interference with the decoding rule

$$a_{i,k} = \int_{-\infty}^{\infty} s'(t) g_k^*(t - iT_s) dt. \tag{5}$$

(The the asteric $*$ denotes the complex conjugate.) The generation of the N modulated subchannels and their detection in the receiver with decoding rule (5) can be realized very efficiently in parallel by use of FFT algorithms in the digital parts of the transmitter and receiver [3].

The Guard–Interval

In order to combat the channel selectivity, a ,,guard interval" has been introduced. This means, that the symbol duration T_s is extended by a guard interval Δ, which should be greater than the memory of the channel. The extended symbols

$$g'_k(t) = \begin{cases} e^{j2\pi kt/T_s} & ; \quad -\Delta \le t < T_s \\ 0 & ; \quad \text{otherwise} \end{cases} \quad (k = 0 \dots N-1) \tag{6}$$

are now transmitted at the rate $1/T'_s = 1/(T_s + \Delta)$, whereas the spacing of the subcarriers (eq. 2) remains the same as above. If only the tails of duration T_s of the transmitted symbols (,,useful signal") are detected, the orthogonality restrictions are preserved, and the transmitted symbols can be detected with the decision rule

$$a_{i,k} = \int_{-\infty}^{\infty} s'(t) g_k^*(t - iT'_s) dt. \tag{7}$$

Due to the mismatch of the transmitted impulses $g'_k(t)$ and the impulse response of the receiver filter $g_k(t)$ (detection rule eq. 7), the signal-to-noise ratio for a given bit-error-probability is degraded by $D = 10 \log T'_s/T_s$. Furthermore, the introduction of the guard interval leads to a reduction of the bandwidth efficiency by the factor $r_B = T_s/T'_s$.

In the following, we will consider a $N = 512$ and a $N = 1024$-carrier OFDM signal with 4-DPSK modulation of each subcarrier and a guard interval of duration $\Delta = T_s/4$. This value leads to a power degradation of $D = 0.97$ dB and a reduction of bandwidth efficiency of $r_B = 0.8$.

3 The HPA–Nonlinearity

The bandpass nonlinearity modelling the high power amplifier (HPA) of the transmitter is described by the memoryless envelope model [4]. The input to the nonlinear amplifier is a generally amplitude and phase modulated bandpass signal

$$s'_{BP}(t) = A(t) \cos\left[2\pi f_c t + \varphi(t)\right]. \tag{8}$$

Since the carrier frequency f_c of the modulated signal is large compared to the bandwidth of the transmitted signal, all harmonics of the nonlinearly distorted signal at multiples of the carrier frequency are ideally rejected by the ,,built-in" first zonal bandpass of the amplifier and the signal at the output of the HPA can be expressed by

$$s_{BP}(t) = \mathbf{g}(A(t)) \cos[2\pi f_c t + \varphi(t) + \mathbf{\Phi}(A(t))]. \tag{9}$$

Since, in the following, we will use only the complex baseband representation of the modulated signals, the input-output relationship of the HPA can be expressed with the complex envelopes:

$$s'(t) = A(t) e^{j\varphi(t)} \xrightarrow{HPA} s(t) = \mathbf{g}(A(t)) e^{j\varphi(t) + \mathbf{\Phi}(A(t))} \tag{10}$$

The two ,,envelope transfer functions" $g(A)$ and $\Phi(A)$ represent the AM/AM and AM/PM conversion of the nonlinear amplifier.

For the following considerations we used three different kinds of nonlinear HPA-models:

- A typical travelling wave tube (TWT) amplifier with strong AM/PM conversion
- A limiting nonlinearity without AM/PM conversion, modelling a solid-state amplifier (SSPA) and
- An idealized amplifier model (ideally linearized) called ,,envelope limiter" (LIM).

The parameters of all HPA-transfer functions are chosen to obtain a normalized characteristic with small signal gain $v = 1$ and the same maximum (saturated) output power P_0. Which type of HPA in a real system would be finally used, depends on many system requirements and on the technological feasibility [5, 6]. With the three HPA models considered here, it is intended to give a estimation of the sensitivity of the OFDM-signal to nonlinear distortions between the best (HPA3) and the worst case (HPA1).

3.1 TWTA

The AM/AM and AM/PM conversion functions of the TWT-model are shown in figure 1. This transfer characteristic is optained by using an approximation with the two-parameter formulas [7]

$$g(A) = \frac{\alpha_A A}{(1 + \beta_A A^2)} \tag{11}$$

and

$$\Phi(A) = \frac{\alpha_\Phi A^2}{(1 + \beta_\Phi A^2)}. \tag{12}$$

The parameters

$$\alpha_A = 1.00 \quad \beta_A = 0.25 \quad \alpha_\Phi = 0.26 \quad \beta_\Phi = 0.25 \tag{13}$$

are chosen to obtain the required normalized characteristic.

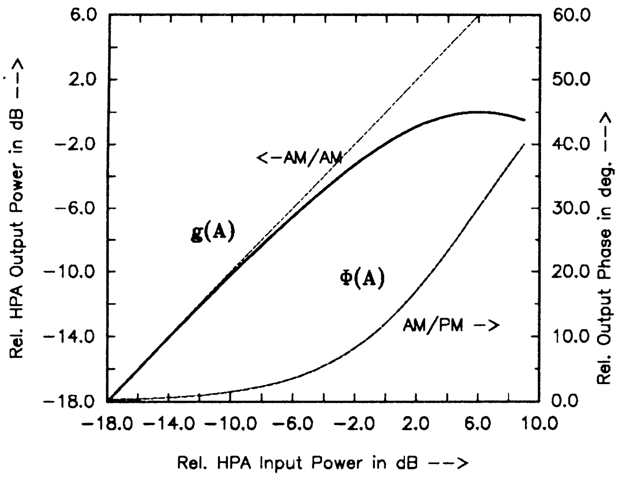

Figure 1: TWT input-output characteristics

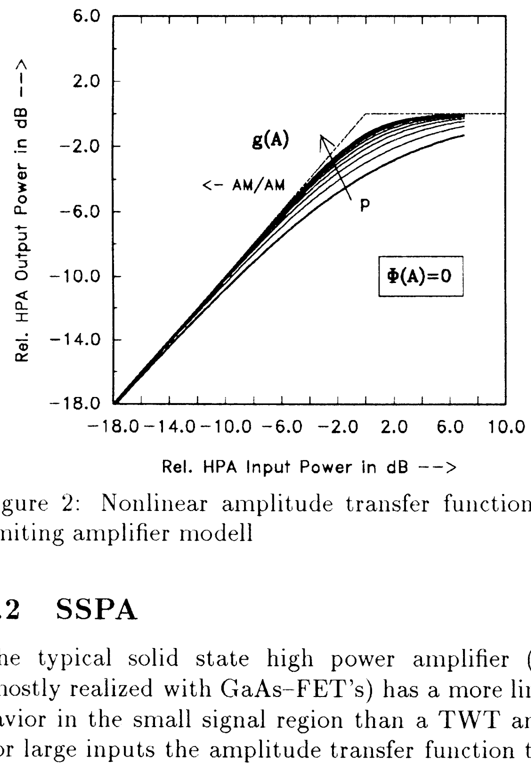

Figure 2: Nonlinear amplitude transfer function of the limiting amplifier modell

3.2 SSPA

The typical solid state high power amplifier (SSPA), (mostly realized with GaAs-FET's) has a more linear behavior in the small signal region than a TWT amplifier. For large inputs the amplitude transfer function tends to an maximum limiting value, produced by current and voltage clipping [8]. The AM/PM conversion of the SSPA is assumed to be small enough, so that it can be neglected. For the AM/AM conversion function $g(A)$ we propose the following analytical expression:

$$g(A) = v \frac{A}{\left(1 + \left[\left(\frac{vA}{A_0}\right)^2\right]^p\right)^{\frac{1}{2p}}} \tag{14}$$

with

$$p > 0, \quad A_0 \geq 0 \quad \text{und} \quad v \geq 0.$$

A_0 is the limiting output amplitude, v is the small signal gain and the smoothness of the transition from the linear region to the limiting region is controlled by the parameter p. The resulting amplitude transfer function for some different values of p is shown in figure 2. With the parameter $p = 3.0$ the measured characteristic of a 1-Watt SSPA is well approximated and this parameter is also used in the following.

3.3 Idealized Amplifier

The third HPA model considered here, represents an idealized amplifier, which could be obtained in the best case, when a real amplifier is ideally linearized for example by a predistortion unit [9]. The amplitude transfer function is ideally linear up to the limiting output amplitude, where it remains constant. The AM/PM conversion has to be zero. This ,,envelope limiter" function is the limiting case of eq. (14) for $p \to \infty$:

$$\lim_{p \to \infty} g(A) = \begin{cases} v \cdot A_0 & ; \quad A > A_0 \\ v \cdot A & ; \quad |A| \leq A_0 \\ -v \cdot A_0 & ; \quad A < -A_0 \end{cases} \tag{15}$$

This transfer function is indicated in figure 2 with the broken line.

4 System Degradation by the HPA–Nonlinearity

In the preceding section it has been shown, that the distortions produced by the nonlinear amplifier are dependent on the envelope fluctuations of the incoming signal $s'(t)$. The known distortions when amplifying a modulated signal with nonconstant envelope are

- additional nonlinear interference in the receiver,
- interference between the inphase– and quadrature components due to AM/PM conversion,
- spectral spreading of the transmitted signal, which can cause adjacent channel interference (ACI) and
- intermodulation effects, which occur, when several channels are amplified in the same HPA.

One method to avoid these problems, is the operation of the HPA in its linear region. Then the operating point of the amplifier is usually given by the ,,output backoff" (OBO) of the HPA with

$$OBO = 10 \log \frac{P_0}{P_s} \quad \text{in dB}, \tag{16}$$

where the reference power P_0 is the maximum output power (saturating power) of the HPA and P_s is the mean output power of the transmitted signal $s(t)$. Unfortunately the electrical efficiency of the HPA is very small for large backoffs, which is of great importance in satellite systems. In order to achieve a good HPA–power efficiency small backoff values are required, which leads to a tradeoff between maximizing output power on the one side and avoiding degradations due to nonlinear distortions on the other side.

Looking at the OFDM-signal in eq. (9), one can assume that such a multicarrier signal must suffer severe degradations when nonlinearly distorted. The peak-power to mean-power ratio ξ_s (crestfactor) of the complex envelope of a N carrier OFDM–signal with 4–DPSK modulation is calculated by

$$\xi_s = 20 \log \frac{N}{\sqrt{N}} = 10 \log N \quad \text{in dB}. \tag{17}$$

N	ξ_s
64	18.06 dB
128	21.07 dB
256	24.08 dB
512	27.09 dB
1024	30.10 dB

Table 1: Crestfactors of some OFDM signals

and some exemplary values of ξ_s are shown in table 1. The large values for ξ_s are a theoretical measure for the amount of the envelope fluctuations of the OFDM-signal. Following these values and assuming an HPA with the idealized transfer characteristic of the envelope limiter (LIM), very large backoffs of the HPA would be required, if the nonlinear distortions (which could destroy the orthogonality and produce intermodulation between the various subchannels) should be completely avoided.

4.1 Power efficiency

The investigations concerning the power efficiency of the OFDM-signal considered here, are made under the special aspect of the nonlinear distortions of the HPA's. Therefore only uncoded transmission and an AWGN-transmission channel are considered. The measure for the power efficieny is taken at a constant bit-error-rate (BER; here $P_b = 10^{-4}$) and it should account for the HPA-backoff, the power efficiency of the modulation format and the degradations due to nonlinear distortions. A fair measure is given by using the normalized minimal signal-to-noise ratio

$$SNR_0 = 10 \log \frac{P_0 T_b}{N_0} \quad (\text{dB}), \qquad (18)$$

which is needed to achieve the wanted BER. T_b is the equivalent duration for one information bit, N_0 is the twosided spectral noise density and P_0 is the given reference power of the HPA. The SNR_0 can be minimized by optimization of the HPA backoff. This becomes more clear, when eq. (16) is used in (18):

$$SNR_0 = 10 \log \frac{P_0}{P_s} \frac{P_s T_b}{N_0} = OBO + 10 \log \frac{E_b}{N_0} \qquad (19)$$

The power efficiency now can be expressed by the sum of the output-backoff and the normalized mean signal-to-noise ratio $10 \log(E_b/N_0)$. The minimum of this value is achieved by adjusting the HPA operating point so as to give the best tradeoff between a low backoff value and low degradation in E_b/N_0. In doing so, technological constraints concerning the peak-power drive level of the HPA have been ignored. This problem should be avoided in reality by using an additional limiter prior to the HPA.

Instead of the absolute value of E_b/N_0, we use in the following only the relative degradation Δ_{E_b/N_0} to a MSK reference system on the AWGN-channel. Then the effective degradation Deg_{eff} of the system is defined by

$$Deg_{eff} = OBO + \Delta_{E_b/N_0} \quad (dB). \qquad (20)$$

A basic degradation of $Deg_{eff} = 3.3$ dB due to the differential decoding of the 4-DPSK subchannels (2.3 dB) and, as shown above, due to the additional degradation of the guard interval (~ 1 dB) have to be expected.

4.2 Bandwidth efficiency

As mentioned above, the power spectral density of a modulated signal with varying envelope is broadened by the nonlinear distortions of a HPA. Of course, this effect of spectral spreading is also a function of the operating point of the amplifier, so that the bandwith-efficiency of the transmitted OFDM-signal is varying with the backoff.

In the linear case and for large N, the OFDM-spectrum goes asymptotically to a ideal bandlimited rectangular spectrum. Using uncoded 4-DPSK for each subchannel, the bandwith-efficiency goes to $R = 2$ bit/s/Hz and $R = 1.6$ bit/s/Hz with the 25%-guard interval. In order to examine the additional reduction in bandwidth efficiency, the spectral spreading of the OFDM-signal after nonlinear amplification has been evaluated. For the specific operating points, where the power efficiency reached an maximum, this is done by calculation of the power spectral densities and comparing the results with the linear spectrum.

5 Results

A $N = 512$ and a $N = 1024$-carrier OFDM signal with 4-DPSK modulation in each subchannel has been tested with each of the three HPA models from section 3. Simulation programs have been written to evaluate the bit-error-rates and the corresponding degradations in Δ_{E_b/N_0} and the broadening of the power spectral densities for the different backoff values. Because of the spectral broadening, the signal had to be simulated in the oversampled form. E.g. for the 512-carrier signal with a 25% guard interval and a fourfold oversampling, $4 \times (1.25 \times 512)$ samples per symbol had to be simulated.

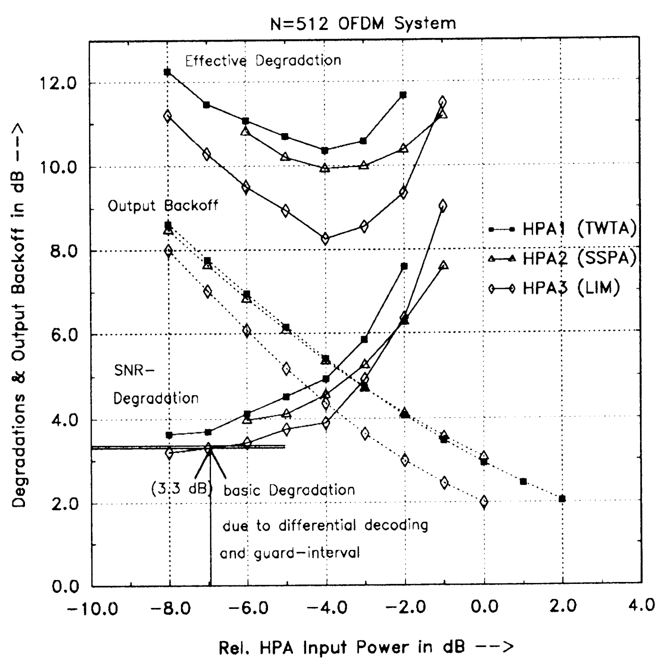

Figure 3: Output Backoff, SNR-Degradation and effective Degradation of a 512-carrier OFDM signal for the three HPA models ($P_b = 10^{-4}$).

In fig. 3 (N=512) and fig. 4 (N=1024) three sets of curves are shown for the three HPA-models as a function

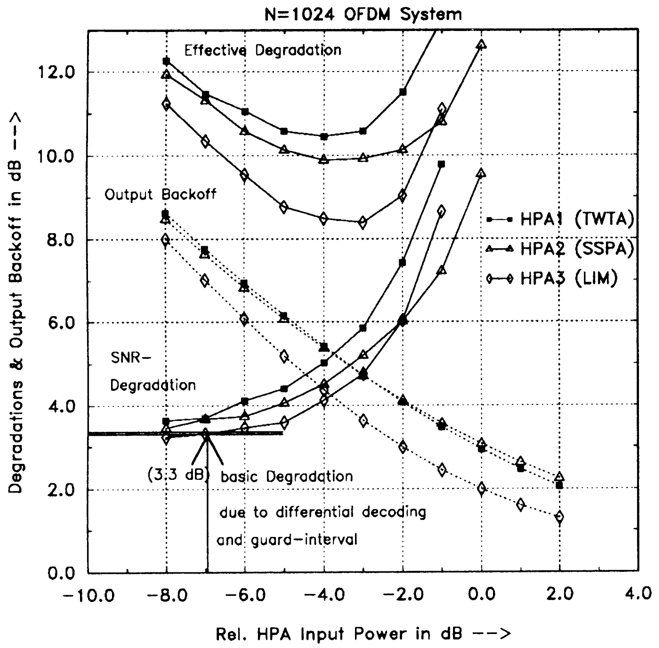

Figure 4: Output Backoff, SNR-Degradation and effective Degradation of a 1024-carrier OFDM signal for the three HPA models ($P_b = 10^{-4}$).

of the relative HPA input power in dB. The results for the different HPA-models are indicated by the different symbols. Beginning at the lower left corner of the figures, the first set of curves shows the degradation in signal-to-noise ratio relative to MSK, Δ_{E_b/N_0}, for a BER of $P_b = 10^{-4}$. For small input drive levels the signal is nearly linearly amplified and, as mentioned above, the basic degradation is $\Delta_{E_b/N_0} = 3.3$ dB due to the differential decoding and the guard interval. For increasing input power the nonlinear distortions, interference and intermodulation, and therefore the SNR-degradation, grows rapidly up. The corresponding output-backoff values for the different drive levels are shown in the second set of curves, which decrease from the left to the right. Finally the effectice degradation as the sum of OBO and SNR-degradation is shown in the third set of curves (see eq. (19)). The minimum of these curves indicate the optimum operating point of the amplifier.

For example, the $N = 512$ carrier OFDM-system with the TWTA amplifier would have the best performance at a relative input power of -4 dB, resulting in an output backoff of $OBO = 5.4$ dB and an effective degradation of $Deg_{eff} = 10.3$ dB. Using the idealized piecewise linear amplifier (HPA3) a smaller backoff can be achieved ($OBO = 4.4$ dB) and the effective degradation is improved by ~ 2 dB ($Deg_{eff} = 8.3$ dB).

The results for the $N = 1024$ carrier system show nearly the same performance, although the range of the envelope fluctuations is doubled and more degradations due to nonlinear effects are expected. The optimum operating points are the same as for 512 subchannels, resulting also in the same output backoff.

Looking at the high peak-power to mean-power ratios of a OFDM signal in table 1, the surprising results of fig.3 and 4 are the relative small backoff values for which the best power efficiency is achieved ($OBO = 4 \ldots 6$ dB). The low backoff implies, that the large signal amplitudes are severely limited by the amplifiers maximum output power, but actually the high amplitudes have a very low probability of occurence (e.g. the maximum amplitude of a 512-carrier 4-DPSK/OFDM signal is reached with a probability of $\Pr_{A_{max}} \sim 10^{-307}$!), so that they produce very few errors. The SNR-degradation in the region of the optimum operating point produced by intermodulation and the limiting effect is below 5 dB relative to MSK for all examples. With regards to the 3.3 dB loss of the differential decoding and the guard interval, this means a degradation in SNR below 1.7 dB relative to the linear 4-DPSK/OFDM signal. The effective degradations in the optimal operation points for the different HPA-models show a margin of ~ 2 dB, which could be gained, when the idealized amplifier (HPA3) is used instead of the nonlinear TWT amplifier (HPA1). As expected, the results for the SSPA-model (HPA2) lie between the two other.

For the optimum operating points of the three different HPA models and the two OFDM-signals the power spectral density has been evaluated by simulation. The results, showing the spectral spreading of the OFDM-signal, are presented in fig. 5 and 6. As can be seen, the regenerated spectral sidelobes of the nonlinearly distorted signals are kept below -20 dB in all cases. Therefore the corresponding B99%-bandwidths don't differ essentially. Numerical evaluation of the B99.9%-bandwidths leads in all cases to a bandwidth expansion in the range of $r'_B = 1.8 \ldots 2.0$. It has to be emphasized, that the nearly same spectral performance for the three different HPA-models is achieved with different backoff values. Of course, the ideally linearized HPA model would allow a better spectral performance as e.g. the TWTA, when compared with the same output backoff.

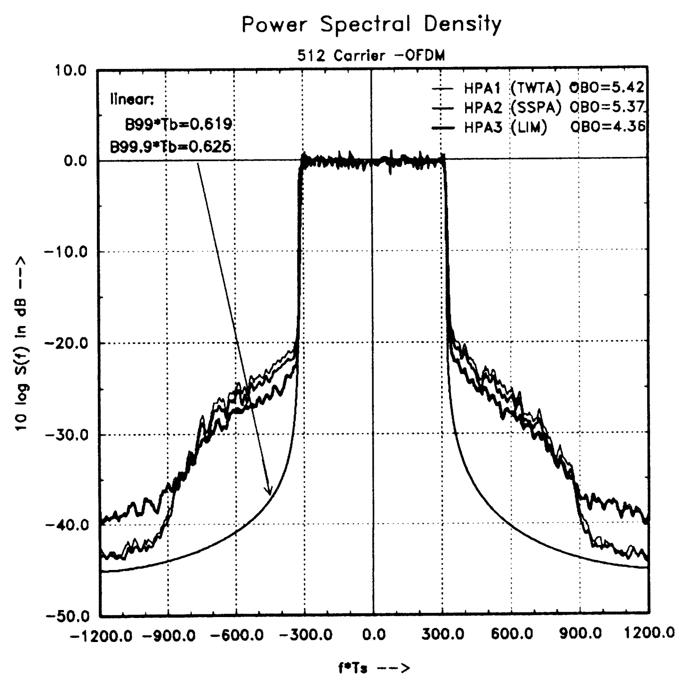

Figure 5: Power spectral density of a 512 carrier OFDM signal with guard interval in the linear case and at the output of the nonlinear amplifiers with optimized backoff values.

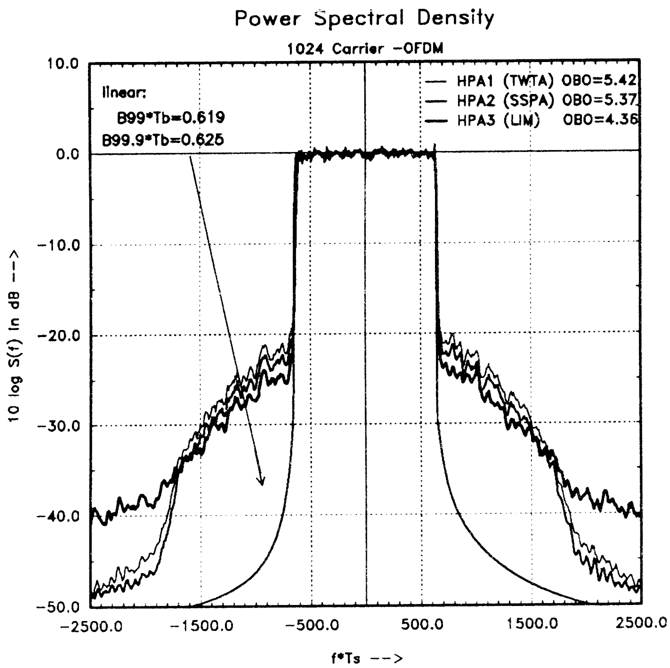

Figure 6: Power spectral density of a 1024 carrier OFDM signal with guard interval in the linear case and at the output of the nonlinear amplifiers with optimized backoff values.

6 Conclusion

The 4-DPSK/OFDM signal proposed for a future digital terrestrial or satellite sound broadcasting system has been expected to be very sensitive to the nonlinear distortions of the high power RF-amplifiers in the transmitter. Because of the high dynamics of the multicarrier signal, a large output backoff has been assumed to be necessary to avoid strong degradations due to intermodulation. The results for a $N = 512$ and $N = 1024$-carrier system and for three different kinds of HPA-models have shown that the best power efficiency of the HPA and the modulation scheme is obtained in the region of an output backoff of $OBO = 4 \ldots 6$ dB. Operating with these backoff values, the degradations in signal-to-noise ratio due to nonlinear distortions are kept in the range of $0.7 \ldots 1.7$ dB relative to the linear 4-DPSK/OFDM signal, while the regeneration of the spectral sidelobes is kept below -20 dB. Although the most serious problem of the proposed sound broadcasting system is the severly selective fading channel to the mobile receivers, the results in this paper concerning the nonlinear distortions of the transmitter HPA could be a useful contribution to the system design, especially for a satellite broadcasting system.

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