Turbo Decoding for Precoded Systems over Multipath Fading Channels

Qing Zhang and Tho Le-Ngoc

Abstract: **A combined precoding and turbo decoding strategy for multi-path frequency-selective fading channels is presented. The precoder and multi-path fading channel are jointly modeled as a finite-state probabilistic channel to provide the multi-stage turbo decoder with its statistics information. Both *a priori* and *a posteriori* probabilities are used in the metric computation to improve the system performance. Structures of the combined turbo-encoder, interleaver, and precoder in the transmitter and two-stage turbo decoder in the receiver are described. Performance of the proposed scheme in fixed, Rician and Rayleigh multi-path fading channels are evaluated by simulation. The results indicate that the combined precoding and two-stage turbo decoding strategy provides a considerable performance improvement while maintaining the same inner structure of a conventional turbo decoder.**

Index Terms: **Fading channels, precoding, turbo codes.**

I. INTRODUCTION

Equalizer is an essential component in broadband communication systems over multi-path fading channels. For applications in which knowledge of the channel can be known by the transmitter, Tomlinson-Harashima (T-H) precoders [1]–[4] have been often used instead of decision-feedback equalizers (DFE) in the receiver in order to avoid performance degradation due to the well-known error propagation effects of the DFE. Turbo codes [5] can approach the Shannon's limit. Turbo decoding concept has been applied to design turbo-equalization techniques for communications systems over inter-symbol interference (ISI) channels [6], [7] and multi-path fading channels [8]. Since the precoder substitutes the DFE, this turbo-equalization approach is not applicable to communications systems using precoders. In [9]–[11], the iterative decoding algorithms have been investigated for the binary precoding systems over partial response magnetic channel. But these iterative algorithms are not suitable for the coded systems using T-H precoding and modulo operator over severe ISI channels. The modulo operator is required to constrain the transmitted power; however, it highly complicates the encoding and decoding processes [5].

This paper considers a turbo decoding algorithm for T-H precoding systems using modulo operator over multi-path fading channel. The modulo operation is used to find and subtract a unique best sequence so that the transmitted signal always falls in a limited amplitude range. At the receiver, the transmitted symbols are recovered by another modulo operator. Applications of turbo codes to systems using precoders need a better combination of the turbo encoder-decoder (codec) and precoder in order to improve the system performance. An optimal receiver should take into account all the states of the turbo encoder, precoder and multi-path channel, which is practically prohibited due to the high complexity. In this paper, a channel state associated with the modulo operation is introduced for the precoding so that the precoder and channel can be jointly modeled as a finite-state probabilistic channel. Turbo decoding techniques for the finite-state channels have been proposed in [12] and [13]. However, it will be shown that these techniques are not suitable to the precoding systems. Alternatively, a two-stage turbo decoder using both *a priori* and *a posteriori* probabilities is presented for turbo codes in precoding systems over multi-path channels.

The rest of the paper is organized as follows. In Section II, the system model is discussed. A finite-state probabilistic channel is presented for the precoding system in Section III. The proposed multi-stage turbo decoding scheme is described in Section IV. Section V discusses the simulation results on performance evaluation. The conclusion is given in Section VI.

II. SYSTEM MODEL

The block diagram of the proposed scheme combining two-stage turbo decoding and equalization using precoding is sketched in Fig. 1. The proposed scheme uses the quadrature amplitude modulation (QAM) for bandwidth-efficient transmission. For simplicity of explanation, we take a quatenary phase-shift keying (QPSK) system as an example in the following discussions.

The information bits are first encoded by two parallel concatenated convolutional codes with interleaver I. The overall code rate of the turbo code is $1/2$. Another interleaver 'τ' is used to break up the encoding memory before QPSK modulation. The transmitter is assumed to have perfect knowledge of the multi-path fading channel impulse response,

$$h^c(t) = \sum_{i=-N_f}^{N_b} h_i^c \delta(t - iT),$$

where T is the symbol duration, and N_b and N_f are the number of taps in pre-cursor and post-cursor, respectively.

We consider both fixed and random h_i^c's. For this, the channel coefficients h_i^c's are assumed to be random variables with Rician distribution,

$$f(x) = \frac{x}{\sigma_x^2} \exp\left[\frac{x^2 + A^2}{2\sigma_x^2}\right] I_0\left(\frac{xA}{\sigma_x^2}\right),$$

where $I_0(\cdot)$ is the zero-order Bessel function of the first kind, and $A^2/2$ and σ_x^2 are the powers of the direct-path and scattered-

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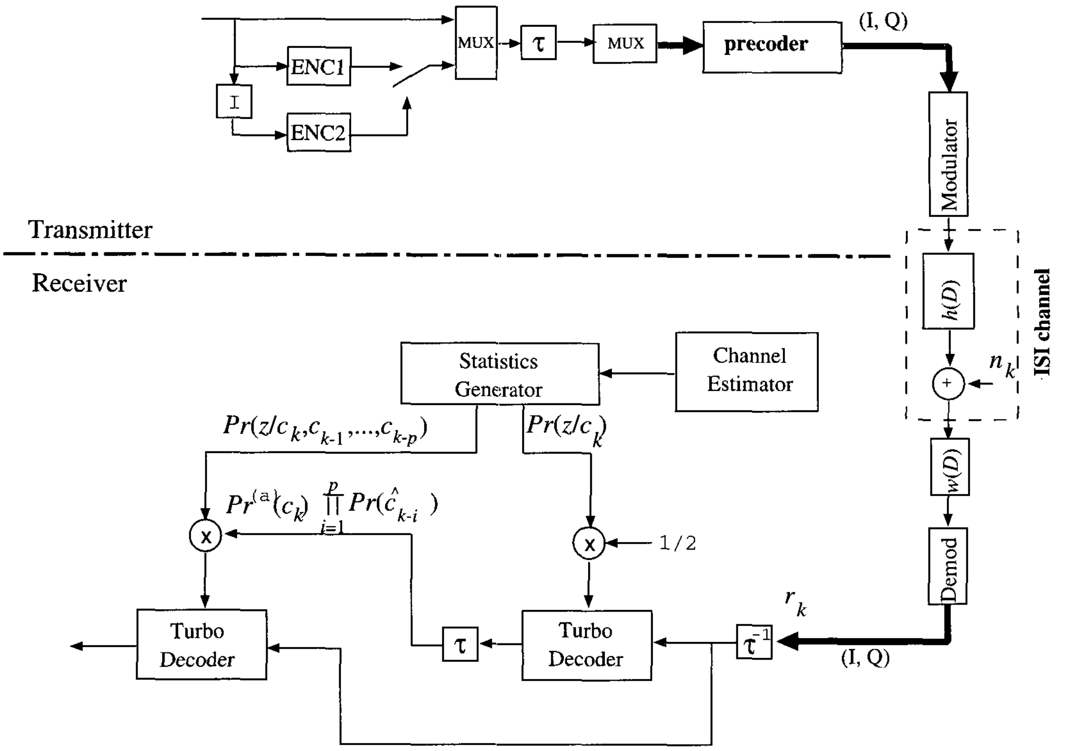

Fig. 1. Block diagram of combined turbo decoding and equalization using precoding.

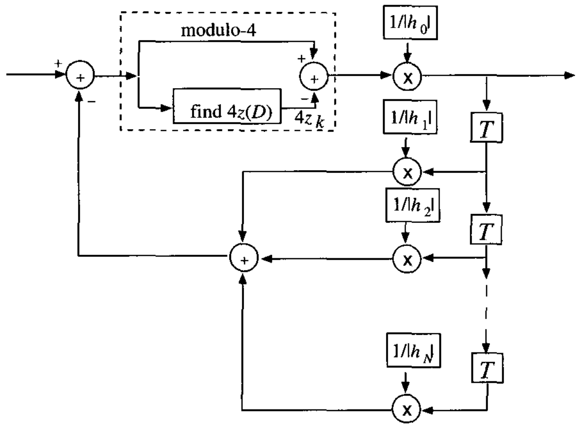

Fig. 2. Block diagram of the precoder.

path components, respectively. The Rician fading channel is characterized by the Rician factor, defined as

$$K = \frac{A^2}{2\sigma_x^2}.$$

The particular cases with $K = \infty$ and 0 correspond to the fixed and Rayleigh fading channels, respectively.

At receiver, the whitening matched filter (WMF), implemented by a feed-forward equalizer (FFE), is used to eliminate pre-cursor coefficients of $h^c(t)$ [3]. The overall impulse response of the multi-path channel and WMF can be represented as an equivalent discrete-time channel model, $h(D) = h_0 + h_1D^{-1} + h_2D^{-2} + \cdots$. In practice, the coefficients of this equivalent channel can be measured at the receiver by sending a short training sequence before each data block. These coefficients are then relayed back to the transmitter for precoding. As in [8], we consider the special case of a channel with coefficients of equal phase, i.e., $h_i = |h_i|\, e^{j\Phi}$. For coherent reception, the phase can be omitted in discussion.

As shown in Fig. 2, the precoder is composed of a feedback filter with impulse response $\Sigma_{i=1} |h_i|\, D^{-i}$ and a modulo-4 operator to restrain the peak value of the transmitted signal. Equivalently, the modulo-4 operation is to find an unique best sequence of $z(D) = z_0 + z_1D^{-1} + z_2D^{-2} + \cdots$ and subtract $4z(D)$ from the output of the feedback filter such that the transmitted signal is confined in the square $[-2, 2) \times [-2, 2)$. The values of z_k are complex with integer real and integer imaginary parts.

III. TURBO DECODING

The outputs of the WMF comprise the real and imaginary parts, indicated by I and Q in Fig. 1. For square M-ary QAM signaling, these two components are statistically independent and identically distributed (i.i.d). Therefore, we can consider one of the components for the sake of simplicity in explanation. Denote the coded sequence by $c(D) = c_0 + c_1D^{-1} + \cdots + c_kD^{-k} + \cdots$ with $c_k \in \{-1, +1\}$, the real signal of the outputs of the WMF, at time k, is expressed by [4]

$$r_k = c_k - 4z_k + n_k,$$

where n_k is the sample of additive white Gaussian noise with variance σ^2. After de-interleaving, the sequence of $(c_k - 4z_k)$ mod 4 is still in the space of the turbo code. Nevertheless, because of the modulo operation, each transition branch in the trellis of the encoder is replaced by a number of parallel branches corresponding to the different integer values of z. The modulo-type decoder searches for the most likely branch among those parallel branches, using the branch metric function given by

$$m(c_k) = \max_z \left\{ -|r_k - (c_k - 4z)|^2 \right\}; z \in \{0, \pm 1, \pm 2, \cdots\}. \tag{1}$$

The exact number of values taken by z depends on the specific multi-path channel. Our statistical evaluation by simulation indicates that the value of z is rarely beyond $\{-1,\ 0,\ +1\}$. Regarding z as a channel state, the combination of precoder and channel can be modeled as a finite-state probabilistic channel. This kind of channel is characterized by the probability distribution of the channel state and the transition probability between the successive states. These probabilistic parameters of the channel state z can be utilized by the maximum *a posteriori* (MAP) algorithm in turbo decoding to improve the performance of precoding systems.

Let s' and s denote the previous and present states in the trellis, respectively. Given a received sequence $\overline{r}$, the soft-output of the MAP decoder, at time k, is defined by [5]

$$Pr(c_k/\overline{r}) = \sum_{s'} \sum_{s} \alpha_{k-1}(s') \gamma(r_k, s', s) \beta_k(s), \tag{2}$$

where $\alpha(\cdot)$ and $\beta(\cdot)$ are the forward and backward probability functions, $\gamma(r_k, s', s)$ represents the transition probability from s' to s, expressed by

$$\gamma(r_k, s', s) = \max_z \left\{ \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{|r_k - (c_k - 4z)|^2}{2\sigma^2} \right] Pr(z) \right\}, \tag{3}$$

where the probability $Pr(z)$ represents the probability distribution of channel state z, reflecting the probabilities of parallel transitions between s' and s. For log-MAP algorithm, the branch metric function becomes

$$m(c_k) = \max_z \left\{ -\frac{|r_k - (c_k - 4z)|^2}{2\sigma^2} + \ln\left(Pr(z)\right) \right\}. \tag{4}$$

Given this metric function, the turbo decoder can work properly.

Also, for the coded systems over the finite-state channels, the decoder can employ a 'superstate' structure combining the encoder and channel states to achieve optimal decoding [12]. However, the 'superstate' structure exponentially increases the decoding complexity. For turbo codes, the coded bits have to be transmitted in a proper order to facilitate the construction of the 'superstate'. Furthermore, it is not applicable to the punctured turbo codes. In [13], the approach to decoding over finite-state Markov channels is using the recursive estimation of the channel state. Nevertheless, the recursion is vulnerable to error propagation and the decoding performance seriously suffers from unreliable estimation. Our simulation results show that the recursive estimation performs even worse in precoding systems. For example, to achieve a BER of 10^{-3}, the error probability of the channel state estimation must be 10^{-5} or better.

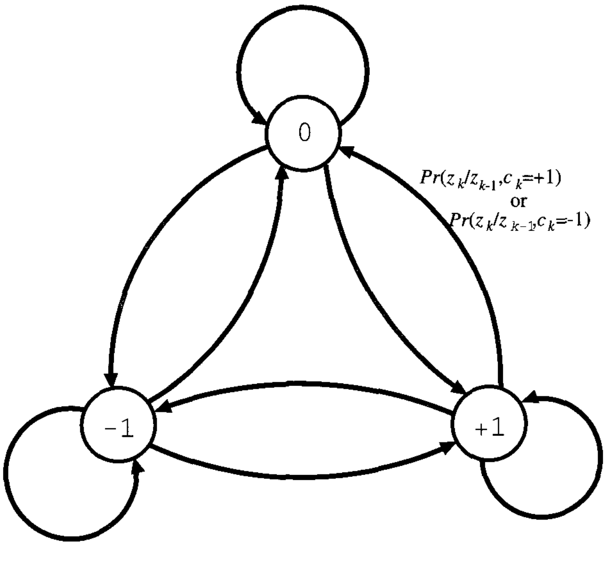

Fig. 3. Channel-state transition diagram.

IV. TWO-STAGE TURBO DECODING

Obviously, the characteristics of the finite-state channel model for precoding systems depend on the channel inputs. The probability of transition to the current channel state is determined by the starting state of the precoder and the previous channel inputs. Given the previous inputs $(c_{k-p}, \cdots, c_{k-2}, c_{k-1})$ and the current input c_k, the conditional probability of transition from the state z_{k-p} at time $(k-p)$ to the current state z_k is denoted by $Pr(z_k/z_{k-p}, c_k, c_{k-1}, \cdots, c_{k-p})$, where p is the number of observation symbols. At the receiver, the channel states can be recursively estimated by using the knowledge of the starting state z_{k-p} and channel input estimates $(\widehat{c}_{k-p}, \cdots, \widehat{c}_{k-2}, \widehat{c}_{k-1}, \widehat{c}_k)$.

The state transition diagram for the introduced Markov channel is shown in Fig. 3 with the assumption of $z \in \{-1, 0, 1\}$. The arrow lines in this diagram represent the transition from the state z_{k-1} to the state z_k and each line comprises two transition branches denoted by the transition probabilities $Pr(z_k/z_{k-1}, c_k = +1)$ and $Pr(z_k/z_{k-1}, c_k = -1)$ corresponding to the inputs of $c_k = +1$ and $c_k = -1$, respectively.

The transition probability distribution $Pr(z_k/z_{k-p}, c_k, c_{k-1}, \cdots, c_{k-p})$ is greatly affected by the channel impulse response $h(D)$ and can be statistically obtained at the precoder. These statistics can be utilized by the decoder as *a priori* information to improve the system performance. Since the error-propagation of the channel state seriously degrades the precoding system performance, it is necessary to dilute the destructive effect of unreliable estimation of z_{k-p}. For this reason, the probability $Pr(z_k/z_{k-p}, c_k, c_{k-1}, \cdots, c_{k-p})$ is averaged over the random variable z_{k-p}. Furthermore, the value of p should be large enough to weaken the dependence of z_k on z_{k-p}. In other words, the *a priori* statistic $Pr(z/c_k, c_{k-1}, \cdots, c_{k-p})$ is utilized in turbo decoder instead of $Pr(z_k/z_{k-p}, c_k, c_{k-1}, \cdots, c_{k-p})$.

As previously mentioned, the probability $Pr(z)$ reflects the probabilities of the parallel branches between two successive

Table 1. Statistic probabilities of $Pr(z/c_k, c_{k-1}, c_{k-2})$.

$c_k c_{k-1} c_{k-2}$	log-$Pr(z=-1/c_k, c_{k-1}, c_{k-2})$	log-$Pr(z=0/c_k, c_{k-1}, c_{k-2})$	log-$Pr(z=+1/c_k, c_{k-1}, c_{k-2})$
000	−3.536	−2.360	-*
010	−2.992	−2.581	-
001	−3.533	−2.346	-
011	−4.843	−2.138	-
100	-	−2.143	−4.906
110	-	−2.346	−3.505
101	-	−2.605	−2.935
111	-	−2.371	−3.530

*: '-' indicates the log-probability tends to negative infinity.

states. However, because the channel state z is related to the channel inputs, given the observation of the previous channel inputs, the joint probability $Pr(z, c_k, c_{k-1}, \cdots, c_{k-p})$ is a more appropriate measure for the branch transition probability. Therefore, in addition to $Pr(z/c_k, c_{k-1}, \cdots, c_{k-p})$, the estimate of $Pr(c_{k-p}, \cdots, c_{k-2}, c_{k-1}, c_k)$ is also needed to derive the joint probability $Pr(z, c_k, c_{k-1}, \cdots, c_{k-p})$. A much more reliable estimate can be provided by the decoder itself to enhance the system performance [7] using a two-stage scheme. As shown in Fig. 1, the first-stage decoder uses the statistic $Pr(z/c_k)$ as *a priori* information in metric calculation defined by

$$\begin{aligned} m(c_k) &= \max_z \left\{ \frac{-|r_k - (c_k - 4z)|^2}{2\sigma^2} + \ln(Pr(z, c_k)) \right\} \\ &= \max_z \left\{ \frac{-|r_k - (c_k - 4z)|^2}{2\sigma^2} + \ln(Pr\,(z/c_k) Pr(c_k)) \right\} \\ &\approx \max_z \left\{ \frac{-|r_k - (c_k - 4z)|^2}{(2\sigma^2)} + \ln\left(Pr\,(z/c_k) Pr^{(a)}(c_k)\right) \right\}, \end{aligned} \tag{5}$$

where $Pr^{(a)}(c_k)$ is the *a priori* probability of channel inputs and $Pr^{(a)}(c_k = +1) = Pr^{(a)}(c_k = -1) = 1/2$ for uniformly distributed binary source. The first-stage decoder provides the second-stage decoder with the reliable *a posteriori* probabilities of $Pr(\widehat{c}_k = +1)$ and $Pr(\widehat{c}_k = -1)$. As shown in Fig. 1, the second-stage decoder uses both *a priori* statistics and *a posteriori* information in the metric function given by

$$\begin{aligned} &m(c_k) \\ &= \max_z \left\{ \frac{-|r_k - (c_k - 4z)|^2}{2\sigma^2} + \ln(Pr(z, c_k, c_{k-1}, \cdots, c_{k-p})) \right\} \\ &= \max_z \left\{ \frac{-|r_k - (c_k - 4z)|^2}{2\sigma^2} \right. \\ &\qquad \left. + \ln(Pr(z/c_k, c_{k-1}, \cdots, c_{k-p})) \prod_{i=0}^{p} Pr(c_{k-i}) \right\} \\ &\approx \max_z \left\{ \frac{-|r_k - (c_k - 4z)|^2}{2\sigma^2} \right. \\ &\left. + \ln(Pr(z/c_k, c_{k-1}, \cdots, c_{k-p}))\, Pr^{(a)}(c_k) \prod_{i=0}^{p} Pr(c_{k-i}) \right\}. \end{aligned} \tag{6}$$

Note that the *a posteriori* probability $Pr(\widehat{c}_k)$ is not used in the metric function because $Pr(\widehat{c}_k)$ contains the soft-input information and the use of $Pr(\widehat{c}_k)$ leads to the repeated use of the soft-input information in decoder.

Since the error events in turbo codes are bursty, the soft-output of SISO decoder must be interleaved to spread the burst errors over the entire date frame prior to the state estimation. For this reason, an interleaver is employed between the turbo encoder and the precoder at the transmitter as shown in Fig. 1.

It can be seen that the proposed two-stage turbo decoding makes use of the existing turbo decoding algorithm. It uses both the *a priori* and *a posteriori* information in soft-input computation, which does not change the inner structure of turbo decoder. Furthermore, the proposed two-stage turbo decoding can be sequentially processed with only one single turbo decoder. In other words, in terms of hardware implementation, the complexity of the proposed two-stage turbo decoder is not much higher than that of the conventional decoder. The small additional hardware complexity is for the decoding control. Sequential processing of two-stage turbo decoding implies twice longer in decoding process.

V. SIMULATION RESULTS

The performance of the combined turbo decoding and equalization using precoding is evaluated by simulation for multi-path fading channels.

The punctured turbo code has the component 4-state convolutional code with generator matrix $[1, \frac{1+D^2}{1+D+D^2}]$. The length of the information data frame is 1024 bits. The turbo decoder consists of two SISO decoders using max-log-MAP algorithm. The number of iterations of turbo decoding is fixed at 5 since further iteration results in negligible performance improvement [5]. The interleaver 'τ' is a random interleaver.

Before sending each data block, the impulse response $h(D)$ of the equivalent discrete-time channel model is produced by the channel estimator using minimum mean-square-error (MMSE) DFE technique. Then, the precoder is built on the basis of $h(D)$. Meanwhile, a statistics generator in the receiver gathers and stores all the statistic information needed in the turbo decoding.

We consider a three-path fading channel with a T-spaced power profile of [0.407, 0.815, 0.407]. Fig. 4 shows the performance of a precoding system using different turbo decoding strategies over this fixed frequency-selective fading channel. The conventional turbo decoding using (1) has the worst performance (indicated by "conventional"). With the knowledge of the

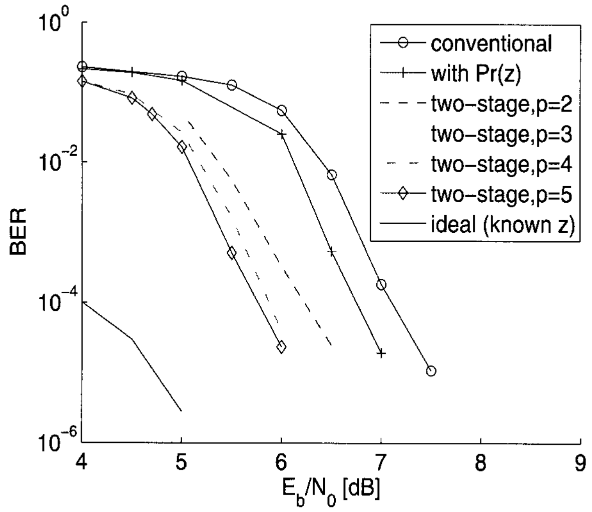

Fig. 4. Performance of precoded systems using different turbo decoding schemes in a three-path frequency-selective fading channel.

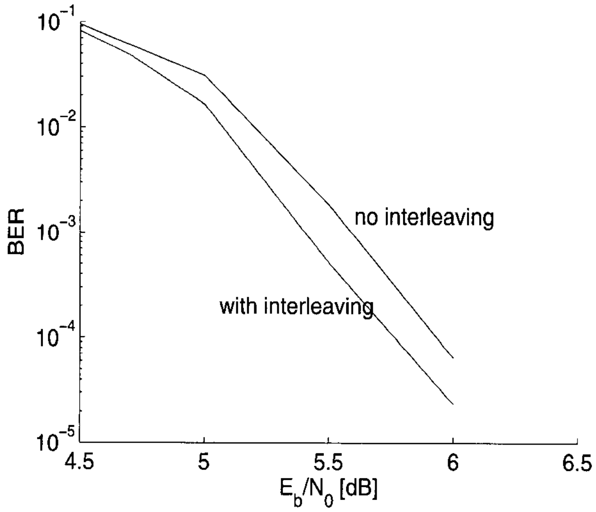

Fig. 5. Effects of interleaving on performance of the precoded system using 2-stage turbo decoding scheme with $p = 5$ in a three-path frequency-selective fading channel.

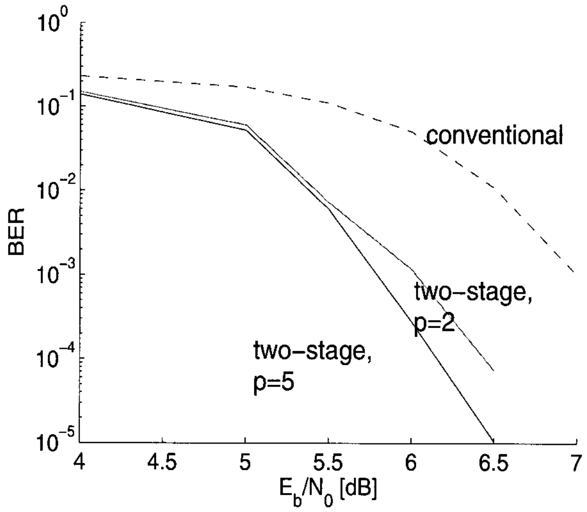

Fig. 6. Performance of precoded systems using different turbo decoding schemes over a three-path Rician fading channel ($K = 10$).

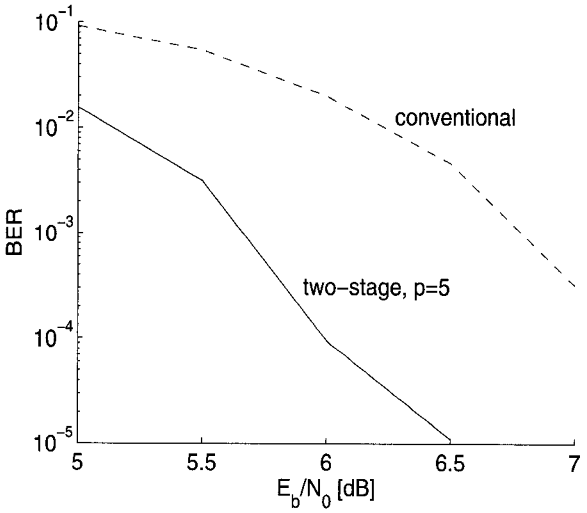

Fig. 7. Performance of precoded systems using different turbo decoding schemes over a three-path Rayleigh fading channel.

a priori probability $Pr(z)$ in (2), the performance of the turbo decoding can be improved, e.g., by 0.4dB at $\mathrm{BER} = 10^{-4}$. For illustration, Table 1 shows the characteristics of this channel in terms of the logarithm of the conditional probabilities $Pr(z/c_k, c_{k-1}, \cdots, c_{k-p})$. The proposed two-stage turbo decoding provides a performance improvement of 1dB to 1.5dB (at $\mathrm{BER} = 10^{-4}$) as the number of observation symbols increases from $p = 2$ to $p = 5$.

For reference, the performance of the *ideal* (but unrealistic) case, in which $z(D)$ is perfectly known by the turbo decoder, is also included in Fig. 4. It indicates a gap of 1.5dB between the ideal performance and that of the proposed two-stage turbo decoding scheme with $p = 5$.

The effectiveness of the interleaver τ between the turbo encoder and precoder is examined by simulation. Fig. 5 shows the performance of a precoded system using the proposed two-stage turbo decoding with $p = 5$ over the same three-path fading channel with and without the interleaver τ. The interleaver offers a performance improvement of about 0.2dB at $\mathrm{BER} = 10^{-4}$.

We also examine the effects of random fading channel on the system performance. The same three-path frequency-selective fading channel with random tap coefficients as previously discussed in Section II is considered. Fig. 6 indicates the performance of a precoding system using different turbo decoding strategies over a three-path Rician fading channel with $K = 10$ dB. The two solid curves show the performance of the proposed two-stage turbo decoder with $p = 2$ and $p = 5$ while the dashed curve represents that of the conventional one-stage turbo decoder using (1). The proposed two-stage turbo decoder with $p = 5$ provides a performance improvement of more than 1dB at $\mathrm{BER} = 10^{-4}$. Similar performance results are obtained in a three-path Rayleigh ($K = 0$) fading channel as shown in Fig. 7.

VI. CONCLUSIONS

We proposed a combined precoding and multi-stage turbo decoding scheme for precoding system over multi-path fading channel. The precoder and the multi-path fading channel are jointly modeled as a finite-state probabilistic channel to provide the *a priori* and *a posteriori* information used in the turbo decoding to improve the system performance. Simulation results show that the proposed turbo decoding can considerably improve the performance of the precoding system over multi-path fading channels while maintaining the inner structure of turbo decoder.

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