Detection of clipped code-division multiplexed signals

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Code-division multiplexing (CDM) is a robust transmission scheme recently adopted for satellite multimedia broadcasting systems. A drawback of CDM is its high peak-to-average power ratio, which can be reduced by clipping the baseband CDM signal. However, clipping introduces in-band noise that may considerably degrade system performance. Proposed is an iterative decision-directed technique for detecting clipped CDM signals. The performance of the algorithm is studied by means of computer simulation. Simulation results show that the proposed technique can provide significant performance improvement compared to a conventional (linear) detection of clipped CDM signals.

Introduction: Code-division multiplexing (CDM) is a transmission scheme suitable for a wide variety of digital communication systems [1]. Recently, CDM technique has been adopted for commercial satellite multimedia broadcasting systems [2, system E]. A drawback of multichannel CDM is its high peak-to-average power ratio (PAPR), which places strict linearity requirements on high power amplifiers [3]. Clipping is one of the simplest and effective methods to reduce PAPR of the CDM signal [4]. However, clipping introduces in-band noise that may significantly degrade system performance.

In this Letter, we introduce a simple decision-directed algorithm for detecting clipped CDM signals. The idea of the algorithm is based on the iterative detection technique recently proposed for multicarrier systems [5]. Our approach is motivated by the structural similarity between CDM signals and multicarrier signals generated by inverse fast Fourier transform (FFT) [3]. In this study, we adopted the quasi-maximum-likelihood (ML) technique [5, 6], which is shown to be less prone to error propagation effects than the decision-aided reconstruction technique proposed in [7]. CDM signals can be clipped either at the Nyquist sampling rate, or at a higher sampling rate. We mainly focus on Nyquist rate clipping. However, the results can also be extended to a higher than Nyquist rate clipping, and other types of nonlinearity.

System model: Consider the model of the CDM transmission system with clipping. In the CDM transmitter, information bits corresponding to each multiplexed channel are first mapped into complex symbols $s^{(k)}$ in accordance with quadrature phase-shift keying (QPSK) signalling format; i.e. the symbols $s^{(k)}$ belong to the alphabet $\{\pm(1+j), \pm(1-j)\}$. The results presented in this Letter can also be extended to high-order modulation formats, but in sequel we shall focus only on QPSK signalling. The sampled baseband CDM signal during one symbol period can be expressed as

$$x_n = \sum_{k=0}^{K-1} s^{(k)} c_n^{(k)}, \quad n = 0, 1, \ldots, N-1 \tag{1}$$

where N is the spreading factor, K the number of CDM channels ($K \le N$), and $\mathbf{c}^{(k)} = \{c_0^{(k)}, c_1^{(k)}, \ldots, c_{N-1}^{(k)}\}$, $k = 0, 1, \ldots, K-1$ is the set of orthogonal signature codes. In this Letter, binary Walsh codes ($c_n^{(k)} = \pm 1$) are assumed to be used as the orthogonal signature codes [1, 2].

To reduce the PAPR of the CDM signal the baseband signal samples x_n are fed to the envelope-clipping device, which performs the following operation

$$y_n = \begin{cases} x_n, & |x_n| \le T \\ Te^{j\arg(x_n)}, & |x_n| > T \end{cases} \quad n = 0, 1, \ldots, N-1 \tag{2}$$

where T is the clipping threshold. The clipping ratio is defined as [7]

$$CR = 10\log_{10}(T^2/\sigma_x^2) \tag{3}$$

where σ_x^2 is the variance of x_n. Clipped signal y_n is then passed to the quadrature modulator, which first multiplies complex input samples with long pseudo-noise (PN) binary spreading sequence to ensure that the adjacent signal samples are not correlated [1, 2], and then performs filtering in order to shape the signal waveform.

Assuming AWGN channel and perfect synchronisation, the received CDM signal after downconversion and despreading can be expressed as

$$r_n = y_n + w_k = x_n + d_n + w_n \tag{4}$$

where w_n is the AWGN term, and d_n is the distortion term that represents clipping noise. We assume here that the channel does not introduce frequency selective multipath (which is a reasonable assumption for fixed satellite links). The results, however, can also be extended to the case of a frequency selective multipath channel.

ML receiver for clipped CDM signals: The optimal ML receiver solves the following minimisation problem [5]:

$$\hat{\mathbf{s}} = \arg\min_{\forall \hat{s}} \sum_{n=0}^{N-1} |y_n^{(\hat{s},T)} - r_n|^2 \tag{5}$$

where $\hat{\mathbf{s}} = (\hat{s}^{(0)}, \hat{s}^{(1)}, \ldots, \hat{s}^{(K-1)})$ and $\mathbf{y}^{(\hat{s},T)} = (y_0^{(\hat{s},T)}, y_1^{(\hat{s},T)}, \ldots, y_{N-1}^{(\hat{s},T)})$ is the reference vector obtained by substituting $\hat{\mathbf{s}}$ in (1)–(2).

Because of clipping, CDM channels lose orthogonality. Hence (5) can only be solved by brute-force search through all possible codewords $\hat{\mathbf{s}}$. ML decoding is therefore infeasible even for an intermediate number of CDM channels.

Quasi-ML detection algorithm: The idea of the quasi-ML algorithm is to iteratively estimate the distortion term d_n using the decision-directed approach. Although the receiver cannot perfectly reconstruct the distortion term d_n, it is possible to estimate d_n, if preliminary decisions are available. In the first iteration, preliminary decisions can be obtained using the conventional (linear) detection algorithm. However, in the next iterations, hard decisions from the previous iteration can be used to re-estimate the distortion term d_n. It is shown [5] that the quasi-ML algorithm provides an improvement if the energy of the distortion term is reduced:

$$E\left[|d_n - \hat{d}_n|^2\right] < E\left[|d_n|^2\right] \tag{6}$$

where $E[\cdot]$ denotes expectation. Condition (6) is verified by simulation results presented in the next subsection.

The iterative quasi-ML detection algorithm adopted for CDM signals is summarised below. Here we assume that the receiver has perfect knowledge of the clipping level T. Initially, the estimate of the distortion term d_n is set to zero ($\hat{d}_n = 0$) and the following steps are performed:

Step 1: By using received signal samples (4), estimates of the complex baseband symbols are obtained as

$$\hat{s}^{(k)} = \left\langle \sum_{n=0}^{N-1} (r_n - \hat{d}_n) c_n^{(k)} \right\rangle \quad k = 0, 1, \ldots, K-1 \tag{7}$$

where $\langle\cdot\rangle$ denotes a decision-making process.

Step 2: The estimate of the transmitted signal x_n is reconstructed in accordance with

$$\hat{x}_n = \sum_{k=0}^{K-1} \hat{s}^{(k)} c_n^{(k)} \quad n = 0, 1, \ldots, N-1 \tag{8}$$

Step 3: The distortion term d_n is estimated as

$$\hat{d}_n = \begin{cases} Te^{j\arg(\hat{x}_n)} - \hat{x}_n, & |\hat{x}_n| > T \\ 0, & |\hat{x}_n| \le T \end{cases} \quad n = 0, 1, \ldots, N \tag{9}$$

Step 4: Steps 1 to 3 are repeated with the new estimate of the distortion term $\hat{d}_n$.

In the last iteration, calculation of (7) is repeated in order to obtain final decisions.

It should be noted that the proposed detection algorithm can easily be extended to other types of nonlinearity, including higher than Nyquist rate clipping. The algorithm can also be applied to coded CDM systems with only minor modifications. In such a case, however, care should be taken to ensure that condition (6) holds.

Owing to the binary structure of signature (Walsh) codes implementation of the quasi-ML detection algorithm (7)–(9) does not require complex multiplications, which greatly simplifies receiver hardware.

Simulation results: Because of the highly nonlinear nature of the algorithm, the performance of the quasi-ML receiver has been analysed by Monte-Carlo simulation method. We studied the performance of the uncoded CDM-QPSK system with spreading factor

$N = 64$, and number of active channels $K = 64$. Truncated M-sequence of 2048-bit length was adopted as the spreading PN-sequence. This spreading sequence was obtained by truncating maximum length sequences of 4095-bit length generated using a 12-stage feedback shift register [2]. Fig. 1 shows the simulated BER performance of the quasi-ML algorithm for two clipping ratio values.

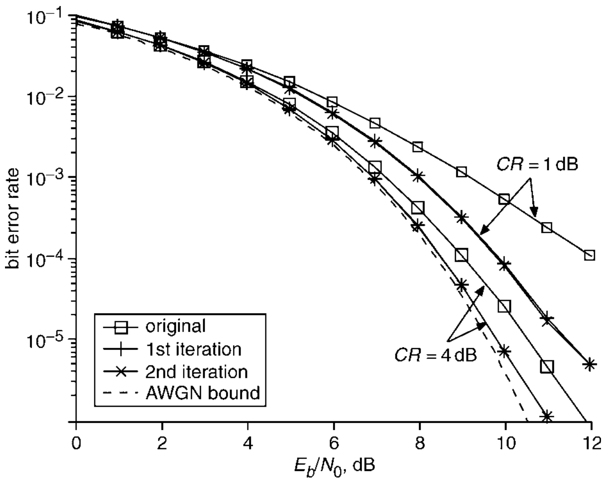

Fig. 1 *BER against E_b/N_0 for conventional and quasi-ML receivers*

It can be seen from Fig. 1 that the proposed algorithm provides an improvement over the conventional receiver, especially at low probabilities of bit errors. It is also seen that the performance of the quasi-ML receiver is saturated after the first iteration.

Conclusion: In this Letter, we have shown that the iterative quasi-ML technique that was originally developed for multicarrier systems can also be adopted for code-division multiplexed signals. It has been shown that this technique can efficiently be used in CDM-QPSK systems when the clipping ratio is 1–4 dB.

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