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SERIALLY CONCATENATED CODED *M*-ARY CONTINUOUS PHASE MODULATION WITH BIT-INTERLEAVER

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ABSTRACT

This letter investigates a serially concatenated convolutional coded *M*-ary continuous phase modulation (CPM). Using the decomposition model of a CPM system, the soft-input-soft-output detectors for *M*-ary CPM is investigated in detail. Based on these, the performance of bit-interleaved coded-modulation (BICM) schemes is studied. Simulation results show that due to the presence of the conversion between symbol and bit likelihoods, so to improve the BER performance by the iterative scheme is no longer the best choice. In the case of the short information frame and low signal-to-noise ratio region, the coded modulation system based *M*-ary CPM can achieve better performance than coded *M*-ary QAM system with the same spectral efficiency. The proposed system is bandwidth- and power-efficient, and moreover it is able to against burst errors effectively.

Keywords: *Iterative Decoding, M-ary Continuous Phase Modulation (CPM), Serial Concatenated Codes*

1. INTRODUCTION

Continuous phase modulation (CPM) is a digital modulation scheme in which memory is added in the phase modulation process to ensure that the phase is a continuous function of time [1, 2, 3]. The benefits of CPM are two-fold: it provides good spectral efficiency and a constant envelope property, which allows the use of low cost non-linear amplifiers. Among CPM, GMSK is an important scheme for its spectral properties being used in Bluetooth, DECT, GSM and CDPD.

The introduction of the turbo codes in 1993 [4] let to a vast research interest in concatenated convolutional codes separated by a pseudorandom bit-interleaver and decoded iteratively. [5] proved that a CPM modulator can be decomposed into a continuous phase encoder followed by a memoryless modulator. Therefore, detailed studies on serially concatenated continuous phase modulation (SCCPM) were presented in many literatures [6, 7, 8, 9, 10]. However, many authors focused on 2-ary modulation, namely MSK especially. In this letter, a bandwidth-efficient serially concatenated convolutional coded *M*-ary $(M>2)$ CPM system with bit-interleaver was investigated.

This letter is organized as follows. In Section 2, the system model(s) under consideration and the receiver structure for each of them are described. The realizations of the soft-input-soft-output detectors for *M*-ary CPM are discussed in detail In Section 3, the performance of system under consideration is presented through simulation. Finally in Section 4, some conclusions for serially concatenated coded *M*-ary CPM with bit-interleaver are drawn.

2. SYSTEM DESCRIPTION

2.1 Transmitter

Let us consider a serial concatenated system as shown in Figure 1. In each frame, a block of K independent information bits are encoded by a convolutional encoder whose output is a block of N -coded bits represented by $X=(x_1,x_2,\cdots,x_N)$. Then, the binary sequence is interleaved by the pseudorandom bit-interleaver and the interleaved sequence $\tilde{X}=(\tilde{x}_1,\tilde{x}_2,\cdots,\tilde{x}_N)$ is sent to the *M*-ary CPM modulator.

2.2 M-Ary CPM Signals And Optimum Coherent Receiver

Continuous Phase Modulation is a constant envelope modulation with time domain representation [1,2,3]:

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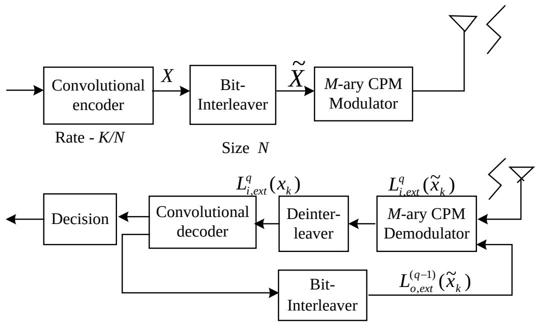

Figure 1: Block Of Serially Concatenated Coded M-Ary CPM With Bit-Interleaver: Transmitter And Receiver

$$\begin{aligned} s(t,\mathbf{a}) &= \sqrt{2E_s/T}\cos(2\pi f_0 t+\varphi(t,\mathbf{a})) \\ &= \sqrt{2E_s/T}\cos(2\pi f_0 t+2\pi h\sum_{i=0}^{n} a_i f(t-iT)) \\ &= \sqrt{2E_s/T}\cos(2\pi f_0 t+2\pi h\sum_{i=n-L+1}^{n} a_i f(t-iT)+\pi h\sum_{i=0}^{n-L} a_i) \\ &= \sqrt{2E_s/T}\cos(2\pi f_0 t+\theta(t,\mathbf{a}_n)+\theta_n) \end{aligned}$$

$$nT \le t \le (n+1)T \qquad (1)$$

Where T is the symbol period; E_S is the energy per symbol; f_o is the carrier frequency, The data $\mathbf{a}=(a_0,a_1,a_2...)$ are M-ary data symbols, M even, taken from the alphabet $\pm 1,\pm 3...\pm(M-1)$, h (0<h<1) is the modulation index, suppose $h=K/P$ (K and P is a pair of relative prime positive), $f(\cdot)$ is the phase response function, and it meets the following condition:

$$f(t)=\begin{cases} 0, & t<0 \\ 1/2, & t>LT \end{cases} \qquad (2)$$

The prefix "L", where it is a positive integer, denotes the length of the response. CPM schemes are denoted by their phase response function or by its derivative $g(\cdot)$ (frequency response). This paper discusses the CPM signal with L = 1 and $f(\cdot)$ is a rectangular pulse.

M-ary modulation technology is one of important technical means to meet the new generation of communication systems with increasingly high transmission data rate. *M*-ary data symbols taken from the alphabet $\pm 1,\pm 3,\pm 5,\cdots,\pm(M-1)$, and CPM modulator occur one of *M*-modulation symbols in the waveform in each data symbol interval. In this case, the total number of phase states is $S_{ML}=P\cdot M^{L-1}$, where P is the denominator of modulation index, L is the length of the phase response.

CPM signals are optimally demodulated using maximum-likelihood sequence detection (MLSD), which consists of a matched filter bank followed by a detector using Viterbi algorithm[1, 2, 3], as shown in Figure 2. Where $r(t)$ is the receiver waveform, h_c and h_s are the impulse responses of the matched filter:

$$h_c(t,\tilde{\mathbf{a}}_n)=\cos[2\pi h\sum_{j=-L+1}^{0}\tilde{\mathbf{a}}_j f((1-j)T-t)],\quad t\in[0,T] \qquad (3)$$

$$h_s(t,\tilde{\mathbf{a}}_n)=\sin[2\pi h\sum_{j=-L+1}^{0}\tilde{\mathbf{a}}_j f((1-j)T-t)],\quad t\in[0,T] \qquad (4)$$

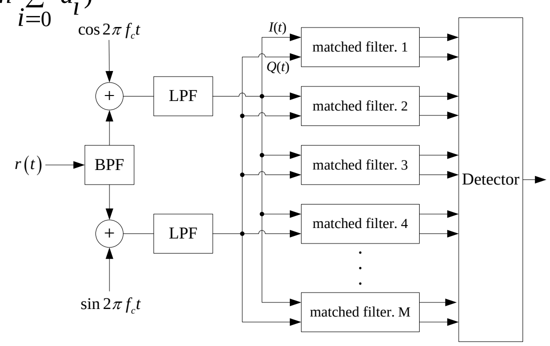

Figure 2a: The Architecture Of CPM Optimal Receiver

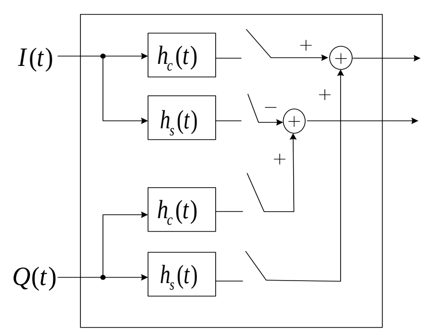

Figure 2b: The Architecture Of Matched Filter

Detector by state trellis search for the path of the minimum Euclidean distance, the traditional method is to use the Viterbi algorithm. CPM as the inner code for serially concatenated system, obtained from the CPM detector should be soft information; therefore, the soft-in-soft-out BCJR

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decoding algorithm [11] is used in this letter. The BCJR algorithm and maximum a posteriori probability (MAP) decoding algorithm are consistent for the convolutional code. Following we derive the BCJR algorithm applied to CPM signal detection branch metric formula.

The receiver observes the signal $r(t)=s(t,\mathbf{a})+n(t)$, where the noise $n(t)$ is Gaussian and white. [1] proved that the likelihood function $p_{r(t)|\tilde{\mathbf{a}}}(r(t)|\tilde{\mathbf{a}})$ in the maximum likelihood sequence estimating (MLSE) receiver is equivalent to the correlated metric $Z_n(\tilde{\mathbf{a}})$:

$$Z_n(\tilde{\mathbf{a}})=\int_{nT}^{(n+1)T} r(t)\cdot A(t)\cos[\omega_0 t+\varphi(t,\tilde{\mathbf{a}})]dt \qquad (5)$$

The receiver computes $Z_n(\tilde{\mathbf{a}})$ for all M^L possible sequences $\tilde{\mathbf{a}}_n=\{\tilde{a}_n,\tilde{a}_{n-1},\cdots,\tilde{a}_{n-L+1}\}$ and all P possible $\tilde{\theta}_n$ over the nth symbol interval. This makes PM^L different values of Z_n. Rewriting (5) using (1) yields:

$$Z_n(\tilde{\mathbf{a}}_n,\tilde{\theta}_n)=\int_{nT}^{(n+1)T} r(t)\cdot A(t)\cos[\omega_0 t+\theta(t,\tilde{\mathbf{a}}_n)+\tilde{\theta}_n]dt \qquad (6)$$

The noise $n(t)$ can be expressed in the bandpass form, $n(t)=x(t)\cos\omega_0 t-y(t)\sin\omega_0 t$, $I(t)$ and $Q(t)$ are In-phase and quadrature components of CPM modulation waveform, and the received quadrature components are:

$$\begin{aligned}\hat{I}(t)&=[\sqrt{2E_s/T}\cdot A(t)I(t)+x(t)]\\ \hat{Q}(t)&=[\sqrt{2E_s/T}\cdot A(t)Q(t)+y(t)]\end{aligned} \qquad (7)$$

By inserting these components in (5) and omitting double frequency terms, we have:

$$\begin{aligned}Z_n(\tilde{\mathbf{a}}_n,\tilde{\theta}_n)=&\cos(\tilde{\theta}_n)\int_{nT}^{(n+1)T}\hat{I}(t)\cdot A(t)\cos[\theta(t,\tilde{\mathbf{a}}_n)]dt\\ &+\cos(\tilde{\theta}_n)\int_{nT}^{(n+1)T}\hat{Q}(t)\cdot A(t)\sin[\theta(t,\tilde{\mathbf{a}}_n)]dt\\ &+\sin(\tilde{\theta}_n)\int_{nT}^{(n+1)T}\hat{Q}(t)\cdot A(t)\cos[\theta(t,\tilde{\mathbf{a}}_n)]dt\\ &-\sin(\tilde{\theta}_n)\int_{nT}^{(n+1)T}\hat{I}(t)\cdot A(t)\sin[\theta(t,\tilde{\mathbf{a}}_n)]dt\end{aligned} \qquad (8)$$

formula (8) is the branch metric formula of CPM signal soft-in-soft-out detection algorithm as that using in BCJR algorithm. Figure 3 shows the BER performances of soft-in-soft-out CPM demodulator. It can be seen that CPM modulation system performance can be changed by changing the modulation index h: with the increase of h, a gradual improvement in performance. Compared to the *M*-ary PSK and *M*-ary QAM modulation system only by changing the bit rate of the encoding scheme, this characteristic of the CPM for the system provides greater flexibility to adapt to the channel environment.

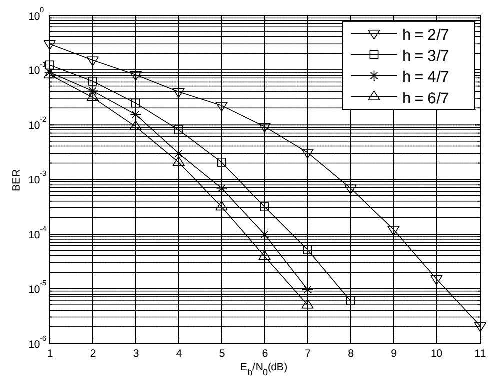

Figure 3: 4-Ary CPM System (N = 1000) BER Performance With Different Modulation Index In AWGN Channel

2.3 Receiver

As shown in Figure 1, the receiver uses a message passing decoder, which passes messages (extrinsic log-likelihood ratios, LLRs) between the soft output inner decoder for *M*-ary CPM and an outer decoder(convolutional decoder) in an iterative fashion. The conversion between symbol probability and bit likelihoods is an indispensable part of system, due to the alphabet of the inner code and the outer code is not the same.

A maximum of Q iterations between the *M*-ary CPM demodulator and outer decoder are used. During the q th iteration ($q=0,1,...,Q-1$), the *M*-ary CPM demodulator uses $R^{(q)}=(r,L_{o,ext}^{(q-1)}(\tilde{x}))$ where is the interleaved extrinsic information obtained from the outer decoder in the $(q-1)$ th iteration. The *M*-ary CPM demodulator produces probability for each *M*-ary data symbols, and using the conversion between symbol probability and bit likelihoods, produces LLRs for each bit in sequence $\tilde{\mathbf{X}}$, given by

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$$L_i^{(q)}(\tilde{x}_k) = \log \frac{P\left(\tilde{x}_k = 0 \middle| \mathbf{R}^{(q)}\right)}{P\left(\tilde{x}_k = 1 \middle| \mathbf{R}^{(q)}\right)} \quad (9)$$

Where $\tilde{x}_k$ is the kth element of $\tilde{\mathbf{X}}$. The extrinsic information obtained form CPM demodulator can be written as $L_{i,ext}^{(q)}(\tilde{x}_k) = L_i^{(q)}(\tilde{x}_k) - L_{o,ext}^{(q-1)}(\tilde{x}_k)$, $\forall k$. This extrinsic information is deinterleaved and input to the convolutional decoder. The convolutional decoder uses the BCJR algorithm and provides extrinsic information $L_{o,ext}^{(q-1)}(x_k)$. The iterative process continues up to $Q-1$ iterations. Clearly, when $Q=0$, this corresponds to the case when there is no iterative demodulation.

3. PERFORMANCE OF SERIALLY CONCATENATED CODED *M*-ARY CPM

The bit error ratio performance limit of a serially concatenated coded *M*-ary CPM modulation system can be calculated by the union bound. Unfortunately, this procedure assumes that the concatenated system using maximum likelihood sequence detection and uniform interleaver. But in practice, sub-optimal iterative decoders and the pseudorandom interleaver are often used in concatenated systems. Following, the system performance is examined through simulation method. When the error bits are greater than 100, or the number of data frames is greater than 20000, the simulation is aborted.

3.1 Iteration Scheme Influence On System Performance

Serial concatenated *M*-ary CPM system using joint iterative demodulation decoding method to optimize the system BER performance, and therefore the number of iterations is an important parameter of the design of serial concatenated *M*-ary CPM system. Can be seen from Figure 4 simulation results：

1) The BER performance curves with 12 iterations and 20 iterations are almost overlapped, thus, an iteration threshold value that is present on the system performance improvement. Consequently, when the number of iterations exceeds this threshold value, the system BER performance will not be improved any more with iterations increasing.

2) When the SNR is less than 7dB, iterative decoding is almost no effect on the system performance. With a further increase of the SNR, the iterative decoding effect on the system increases gradually. When BER $=10^{-6}$, the system performance with 12 iterations only about 0.3dB gains, this may be due to the presence of the conversion between symbol and bit likelihoods. Therefore, there are tradeoffs between system gains and system complexity increases by iterative decoding. In the next simulation, we only consider the case of no iterations with specific projects.

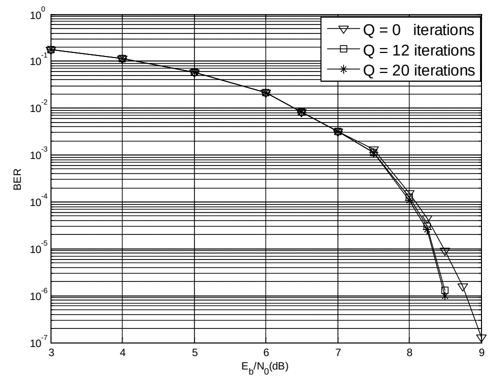

Figure 4: Serial concatenated coded M-ary modulation system BER performance with iteration schemes in AWGN channel, and the spectral efficiency is 1.5b/s/Hz. (Parameters: information frame length: 1536; convolution code generator polynomial is $(5, 7)_8$; 8-CPM (h=1/2))

3.2 Modulation Scheme Influence On System Performance

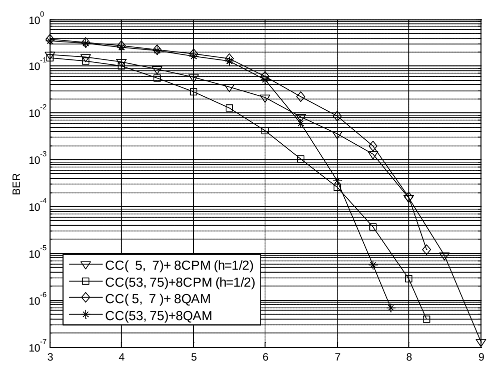

Figure5: Serial concatenated coded M-ary modulation system BER performance with different modulation schemes in AWGN channel, and the spectral efficiency is 1.5b/s/Hz. (Parameters: information frame length: 1536; convolutional code generator polynomial are $(5, 7)_8$ and $(53, 75)_8$; 8-ary CPM (h=1/2)).

Figure 5 shows convolutional coded 8-ary CPM modulation systems BER performance simulation

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results in AWGN channel. For comparison purposes, the two coded 8-ary QAM modulation system performance curves are also given in the figure. Can be seen from Figure 5 simulation results:

1) When the modulation methods are 8-ary CPM and 8-ary QAM, $(53, 75)_8$ convolutional coded modulation systems performance outperform that with $(5, 7)_8$ convolutional code. And this superiority also gradually increases with the increase in SNR.

2) When the outer code is $(5, 7)_8$ convolutional code, in low signal-to-noise ratio region, the coded modulation system based *M*-ary CPM can achieve better performance than coded *M*-ary QAM systems with the same spectral efficiency. When signal-to-noise ratio is greater than 8dB, which is in the opposite situation.

3) When the outer code is $(53, 75)_8$ convolutional code, the coded 8-ary CPM modulation system performance is better than that with 8-ary QAM modulation.

Therefore, the following conclusions can be drawn: In the case of the short information frame and in low signal-to-noise ratio region, the coded modulation system based *M*-ary CPM can achieve better performance than coded *M*-ary QAM systems with the same spectral efficiency.

4. CONCLUSION

Serial concatenated coded *M*-ary modulation system can convert burst bit errors into fewer *M*-ary symbol errors, which is very suitable for communication system with poor channel such as satellite communication, deep space communication et al.

The contributions of this paper can be summarized as follows: due to the presence of the conversion between symbol and bit likelihoods, so to improve the BER performance by the iterative scheme is no longer the best choice. In the case of the short information frame and low signal-to-noise ratio region, the coded modulation system based *M*-ary CPM can achieve better performance than coded *M*-ary QAM systems with the same spectral efficiency.

5. ACKNOWLEDGEMENT

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