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Effect of Nonlinear Amplifiers of Transmitters in the CDMA System Using Offset-QPSK

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SUMMARY This paper deals with study results on the effect of nonlinear amplification in the CDMA system using offset-QPSK signals bandlimited with a square-root cosine roll-off filter. As a result of the study, it is shown that the nonlinear amplification does not affect bit error rate performance with reasonable out-of-band emission characteristics when the roll-off factor of the transmit filter is one.

key words: *radio communication, nonlinear amplifier, CDMA, offset-QPSK*

1. Introduction

Code-Division Multiple-Access (CDMA) system using direct-sequence spread-spectrum (DS/SS) scheme has attractive features for mobile communication systems, such as the robustness against intersystem interference and multi-path fading, and the asynchronous multiple-access capability.

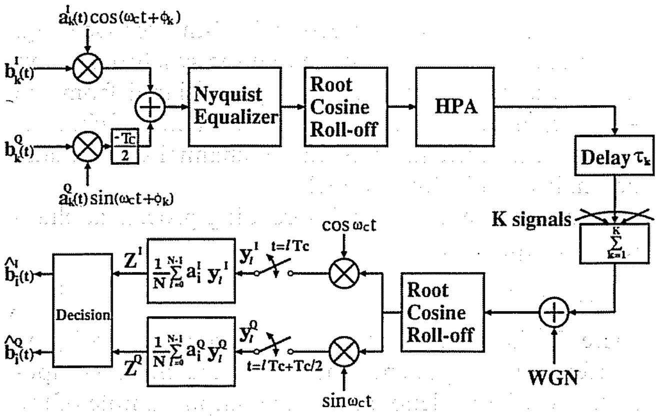
In mobile communication systems, in order to achieve high power efficiency, high power amplifiers of mobile transmitters often have nonlinear characteristics, which may spread the frequency spectrum of the signal and degrade the error rate performance. One of the ways to avoid the effect of the nonlinear distortion is to use the modulation methods that have constant or quasi-constant envelope such as minimum-shift keying (MSK) or offset quadrature phase-shift keying (offset-QPSK).

In this paper, we discuss the effect of nonlinear amplifiers of transmitters in the CDMA system using offset-QPSK, and evaluate the bit error rate (BER) performance taking account of the out-of-band emission. As for the nonlinearity of the transmitter amplifier, an ideal band-pass hard limiter (BPHL) and an actual class-C amplifier are considered.

2. System Model

Figure 1 shows the system model. In the figure, $b_k^I(t)$ and $b_k^Q(t)$ represent transmitted information signals of the k-th user. In this paper, these signals are assumed to be constant, $+1$. The spreading signals for k-th user, $a_k^I(t)$ and $a_k^Q(t)$, are spreading sequences of rectangular pulses of duration T_c. We assume that the spreading sequence is Gold sequence with the length $N = 1{,}023$. As offset-QPSK is employed, the signal of channel Q is delayed by $T_c/2$ relative to that of channel I.

After spreading and modulation, the signal is applied to the Nyquist equalizer (a waveform shaping filter with impulse response $\tau/\sin\tau$) and filtered by the square-root cosine roll-off filter. The filtered signal is then amplified by the nonlinear high power amplifier (HPA).



HPA: High Power Amplifier
WGN: White Gaussian Noise

Fig. 1 System model.

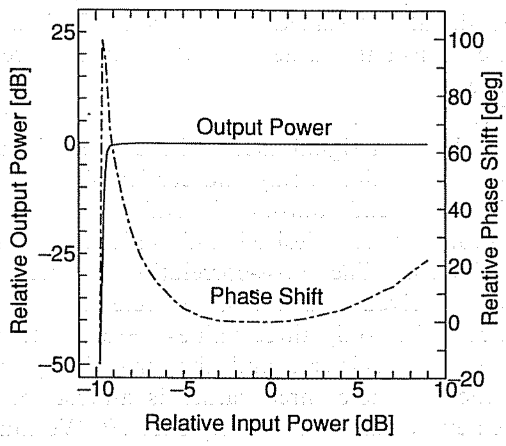


Fig. 2 Nonlinearity of a class-C amplifier.

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We consider two kinds of nonlinearity of the HPA. One is a band-pass hard limiter (BPHL). This is one of the typical nonlinearity, which can be implemented with a band-pass filter followed by a hard limiter at the input to a power amplifier. The other nonlinearity considered is an actual class-C amplifier which is used for mobile (ship) terminals of the INMARSAT system with 30 W of output power in L-band.⁽¹⁾ The transfer characteristics of the amplifier is shown in Fig. 2.

In this paper, the CDMA system is assumed to include K users having asynchronous access to the system. A signal from k-th user has independent delay τ_k and initial carrier phase ϕ_k. The distributions of τ_k and ϕ_k are assumed to uniformly distribute over $[0, NT_c]$ and $[0, 2\pi]$, respectively.

At the input of receiver, these K signals and white Gaussian noise are band-limited by the filter which has the same frequency response as that of the transmit filter, then demodulated, despread, and applied to the decision circuit.

3. Bit Error Rate

Let us consider the receiver for i-th user (see Fig. 1). In the analysis, we assume that the synchronization of the receiver for the desired signal (signal from the i-th user) is perfect. Since the performance of channel I is considered the same as that of channel Q, we make the analysis only for channel I.

The sample Z^I, after despreading process at channel I, is expressed as

$$Z^I = Z_D^I + Z_U^I + Z_N^I, \qquad (1)$$

where Z_D^I is the desired signal component, Z_U^I is the interference component, and Z_N^I is the noise component. Now let us denote Z_k^I as the output sample of the signal component from k-th user after despreading where there is only a signal from k-th user (and no noise exist). Then we have $Z_D^I = Z_i^I$ and $Z_U^I = \sum_{k=1, k\neq i}^{K} Z_k^I$.

As the synchronization at the receiver for the desired signal is assumed to be perfect, Z_D^I is a deterministic constant value for the given spreading sequence.

The interference component Z_U^I is random, because the each signal except the desired signal has independent random delay and carrier phase.

The despread output depends on the cross-correlation between desired and undesired (interference) signals. The cross-correlation between Gold sequences derived from the same preferred pair of M sequences takes only three values (-65, -1, 63 for 10-stage shift register), and the probability of the occurrence of these three values is almost the same between every pair of Gold sequences.⁽²⁾ We thus first calculate the $p(Z_k^I)$, the probability density function of Z_k^I, by computer simulation using typical pair of Gold sequences for spreading. Then, assuming that $p(Z_k^I)$ is identical for any k, we obtain $p(Z_U^I)$, the probability density function of Z_U^I, by $(K-2)$-fold convolution of $p(Z_k^I)$.⁽³⁾ Figure 3 shows the probability density functions of the interference components Z_U^I normalized by desired signal component Z_D^I where the number of signals $K=11$, 51 and 101 assuming that the transmitter amplifier is BPHL.

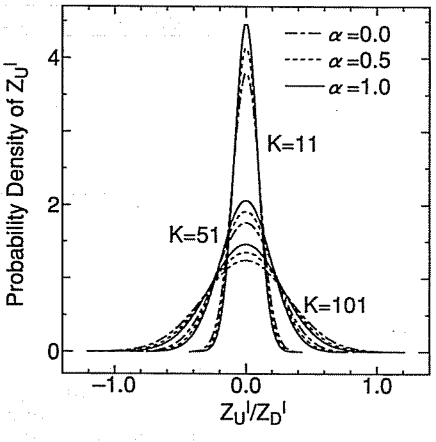


Fig. 3 Probability density function of Z_U^I.

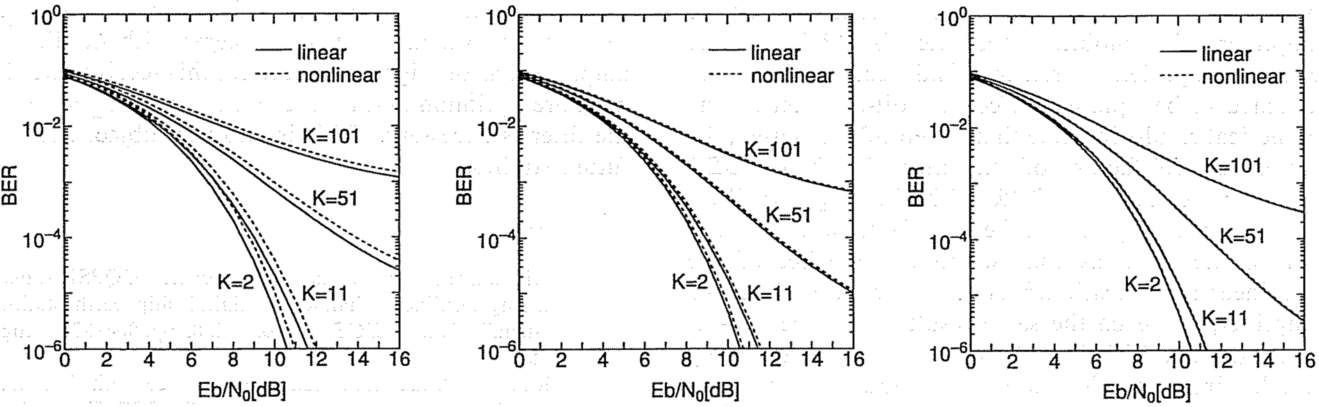
Since the noise component Z_N^I is band-limited and despread white Gaussian noise, it is also random value, which has zero-mean Gaussian distribution. The variance of this component is $\sigma^2 = N_0/(4NT_c)$, where N_0 is the one-sided power spectral density of the noise.

The BER performance P_e of channel I is expressed as:

$$P_e = \frac{1}{2}\int_{-\infty}^{+\infty} p(Z_U^I) \cdot \mathrm{erfc}\left(\frac{Z_D^I + Z_U^I}{\sqrt{2}\cdot\sigma}\right) dZ_U^I. \qquad (2)$$

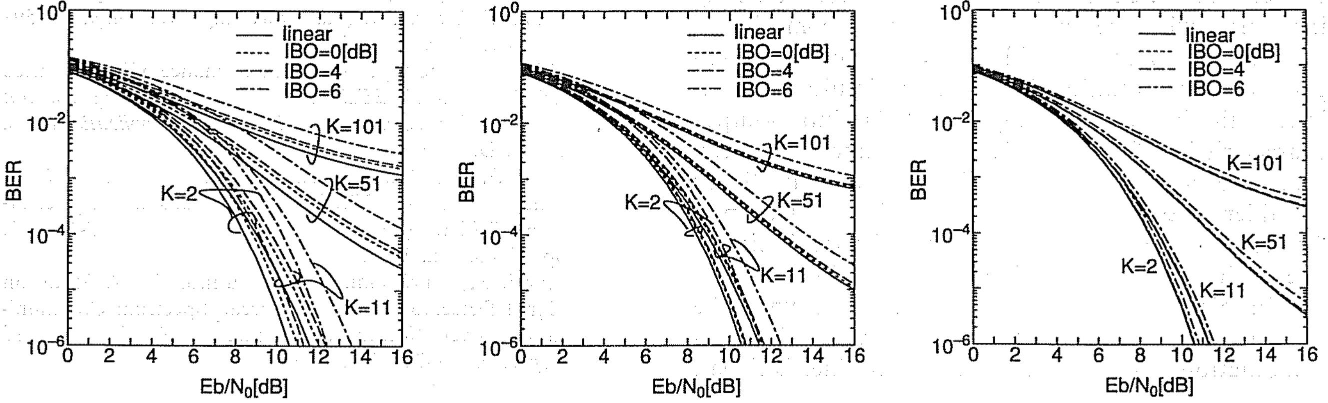
Numerical examples for the systems with BPHL are given by dashed lines in Fig. 4(a)-(c), where E_b is the energy of an information bit. The results for linear amplifier are also shown by the solid lines. The dashed lines in Fig. 5(a)-(c) show BERs for the class-C amplifier with the different input back-off (IBO).

Figures 4 and 5 indicate that the BER performance is improved by increasing the roll-off factor α in both BPHL and class-C amplifier. This can be explained as follows: the fluctuation of signal envelope becomes smaller as the roll-off factor α is chosen larger, which means that the effect of nonlinear amplification on Z_D^I and also the variance of the interference component Z_U^I become smaller. In the case where α is the largest ($\alpha=1.0$), the effect of nonlinearity on the BER performance is negligibly small for the systems with BPHL and the class-C amplifier with proper IBO. In the system with the class-C amplifier, the BER performance is considerably degraded with large IBO. This phenomenon is caused by the fact that the effect of the AM/PM conversion is dominant and results in large



(a) $\alpha=0.0$ (b) $\alpha=0.5$ (c) $\alpha=1.0$

Fig. 4 Bit error rate (BPHL).



(a) $\alpha=0.0$ (b) $\alpha=0.5$ (c) $\alpha=1.0$

Fig. 5 Bit error rate (class-C amplifier).

phase offset in the PSK signal, when IBO is large.

4. The Power of Out-of-Band Emission

Even in CDMA system, in which the spectrum of signals are widely spread, out-of-band emission has to be suppressed in order to avoid interference to other systems in adjacent frequency bands. Figure 6 shows the out-of-band power for an offset-QPSK signal at the output of the class-C amplifier with 0 dB IBO. (For BPHL, we can have almost the same characteristics.⁽⁴⁾) In this figure, the horizontal axis represents the frequency difference from the carrier frequency normalized by $1/T_c$, and the vertical axis represents the power falling at the band outside the frequency on the abscissa, and normalized by the total signal power. We can conclude from Fig. 6 that the out-of-band power becomes smaller when α is larger. This conclusion is interesting, because small α gives a narrow signal in the system with a linear amplifier.

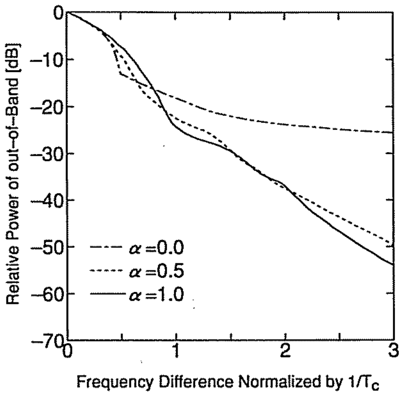


Fig. 6 Out-of-band power (class-C amplifier with IBO=0 dB).

5. Conclusion

The BER performance in the CDMA system using offset-QPSK modulation has been evaluated, when the amplifier of a mobile transmitter is BPHL or the class-C amplifier. Transmit and receive filters are assumed to be square-root cosine roll-off filters. The numerical results indicate that, when BPHL is used, the larger roll-off factors of the filter give better BER performance, and the BER with the largest roll-off factor ($\alpha=1.0$) gives the best performance, which is almost the same as that without the effect of the nonlinear amplification.⁽⁵⁾ Also in the case of class-C amplifier, we reach the same results: with the roll-off factor $\alpha=1.0$, BER degradation by nonlinearity is very small. From the viewpoint of spurious power out of designated bandwidth, the roll-off factor $\alpha=1.0$ gives the best performance both for BPHL and the class-C amplifier.

In the case of class-C amplifier, the larger IBO makes the BER worse. This is because the AM/PM conversion, which is dominant, is not monotonically increasing with the input level. These complicated nonlinearity of the amplifier, however, can be compensated with additional nonlinear circuit, a linearizer, at the input of the amplifier.⁽⁶⁾ The input-output characteristics of the amplifier with the linearizer correspond to a soft limiter, which is partially linear amplifier without AM/PM conversion. The performance of the CDMA systems with the soft limiter is one of the questions remained to be considered.

In this paper, we consider only the cases where the transmit and receive filters are the same. With this combination of the filters, when the amplifier is linear, the receive filter matches the received signal and gives the best performance. In the systems with nonlinear amplifiers, as the signal is distorted, this receive filter is no more optimum and to find out the best selection of the filter is necessary. This is another subject left for future studies.

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