Integration of Code Diversity and Long-Range Channel Prediction in Wireless Communication

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***Abstract*—Code diversity integrates space-time coding with beamforming by using a small number of feedback bits to select from a family of space-time codes. Different codes lead to different induced channels at the receiver, where Channel State Information (CSI) is used to instruct the transmitter how to choose the code. Feedback can be combined with sub-optimal low complexity decoding of the component codes to match Maximum-Likelihood (ML) decoding performance of any individual code in the family. It can also be combined with ML decoding of the component codes to improve performance beyond ML decoding performance of any individual code. Prior analysis of code diversity did not take into account the effect of the mobile speed and the delay in the feedback channel. This paper demonstrates the practicality of code diversity in space-time coded systems by showing that predicted performance gains based on instantaneous feedback are largely preserved when the feedback is based on long-range prediction of rapidly time-varying correlated fading channels. Simulations are presented for two channel models; the first is the Jakes model where angles of arrival are uniformly distributed and the arrival rays have equal strengths, and the second is a model derived from a physical scattering environment where the parameters associated with the reflectors vary in time and the arrival rays have different strengths and non-symmetric arrival angles[1].**

I. Introduction

In multiple-input multiple-output (MIMO) wireless communication systems, coding techniques such as space-time coding were introduced to improve reliability while maintaining a high transmission rate in an open-loop framework.

Many close-loop techniques were introduced to further improve the system performance. Beamforming (see [1]) is a general technique intended to improve channel capacity by feeding back the index for the best precoding matrix without considering specific code structures. Viswanath *et al.* [2] proposed opportunistic beamforming to optimize the total throughput for multi-user systems, where the base station induces channel fluctuation deterministically and selects the user with the highest SNR. Assuming the statistics of CSI are known at the transmitter, precoding can be used to minimize the average pairwise error probability [3] for channels with cross correlations. However, none of these techniques takes advantages of specific coding structures and analysis of delayed feedback is lacking. Code diversity has been proposed and intensively studied recently [4–6] in the framework of space-time codes which employ specific correlation structures. In the code diversity framework, a small number of feedback bits select the best code from a family of appropriately designed codes. This has been shown to greatly improve decoding performance even with sub-optimal low complexity decoders. This paper will first review the principle of code diversity, demonstrate its significance in terms of decoding performance / complexity and discuss systems implementation issues. Then, we integrate code diversity in wireless communication with long range channel prediction for mobile radio channels.

In previous work concerning code diversity, researchers assumed that channel has no time correlation and that the feedback link has no delay. In this paper, we consider rapidly time-varying correlated fading channels, which are typical of fielded mobile communication systems. We also suppose that there is a certain delay in the feedback link. In this setting, in order to accurately implement code diversity, we require long-range channel prediction [7, 8] to compensate for the feedback delay. For channel models, we consider the Jakes model and a more realistic model derived from a specific physical environment, both of which exhibit time correlation. We first review linear autoregressive channel prediction and methods to increase its accuracy, especially in the low SNR regime. Then, we explain how to combine code diversity with channel prediction and illustrate the design principles. Simulations and comparisons are provided to quantify the value of the combination.

The paper is organized as follows. Section II studies the receive structure of space-time codes and introduces the channel models. Code diversity is reviewed and discussed in Section III together with one application example. Section IV illustrates the methodology of realizing code diversity through long-range channel prediction and it also provides simulations associated with ideal Jakes model and a physical model. The conclusion is provided in Section V.

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II. System Model

In a space-time coded wireless communication system with N_t transmit antennas and N_r receive antennas, the received signal $\mathbf{Y} \in \mathcal{C}^{N_r \times T}$ is given by

$$\mathbf{Y} = \mathbf{H}X + \mathbf{N} \tag{1}$$

where $\mathbf{H} \in \mathcal{C}^{N_t \times N_r}$ is the channel matrix with the entry h_{ji} representing the complex channel gain between the i^{th} transmit antenna and the j^{th} receive antenna; X represents a $N_t \times T$ block codeword where T represents the number of time slots one codeword covers and $\mathbf{N}$ is the corresponding additive noise matrix. In this paper, we suppose the additive noise is symmetric complex gaussian with zero mean and variance $2\sigma_n^2$.

An important feature of many algebraic constructions of space-time codes is *exchangeability* of structure (correlation) at the transmitter and structure at the receiver. Exchangeability means that we can rewrite (1) as:

$$\mathbf{y} = \mathcal{H}\mathbf{x} + \mathbf{n} \tag{2}$$

where $\mathbf{y} \in \mathcal{C}^{N_r T \times 1}$; $\mathcal{H} \in \mathcal{C}^{N_r T \times L}$; L is the number of distinct symbols transmitted during one block of T symbol periods; $\mathbf{x} \in \mathbb{C}^{L \times 1}$ is the transmitted signal and $\mathbf{n} \in \mathcal{C}^{N_r T \times 1}$.

Equation (2) captures the perspective of the receiver, where the induced channel is assumed to be known, and the problem is to estimate the transmitted signals. Exchangeability of structure from transmitter to receiver is possible for linear dispersion codes [9] with real-valued dispersion matrices, the Golden code [10], the Silver code [11] and many others.

We consider the Jakes fading model [12, 13] to simulate the time-varying correlated Rayleigh fading waveforms. Note that the Jakes model is an ideal model where the arrival rays have equal strengths and uniformly distributed arrival angles. In Section IV, a model derived from a particular physical scattering environment is also employed [14]. Both of these models are intended to capture the characteristics of a realistic communication channel.

III. Code Diversity

Code diversity was introduced by Tan and Calderbank [6] and then extensively studied in [4, 5]. The code diversity scheme uses a small number of feedback bits to select the best code from a family of space-time codes. In this section, we will review the phase adaptation method of inducing code diversity which is described in greater detail in [4, 5].

With phase adaptation, feedback from the receiver modifies the phases of channel gains as follows

$$h_{ij} \rightarrow h_{ij} \times e^{i\frac{2\pi k_{ij}}{K}}$$

where $k_{ij} \in \{1, 2..., K\}$ is the feedback information and K determines the number of feedback bits. It is shown that the algorithm only needs to modify phases of a small subset of the channel gains [4, 5].

Let $\{h_{ij}\}$ denote the set where the phases of channel gains h_{ij} are modified and let $\{\hat{k}_{ij}\}$ denote the feedback selection information. Then the receiver selects $\{\hat{k}_{ij}\}$ which

- first maximizes the rank of $\mathcal{H}^\dagger\mathcal{H}$, *i.e.* $d = \mathcal{R}(\mathcal{H}^\dagger\mathcal{H})$ (Let $d_{\max} = \max \mathcal{R}(\mathcal{H}^\dagger\mathcal{H})$)
- and second maximizes $\left(\prod_{i=1}^{d_{\max}} \omega_i\right)$, where ω_i are the nonzero eigenvalues of $\mathcal{H}^\dagger\mathcal{H}$.

If $d_{\max} = L$, *i.e.* $\mathcal{H}^\dagger\mathcal{H}$ has full rank, then the receiver selects $\{\hat{k}_{ij}\}$ as

$$\{\hat{k}_{ij}\} = \underset{k_{ij} \in \{1,2...,K\}}{\operatorname{argmax}} \, det(\mathcal{H}^\dagger\mathcal{H})|_{\{h_{ij}\} \rightarrow \{h_{ij} \times e^{i\theta_{ij}}\}}. \tag{3}$$

It is shown in [5] that given a channel realization $\mathcal{H}$, the average error probability $P_{e|\mathcal{H}}$ satisfies

$$P_{e|\mathcal{H}} \propto \left(\prod_{i=1}^{d} \omega_i\right)^{-1} \tag{4}$$

and the channel capacity $C_{\mathcal{H}}$ satisfies

$$C_{\mathcal{H}} \propto \tfrac{1}{T}\rho^d \log\left(\prod_{i=1}^{d} \omega_i\right). \tag{5}$$

where ρ is the signal to noise ratio.

It is, by maximizing d and $\left(\prod_{i=1}^{d} \omega_i\right)$ that code diversity optimizes both the average error probability and the channel capacity. In the code diversity framework, the performance of low complexity decoders can be significantly improved to match that of the maximum-likelihood decoders.

The code diversity scheme can be applied to exchangeable space-time codes and we refer the reader to [5] for more examples.

IV. Realizing Code Diversity through Long-Range Channel Prediction

The code diversity scheme considered in [4–6] assumes that the feedback is *instantaneous*, *i.e.* there is no delay in the feedback link. In practice, feedback is always *delayed*. In the mobile radio transmission environment, the channel is typically rapidly time-varying, and the channel state information at the transmitter is outdated due to the feedback delay. To enable code diversity in mobile radio systems, we compensate for delay by predicting the channel.

A. Long-Range Channel Prediction

Long-range channel prediction was comprehensively studied in [7, 8]. The minimum mean square error (MMSE) prediction of the future channel coefficient h_{n+k} based on p previous samples $h_n, h_{n-1}, \cdots, h_{n-p+1}$ is given by

$$\hat{h}_{n+k} = \sum_{j=1}^{p} d_j h_{n+1-j} \tag{6}$$

where k is the prediction range, p is the predictor order, and the coefficients d_j are computed using the orthogonality principle [7]. In practice, adaptive tracking methods are employed to keep up with the variation of the channel statistics [8]. Given fixed filter size p, the predictor in equation (6) employs low sampling rate (5 to 10 times the maximum Doppler shift) and exploits large sidelobes of the fading channel autocorrelation function to predict reliably sufficiently far ahead to enable adaptive transmission [7].

Since the performance of the predictor in (6) is limited at medium and low SNR [15, 16], highly oversampled pilot symbols are employed to perform noise reduction prior to prediction in [15]. To improve the spectral efficiency and reduce the bandwidth occupied by pilots, data-aided noise reduction method was proposed for adaptive modulation systems in [16]. While we employ the high-rate pilot method in this paper, data-aided noise reduction can be extended to code diversity systems and is expected to provide similar prediction accuracy at much lower pilot rate. Moreover, while we predict antenna gains in (6) individually, joint prediction can reduce complexity and improve accuracy [8, 17]. In our simulation, the pilot symbols are transmitted at the rate of $100 f_{\text{dm}}$. The noise reduction is performed using four filters with smoothing lags $\{0, 2, 5, 10\}$ [16] and filter order 50. The outputs of these noise-reduction filters are down-sampled at the rate of $10 f_{\text{dm}}$ and then fed into the MMSE predictor, which has filter order of 20.

B. Predicted Code Diversity

In this subsection, we use Jafarkhani's QOSTBC [18] to illustrate the prediction of code diversity. In a 4×1 system, the induced channel matrix $\mathcal{H}$ in equation (2) for QOSTBC is

$$\mathcal{H} = \begin{pmatrix} h_1 & h_2 & h_3 & h_4 \\ -h_2^* & h_1^* & -h_4^* & h_3^* \\ -h_3^* & -h_4^* & h_1^* & h_2^* \\ h_4 & -h_3 & -h_2 & h_1 \end{pmatrix} \quad (7)$$

where the channel coefficients h_1, h_2, h_3 and h_4 are generated from the Jakes model [13].

Given phase adaptation on the phase of h_1, the code diversity algorithm is

$$\begin{aligned} k^* &= \underset{k \in \{1,2\ldots,K\}}{\operatorname{argmax}} \; det(\mathcal{H}^\dagger \mathcal{H})\big|_{h_1 \to h_1 e^{i\frac{2\pi k}{K}}} \\ &= \underset{k \in \{1,2\ldots,K\}}{\operatorname{argmin}} \; |b|\big|_{h_1 \to h_1 e^{i\frac{2\pi k}{K}}} \end{aligned} \quad (8)$$

Based on the long range prediction, we have a predicted induced channel matrix $\tilde{\mathcal{H}}$. Using the predicted channel, the predicted code diversity algorithm decides on

$$\tilde{k}^* = \underset{k \in \{1,2\ldots,K\}}{\operatorname{argmax}} \; det(\tilde{\mathcal{H}}^\dagger \tilde{\mathcal{H}})\big|_{\tilde{h}_1 \to \tilde{h}_1 e^{i\frac{2\pi k}{K}}} \quad (9)$$

We adopt the linear MMSE prediction of the channel coefficients with the parameters in Table I.

TABLE I
CHANNEL PREDICTION PARAMETERS

Parameters	Values
Pilot rate	10KHz
Data rate	100KHz
Predictor order	20
Prediction range	2 ms
Sampling rate for predictor	1KHz
Maximum Doppler frequency	100Hz

Simulations in Fig. 1 and Fig. 2 show comparisons of different schemes of the linear Zero Forcing (ZF) decoding and ML decoding with symbols on 4-QAM. In Fig. 1 and Fig. 2, 'Without CD' represents decoding without code diversity; 'Mismatch-CD' represents implementing code diversity by assuming no feedback delay; 'Pred-CD' represents implementing code diversity based on long-range channel prediction and 'CD' represents implementing code diversity with perfect channel prediction. It is shown that the performance of the predicted code diversity scheme approaches the performance of the perfect code diversity scheme.

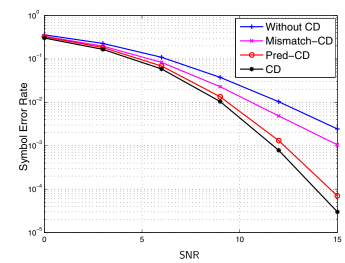

Fig. 1. Linear ZF decoding of QOSTBC using predicted code diversity.

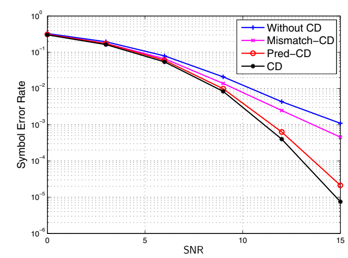

Fig. 2. ML decoding of QOSTBC using predicted code diversity.

Now we vary the prediction range for the linear ZF decoding of Jafarkhani's QOSTBC. Simulations in Fig. 3 show that as the prediction range increases, the performance of the predicted code diversity scheme deteriorates to the performance of the scheme without code diversity. This is reasonable since the prediction becomes less accurate as the prediction range increases. In practice, prediction ranges of 2-3ms are often sufficient to compensate for the feedback delay.

C. Predicted Code Diversity in a Physical Environment

The Jakes channel model simulates time-varying correlated mobile radio channel yet it might not be able to capture all environmental properties. In this subsection, we consider a realistic physical model as shown in Fig. 4. The data set of this model represents a realistic scenario where the incoming angles of reflections vary fast due to the reflectors closely placed to the route of mobile user. The nonstationary nature of this data set makes it challenging to predict [14]. To keep up with channel parameter variations, we employ the Burg

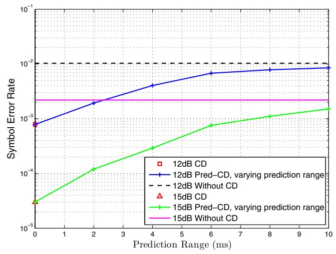

Fig. 3. Linear ZF decoding of QOSTBC with varying prediction range at SNR=12,15 dB.

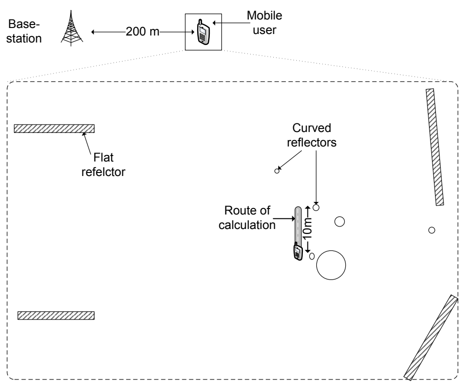

Fig. 4. Geometry of physical model with antenna array at the base station.

predictor with high pilot rate-based noise reduction proposed in [19].

In this scenario, the antenna-array is installed at the base-station, while mobile user has only one antenna. Table II shows additional parameters used in simulation.

TABLE II
PHYSICAL MODEL PARAMETERS

Parameters	Values
Prediction Range	3ms
Carrier frequency	1GHz
Antenna separation	3 wavelengths (0.9 m)

Simulation in Fig. 5 shows that the performance of the predicted code diversity scheme matches that of the perfect code diversity scheme and it outperforms the 'Mismatch-CD' scheme and the 'without CD' scheme by a large degree in the realistic channel settings.

V. CONCLUSION

We have first reviewed the code diversity scheme for space-time coded systems with no delay in feedback link. We have then illustrated the methodology of using the long-range channel prediction to implement the code diversity in systems with feedback delay and rapidly time-varying channels. We have shown that realizing code diversity through the long-range channel prediction results in a significant performance improvement.

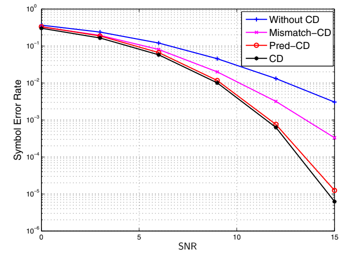

Fig. 5. Linear ZF decoding of QOSTBC using predicted code diversity in a physical model.

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