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CODING FOR LIMITER-DISCRIMINATOR BASED CPM TRANSCEIVERS IN A RAYLEIGH, FAST FADING CHANNEL

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Abstract – A coding technique for limiter-discriminator based CPM transceivers is proposed for use in Rayleigh, fast fading environments. The proposed technique maintains the same bandwidth to information rate ratio as the uncoded system and therefore does not cause bandwidth expansion. The performance of the proposed coding scheme is compared to trellis coded modulation (TCM) and found to be better. It is also found that the increase in performance as the code complexity is increased is larger for the proposed scheme than for TCM.

I. Introduction

Limiter-Discriminator (L-D) detection is a simple, robust demodulation technique that has received much interest, e.g., [1]–[8]. This technique has the advantage of being very robust, which is necessary in fading environments, and very simple, which makes it attractive for portable and hand-held devices.

Portable communication systems all suffer from the effects of fading. In order to improve the performance of communication systems, channel coding techniques are a necessity. In previous work on L-D detection, the coding aspect has not been examined so it is not clear what coding techniques are appropriate for L-D based systems.

Another problem that portable communication systems face is the limited frequency spectrum. Conventional coding techniques involve a decrease in the information rate or equivalently an increase in the bandwidth required to transmit the signal. Thus, it is desirable to use a coding technique that does not require an increase in the required bandwidth.

In this paper, we propose a coding technique for Continuous Phase Modulation (CPM) transceivers that use a L-D detector in fast, Rayleigh fading environments. The proposed technique has the same bandwidth to information rate ratio as the uncoded system, so an increase in the required transmission bandwidth is not necessary. We restrict our attention to CPM schemes because of the properties of CPM which make it a good choice for communication over fading channels: bandwidth efficiency and constant envelope.

The performance of the communication systems examined in this paper was found by using computer simulations. Each system was implemented digitally using the Signal Processing Worksystem (SPW) [1] from Comdisco Systems. The error probabilities were then found using Monte Carlo simulations. The reason for using simulations is that analytical techniques are difficult to apply and subject to simplifying assumptions. For fast fading environments, the complexity is increased further. Also, if some simplifying assumptions are used, important effects may be lost.

II. Transceiver Structure

The communications system that is used in this paper is shown in Fig. 1. A data source produces equiprobable symbols, $a_k \in \{-1, 1\}$, every T_0 seconds. These symbols are fed into a rate r convolutional encoder, which produces encoded symbols, b_k, every T seconds. In the actual implementation, the b_k are binary, but when a multilevel modulation scheme is used, the bits are grouped to form multilevel symbols, e.g., when 4-level FSK is used, the bits are taken two at a time to form quaternary symbols.

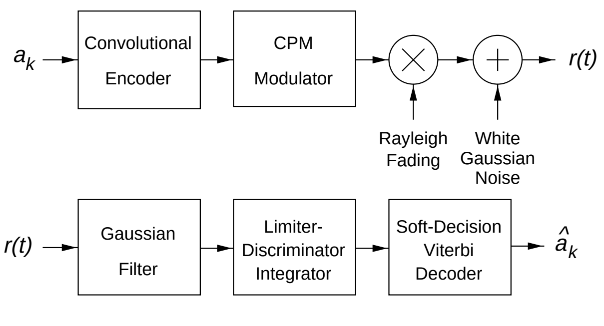

Fig. 1. Communication System Model

[1]Signal Processing Worksystem is a registered trademark and SPW is a trademark of Comdisco Systems, a business unit of Cadence Design Systems, Inc.

TABLE I

CPM Modulation Schemes

Modulation	h	L	b_k	$g(t)$
Binary FSK	1	1	$\{-1,1\}$	$1/(2T)$
4-level FSK	1/3	1	$\{-3,-1,1,3\}$	$1/(2T)$
MSK	0.5	1	$\{-1,1\}$	$1/(2T)$
GMSK	0.5	3	$\{-1,1\}$	$K\{\mathrm{erf}[cB_b(t+\frac{T}{2})]$
$(B_bT = 0.5)$				$-\mathrm{erf}[cB_b(t-\frac{T}{2})]\}$, $c=\pi\sqrt{2\ln 2}$

The encoded symbols are then sent to a CPM modulator. The output of the modulator is given by

$$s(t) = A\cos\left(2\pi f_c t + 2\pi h \sum_k b_k \int_{kT}^{t} g(\tau - kT)d\tau\right), \quad (1)$$

where h is the modulation index and $g(t)$ is the frequency pulse, which is zero outside the interval $[0, LT]$ and is normalized so that its area is equal to $1/2$. The parameter L is the memory length of the modulation. CPM terminology and notation in this paper follow [9].

In this paper, we consider four types of CPM: GMSK, MSK, FSK and 4-level FSK. CPM schemes can be completely defined by h, L and $g(t)$. In Table I, we list these parameters for the modulation schemes used in this paper. Note that quaternary symbols are required for 4-level FSK.

A rough comparison of the bandwidth efficiency of the FSK and MSK modulation schemes can be done by comparing the modulation index. Since the frequency pulse is the same for binary FSK, 4-level FSK and MSK, the modulation index multiplied by the largest value of b_k is the largest frequency deviation of the modulation scheme. This gives a rough bandwidth measure. From Table I, we can see that using this bandwidth measure, the binary FSK and 4-level FSK scheme have the same bandwidth. Compared to these two schemes, MSK has half the bandwidth. As for GMSK, the 99.9% power bandwidth, i.e., the bandwidth in which 99.9% of the signal power is contained, is roughly half that of MSK [10].

A more complete comparison of the bandwidth properties of the modulation schemes would include some discussion of the co-channel interference effects. However, since there are many ways to measure bandwidth and since such a discussion would detract from the main point of the paper, we limit our treatment of the transmitted spectral properties to that given above.

The channel model used in this paper is the standard flat, Rayleigh fading model with additive white Gaussian noise (AWGN) [11]. The spectrum of the fading signal is given by

$$S(f) = \begin{cases} \frac{H_0}{\sqrt{1-\left(\frac{f}{B_f}\right)^2}} & |f| < B_f \\ 0 & otherwise \end{cases} \quad (2)$$

where H_0 is a constant and B_f is the fading bandwidth. The AWGN has a white power spectral density equal to N_0.

Since the amplitude of the received signal varies due to the fading, the signal-to-noise ratio is given by [12] $\overline{SNR} = \langle |fading|^2 \rangle E_b/N_0$, where $\langle |fading|^2 \rangle$ is the average value of the squared magnitude of the fading signal and E_b is the energy required to transmit each bit.

The receiver begins by removing out-of-band interference with a pre-detection filter. In this paper, we use a Gaussian filter with a $3dB$ bandwidth denoted by B. This type of filter was also used in our previous work on limiter-discriminator detection [13]. Next, a L-D detector converts the modulated signal to baseband. The limiter part of the detector removes any envelope variations in the signal so that the discriminator output is only a function of the signal phase. The discriminator part of the detector ideally outputs the derivative of the the signal phase, i.e., the instantaneous frequency. Therefore, the response to $\rho(t)\cos(2\pi f_c t + \theta(t))$ is $d\theta(t)/dt$, where $\rho(t)$ is the time varying envelope and $\theta(t)$ is the signal phase.

An integrator integrates the baseband signal for T seconds, samples the result and then resets the integrator. We assume that the receiver is perfectly synchronized so that the sample times are on the symbol boundaries. Finally, the samples are passed to a soft-decision Viterbi decoder, which produces estimates, $\hat{a}_k$, of the input symbols, a_k.

III. The Proposed Coding Method

In conventional coding methods, a decrease in the information rate, or equivalently an increase in the required transmission bandwidth, is necessary. One way to avoid this problem is to use Trellis Coded Modulation (TCM) [14].

To implement TCM in an non-coherent system such as is considered in this paper requires the use of multi-level signalling, e.g., 4-level FSK. Unfortunately, the signal distortion due to fading tends to make multi-level decisions less reliable than binary decisions. In addition, the modulation index must be reduced so that the required bandwidth is the same as the uncoded system, i.e., the transmitted frequencies must be made closer together than for the uncoded binary system.

As an alternative to TCM, we propose the following method. Compared to a benchmark, the proposed method uses a more bandwidth efficient mod-

TABLE II

CONVOLUTIONAL CODE PARAMETERS

Code Rate	d_{free}	States	Generator Sequences*
2/3	3	4	$\begin{bmatrix} 6 & 2 & 6 \\ 2 & 4 & 4 \end{bmatrix}$
2/3	5	16	$\begin{bmatrix} 7 & 1 & 4 \\ 2 & 5 & 7 \end{bmatrix}$
1/2	5	4	$\begin{bmatrix} 5 & 7 \end{bmatrix}$
1/3	8	4	$\begin{bmatrix} 5 & 7 & 7 \end{bmatrix}$
1/4	10	4	$\begin{bmatrix} 5 & 7 & 7 & 7 \end{bmatrix}$

* The ijth element is $g_i^{(j)}$ as defined in [15].

TABLE III

PROPOSED CODING METHOD PARAMETERS

Modulation Format	Code Rate	Filter BW (BT)
FSK (Benchmark)	1	1
MSK, GMSK	2/3	2/3
MSK, GMSK	1/2	1/2
MSK, GMSK	1/3	1/3
MSK, GMSK	1/4	1/4

ulation scheme in conjunction with a rate r convolutional code and an pre-detection filter bandwidth of $B \cdot r$. Since the information rate is decreased by using a convolutional code, the ratio of the bandwidth to the information rate is the same as the benchmark scheme.

In the proposed scheme, the required bandwidth is roughly adjusted by changing the modulation scheme and more finely controlled by the pre-detection filter. Since the bandwidth of the modulation scheme cannot be changed, the pre-detection filter bandwidth, B, is used as the required bandwidth.

In this paper, we consider as a benchmark, binary FSK ($h = 1.0$) with a pre-detection filter bandwidth given by $BT = 1$. For the bandwidth efficient modulation schemes, MSK and GMSK are used. The convolutional codes that we use are taken from pages 330-331 of Lin & Costello [15]. These codes, whose parameters are listed in Table II, have the maximum d_{free} for a given rate and number of encoder states. There are several combinations of code rates and pre-detection filter bandwidths that are possible. In Table III, we list the combinations that are considered in this paper.

We will also compare the performance of the proposed code with that of TCM. The TCM codes that are considered are taken from [14]. These codes are combined with 4-level continuous phase FSK modulation with a modulation index $h = 1/3$. It should be noted here that these TCM codes were designed for the AWGN channel. Although there are TCM codes designed specifically for fading channels, they use PSK signal constellations. In this paper, we are interested in CPM schemes. Also, since we are using L-D detection, PSK signals are not appropriate. Therefore, we use the above TCM codes.

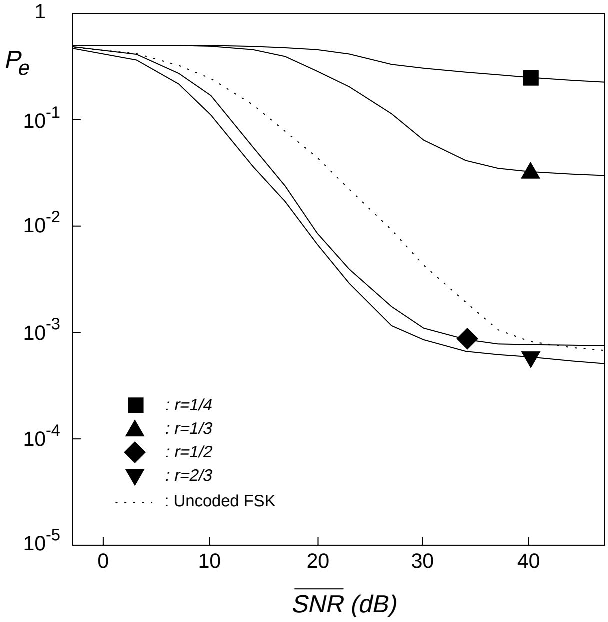

Fig. 2. Performance of MSK schemes for $B_fT = 0.05$ using 4-state codes.

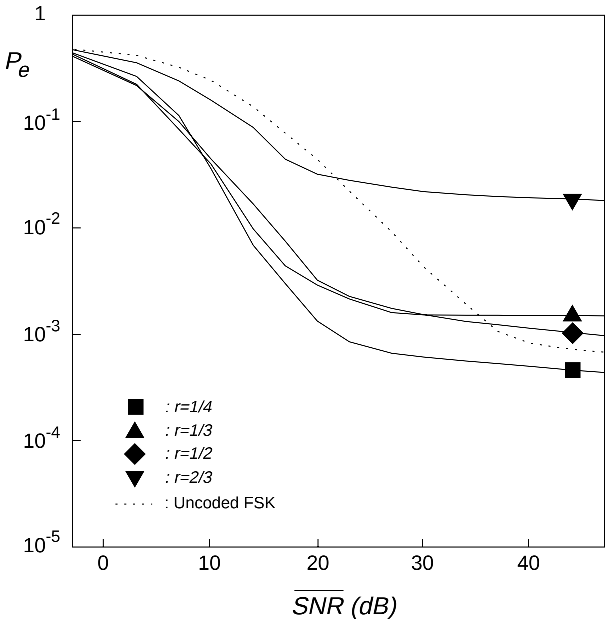

Fig. 3. Performance of GMSK schemes for $B_fT = 0.05$ using 4-state codes.

IV. PERFORMANCE

We simulated the performance of the proposed coding schemes for two fading rates given by $B_fT = 0.05$ and $B_fT = 0.01$. The results for $B_fT = 0.05$ are

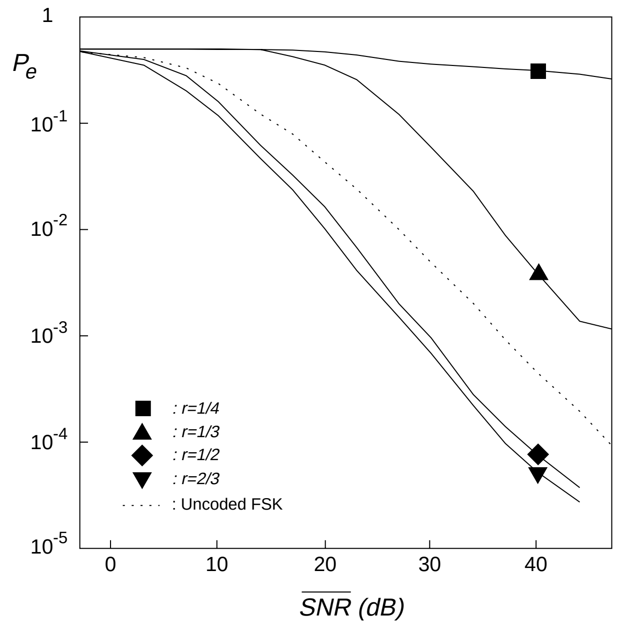

Fig. 4. Performance of MSK schemes for $B_fT = 0.01$ using 4-state codes.

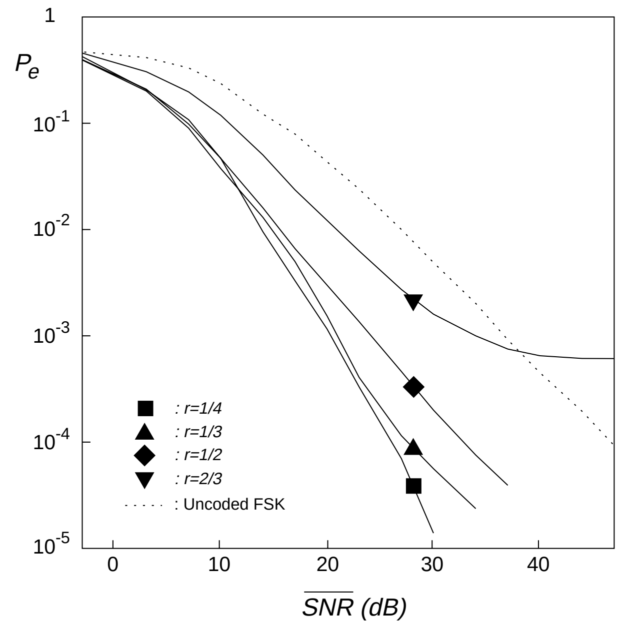

Fig. 5. Performance of GMSK schemes for $B_fT = 0.01$ using 4-state codes.

shown in Figs. 2 and 3 for MSK and GMSK respectively, while the results for $B_fT = 0.01$ are shown in Figs. 4 and 5 respectively. In all cases, the convolutional codes that are used are the 4-state codes listed in Table II.

The results for MSK show that a rate of 2/3 gives the best performance. The error floor is better than that of uncoded FSK and the performance of the proposed scheme at $P_e = 10^{-3}$ is approximately $10dB$ better for $B_fT = 0.05$ and $8dB$ better for $B_fT = 0.01$. As the rate and filter bandwidth decrease, the performance of the proposed coding scheme becomes worse. This is due to the fact that the performance of the system without coding becomes worse as the bandwidth is decreased. On the other hand, if the bandwidth of the system is increased the performance of the proposed system will become worse, since the uncoded error rate of MSK is higher than the that of FSK.

For GMSK, however, a rate of 1/4 gives the best performance. At $P_e = 10^{-3}$, the improvement over uncoded FSK is approximately $15dB$ for $B_fT = 0.05$ and $16dB$ for $B_fT = 0.01$. For GMSK, the performance as the rate and bandwidth decrease gets better because the performance of the system without coding is not affected as much by a decrease in filter bandwidth. This is due to the bandwidth efficiency of GMSK. However, if the bandwidth is decreased too much, the performance of the proposed system will become worse.

In both cases, we can see that the best code rate is roughly equal to the bandwidth efficiency of the modulation scheme relative to FSK. This can be explained as follows. The performance of the system without coding is not affected by a decrease in the pre-detection filter bandwidth up to a certain point, which depends on the bandwidth efficiency of the modulation scheme. However, the performance of the code improves as the rate is lowered. Therefore, the net result is an improvement in performance relative to the uncoded system. After a certain point, the performance of the system without coding decreases faster than the code performance improves, resulting in a net decrease in performance. Since GMSK is more bandwidth efficient than MSK, a lower rate and filter bandwidth can be used.

In Figs. 6 and 7, the performance of the proposed coding scheme is compared to TCM for $B_fT = 0.05$ and $B_fT = 0.01$ respectively. From the figures, we can see that the proposed coding scheme results in better performance than TCM. At an error rate of 10^{-3}, the proposed scheme is approximately $10dB$ better than TCM for $B_fT = 0.05$ and $6dB$ better for $B_fT = 0.01$. We can also see that the performance of the proposed coding scheme improves much more than TCM when the code complexity is increased. The difference in performance can be attributed to the fact that multi-level decisions, such as those necessary in TCM, are less reliable for the L-D system examined in this paper.

V. Conclusions

In this paper, we have proposed a coding technique for use with a limiter-discriminator based CPM transceiver in Rayleigh, fast fading environments. The proposed technique has the same bandwidth to information rate ratio as the uncoded system. The

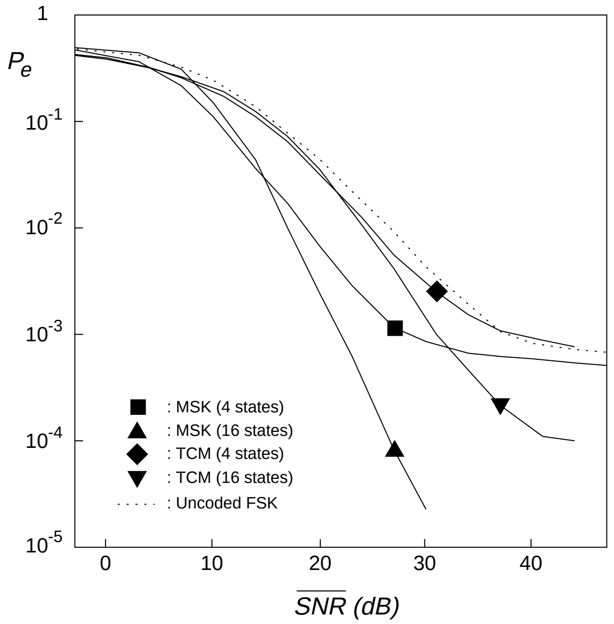

Fig. 6. Performance comparison of MSK ($r = 2/3$) and TCM using 4 and 16 state encoders for $B_f T = 0.05$.

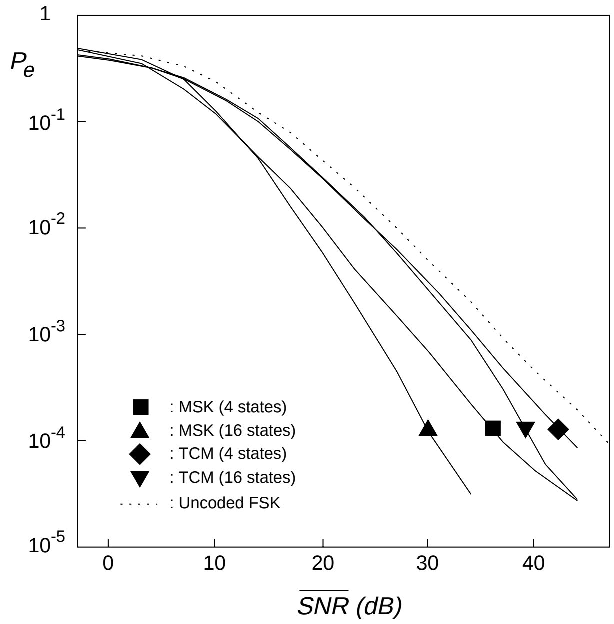

Fig. 7. Performance comparison of MSK ($r = 2/3$) and TCM using 4 and 16 state encoders for $B_f T = 0.01$.

performance of the proposed system was evaluated by computer simulations and found to give an improvement of $10dB$ to $15dB$ over the uncoded system at an error rate of 10^{-3}.

The proposed coding scheme was also compared to TCM. The performance of the proposed scheme was found to be approximately $6dB$ to $10dB$ better than that of TCM at an error rate of 10^{-3}. It was also found that the performance improvement obtained by increasing the code complexity is larger for the proposed scheme than for TCM.

The results in this paper were obtained for practical code rates and modulation schemes, so the bandwidth was measured by the bandwidth of the predetection filter. Of course, the results may vary if different bandwidth measures and modulation formats are used, but the main idea of combining bandwidth efficient modulation schemes with coding to improve performance is still valid.

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