Selective Transmitter Diversity and Channel Inversion for Mobile Radio Systems*

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ABSTRACT

Transmitter diversity at the base station of a cellular mobile radio system provides a means to achieve performance gains similar to those obtained with mobile-station receiver diversity, but without the complexity of a mobile-station receiver antenna array. We investigate Selective Transmit Diversity (STD) in the downlink of the Wideband Code Division Multiple Access (WCDMA) mobile radio channel system. For fast vehicle speeds, we utilize long range fading prediction to enable performance of the STD system for standard stationary fading models, as well as for a novel physical model that accounts for the realistic nonstationarity of the fading channel. Finally, we evaluate the gain of the combined STD and the truncated channel inversion power control method.

KEY WORDS: Mobile Radio, Transmitter Diversity, Code Division Multiple Access (CDMA), WCDMA, adaptive transmission, modeling and estimation of fading channels.

1. INTRODUCTION

The WCDMA has been developed as a predominant radio access technology for the next generation global wireless standard [1, 2]. One of the novel features of WCDMA is support for transmitter antenna diversity for the downlink [3, 4, 5]. In particular, Selective Transmitter Diversity (STD) is a closed-loop method that offer significant diversity advantages over open loop techniques (e.g. Orthogonal Transmitter Diversity (OTD)), but requires feedback of channel state information (CSI) from the mobile to the base station. In practice, the performance of STD can be degraded due to imperfect and delayed CSI. In particular, even small delay can result in significant degradation due to the time varying nature of the fading channel [6]. In this paper, we utilize the long-range prediction method (LRP) [7, 8, 9] to improve the performance of the Selective Transmitter Diversity technique. The LRP is the Minimum Mean Square Error (MMSE) adaptive prediction method based on the autoregressive (AR) modeling of the fading channel. It forecasts the fading conditions much further ahead than the conventional methods due to its longer memory span achieved using lower sampling rate for fixed model order. The accurate prior knowledge of the channel for the entire duration of the next frame or slot, provided by LRP, enables more efficient antenna switching at the transmitter. In [10, 12], performance of STD aided by LRP was analyzed for flat and multipath fading channels using the standard Jakes model. In this paper, we also use a realistic novel physical fading channel model [9, 11] to demonstrate that accurate prediction enables STD for mobile radio channels. While we concentrate on flat fading, the results could be extended to multipath fading prevalent in WCDMA systems as proposed in [10,12,13]. Finally, we investigate joint STD and power control. While power control is almost always used in CDMA systems, it can be unreliable for fast vehicle speeds without accurate channel prediction. We show that significant gains can be achieved when STD is combined with truncated channel inversion (TCI) adaptive power control method [15] when aided by LRP.

2. SELECTIVE TRANSMITTER DIVERSITY (STD) AND WCDMA SYSTEM

In this paper, we apply STD in the downlink of the W-CDMA channel [1]. We assume the receiver estimates and predicts the channel based on the pilot symbols, and feeds back the CSI (e.g. antenna selection bits) to the transmitter at the pilot symbol transmitting rate of 1.6KHz. The long-range channel prediction is applied to predict the fading channel condition for the downlink. The details of this prediction method for WCDMA were described in [9, 12]. In the following results, BPSK is used as a modulation scheme with the transmission data rate is 80 kbps and the Maximum Doppler shift f_{dm}=200Hz.

To perform STD, the transmitter continuously monitors the channel conditions based on the feedback from the receiver, and selects the antenna with the strongest channel power as the transmission antenna. In this paper, we will concentrate on the flat fading STD channel with 2 antennas illustrated in Figure 1. STD with multipath fading was investigated in [10,12,13]. The

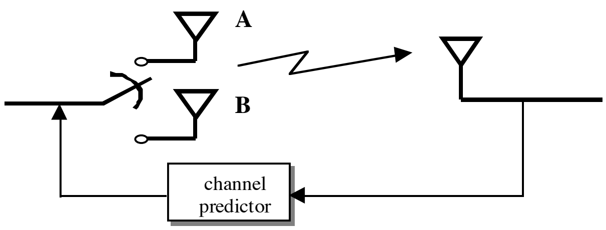

Figure 1. Operation of STD for two transmitter antennas

channels from the two antennas to the mobile are modeled as i.i.d. Rayleigh fading with complex fading coefficients c_1 and c_2, and fading gains $\alpha_1(t)$ and $\alpha_2(t)$, respectively. First, we use the 9-oscillator Jakes model to model the channels in simulations. Later in the paper, a realistic non-stationary model is utilized. Additive white Gaussian noise is present at the receiver. Assuming perfect CSI at the transmitter, the transmission channel becomes $c_s(t)$, where s = $\arg\, marx_{s\in\{1,2\}}\{|c_s(t)|\}$. The probability density function (pdf) of the amplitude of $\alpha = |c_s(t)|$ for L transmission antennas can be calculated as (see references in [13]):

$$f_{\alpha}^{SC}(x) = \frac{Lx}{\sigma^2}(1-e^{-\frac{x^2}{2\sigma^2}})^{L-1}e^{-\frac{x^2}{2\sigma^2}} \qquad (1)$$

where $2\sigma^2$ is the average channel power for each antenna. The theoretical BER for the STD system was derived in [12, 13].

In a practical implementation of the STD scheme, the antenna switching rate might be limited by hardware constraints or system complexity. A lower switching rate is often desirable (e.g. antenna switches at a rate of 400Hz instead of 1600Hz was proposed in [14]), so we give results at several antenna switching rates. We implement multiple step prediction [13, 9] to forecast the fading gain during the upcoming interval in which the transmission is operated with a fixed antenna, and choose the transmission antenna based on the average predicted powers for that interval. In the Bit Error Rate (BER) comparison (Figure 2) for the antenna switching rate of 400Hz, both the delayed CSI and the predicted CSI are determined based on the received channel samples delayed by one slot (0.625ms) relative to the beginning of the switching interval. We observe that at least 3 dB of performance gain (for BER less 10^{-3}) can be achieved by using the average of the predicted CSI relative to using a single predicted CSI (i.e. predict fading power at the beginning of a four-slot frame). When prediction is not utilized (delayed CSI), STD at this switching rate has poor performance.

In Figure 3, we compare STD with different switching frequencies. The prediction results in the gain of at least 4dB for all switching rates, and switching at the slot rate (1.6KHz) has near-ideal performance when LRP is used.

In the above study, we used the stationary Jakes model for the simulations. Below we test STD aided by LRP for our non-stationary realistic physical model described in [9, 11, 13]. This model includes the variation of parameters associated with individual reflectors as the mobile moves past them. The configuration shown in Figure 4 is used to generate the realistic physical channel. Here, 10 spherical reflectors are randomly set on two sides of a one-way road that is 100 meters long and 4 meters wide. The two antennas A and B at the base station are 100 meters away from the road, and are spaced 0.72 meters, i.e. 2.4 wavelengths apart. This will guarantee that fading paths from antennas A and B are not strongly correlated. (The correlation coefficient 0.2 was estimated for the generated data set). Further assume that the vehicle drives along the road at the speed of 30 miles/hr (f_{dm} = 45 Hz when the carrier frequency is 1 GHz.) We sampled the channel at the rate of 500 Hz and

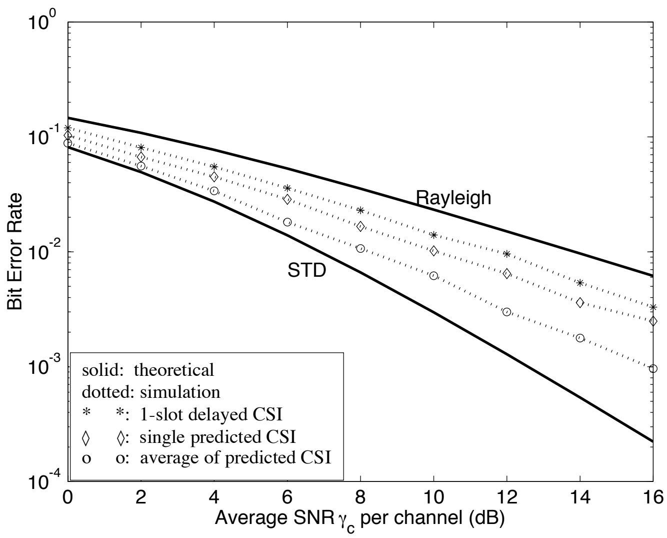

Figure 2. BER performance improvement using average of predicted CSI. (f_{dm} = 200 Hz, 9-oscillator Jakes model). Antenna switches at a rate of 400 Hz.

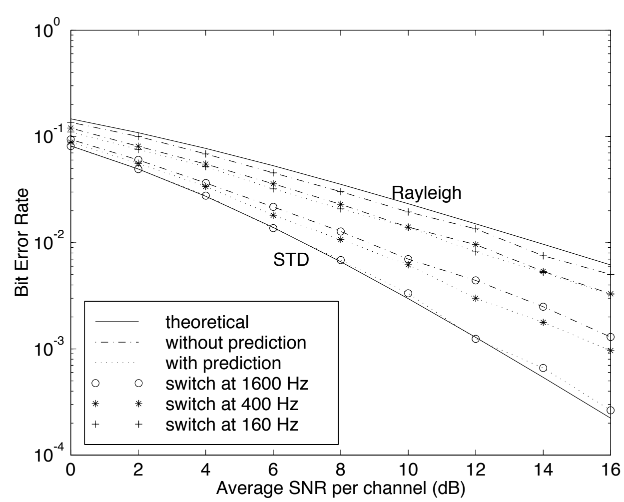

Figure 3. BER performance of STD over flat Rayleigh fading channel with and without prediction for various antenna switching rates. (f_{dm} = 200 Hz, 9-ocsillator Jakes model).

collected 3750 sample points along the 100 meter road. We subtracted the mean from the data set and normalized the average fading channel power to unity to obtain two approximately independent flat fading channels from antennas A and B. We further examined the generated physical fading channel through both calculation of the pdf of the data set and simulation of the BER of BPSK over the fading channel. The results confirms that the interference pattern created under the environment shown in Figure 4 is very close to the Rayleigh fading channel. Using generated data described above, we interpolated 50 data rate points between 2 original sample points to obtain fading channel samples corresponding to the data rate of 25kbps.

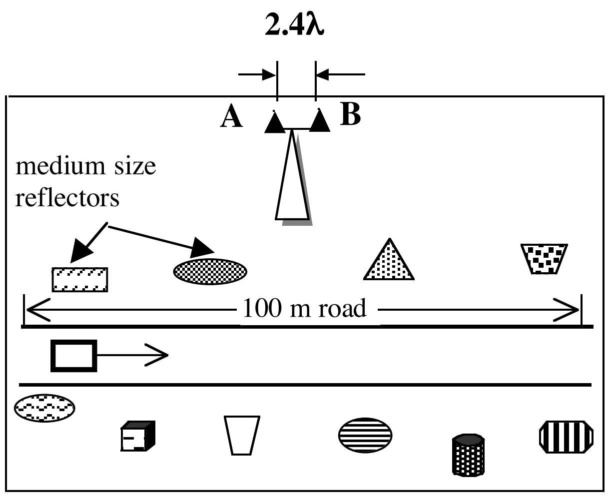

Figure 4 Generation of realistic physical model for selective transmitter diversity (STD).

Now we describe the application of the long-range channel prediction method in the STD system for the physical model data. The antenna switching rate was 500Hz. In our simulation, the observation interval of 50 sample points (i.e. first 1.33 meters) was used to initialize the AR model parameters. During transmission (last 3700 sample points or 98.67 m), the feedback delay for the predicted and outdated CSI was 2 ms. We chose model order p=30 and assumed the observation samples had high SNR. In Figure 5, we compared the BER performance of 3 different approaches: (1) predict the channel with fixed model coefficients computed during the observation interval; (2) predict the channel with the adaptation of model parameters using the least mean squares method (LMS) (the adaptive LRP was described in [9]); (3) use 2ms delayed CSI without prediction. We observe that performance of STD with channel prediction is much better than that with delayed CSI. Also, prediction with adaptation can further improve performance for this non-stationary fading channel and achieves almost the same BER performance as with perfect CSI (physical model, STD switch at 25 KHz.) Thus, the simulation results presented in this section demonstrate that the long range channel prediction algorithm enables STD for the realistic non-stationary physical model data.

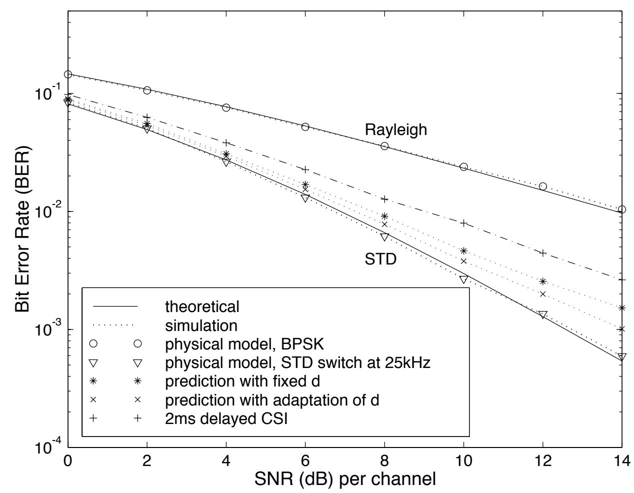

Figure 5. BER performance over generated physical model data.

3. COMBINED STD AND TRUNCATED CHANNEL INVERSION

In the truncated channel inversion method (TCI) power control method [7, 15] transmission is avoided when the instantaneous channel power falls below a certain threshold (during deep fades), and the transmitted power is proportional to the inverse of the fading channel power when it is above the threshold. While TCI results in improved power and bandwidth efficiency, it is not a practical method since it requires large transmitter power fluctuation. In addition, its performance improvements are achieved at the expense of a lower normalized data rate (bandwidth efficiency), since the data is not transmitted when the fading level is below the threshold. These weaknesses of TCI can be greatly mitigated by combining TCI with STD because the fades can be substantially smoothed out through the selection of the best antenna. Moreover, the STD with the adaptive power control can achieve significant performance gain without the requirement of a large number of antennas at the base station. Figure 6 illustrates our proposed combined STD + TCI scheme for two transmitter antennas. At the base station, the transmitter selects the antenna with the strongest channel as the transmission antenna, then TCI is applied to the transmission antenna.

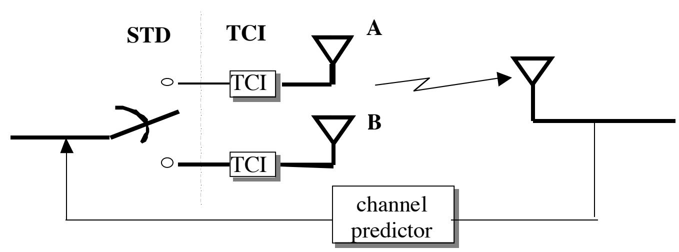

Figure 6 Driving configuration of STD + TCI scheme.

In this STD + TCI scheme, our long range channel prediction is used for both antenna selection (STD) and adaptive power control (TCI). As above, we assume each antenna experiences independent flat Rayleigh fading and the average channel power for each antenna is normalized to unity. In our theoretical analysis, both STD and TCI are operated at the symbol rate.

As shown in Figure 6, let { $c^A(t)$} and { $c^B(t)$} represent the complex fading coefficients for antenna A and B. Then the transmission channel for STD becomes $c^S(t)$, where S = $\arg\max_{\text{A or B}} \{|c_A(t)|^2, |c_B(t)|^2\}$. When STD is operated with TCI, at the output of the matched filter and sampler, the new modified discrete-time received signal is given by:

$$y_k = \frac{c_k^S}{\hat{c}_k^{S'}} b_k + z_k, \tag{2}$$

where $\hat{c}_k^{S'}$ is the predicted channel coefficient, and $S' = \arg\max_{A \text{ or } B} \{|\hat{c}_k^A|^2, |\hat{c}_k^B|^2\}$. In our theoretical analysis, we assume perfect CSI, i.e. $\hat{c}_k^{S'} = c_k^S$. The pdf of $\alpha^S = |c^S(t)|$ is given by $f_{\alpha^S}(x) = 4x(e^{-x^2} - e^{-2x^2})$. When TCI is operated with the threshold ρ, the average power of STD+TCI is calculated as [13]

$$E\{\frac{1}{(\alpha^S)^2} \mid \frac{1}{(\alpha^S)^2} < \frac{1}{\rho}\} = \frac{2}{1-(1-e^{-\rho})^2}(\Gamma_{in}(0,\rho) - \Gamma_{in}(0,2\rho)) \tag{3}$$

where $\Gamma_{in}(0, \rho)$ is the incomplete Gamma function [16]. Unlike in the single antenna case, when total channel inversion (without the threshold, or ρ = 0) is applied, the average power is not infinite. It becomes $E\{\frac{1}{(\alpha^S)^2}\} = 2\ln 2$ [13]. This means that when STD + TCI is applied, we can achieve 100% throughput without infinite power boost.

For a given threshold ρ, the throughput of STD+TCI is calculated as:

$$P_r\{(\alpha^S)^2 > \rho\} = \int_\rho^\infty f_{\alpha^S}(x)dx = 1-(1-e^{-\rho})^2. \tag{4}$$

threshold ρ	STD+ TCI (dB)	TCI only (dB)
0.0	**1.42**	**∞**
0.1	**0.83**	**3.0**
0.2	**0.32**	**1.76**
0.3	**-0.15**	**0.87**
0.4	**-0.56**	**0.0**
0.5	**-0.94**	**-0.35**
0.6	**-1.29**	**-0.82**

Table 1 Comparison of average transmitted power for STD+TCI and TCI only schemes.

threshold ρ	STD+ TCI (dB)	TCI only (dB)
0.0	**100.0**	**100.0**
0.1	**99.09**	**90.48**
0.2	**96.71**	**81.87**
0.3	**93.28**	**70.08**
0.4	**89.13**	**67.03**
0.5	**84.52**	**60.65**
0.6	**79.64**	**54.88**

Table 2 Comparison of throughput (%) for STD+TCI and TCI only schemes.

The average power (3) and throughput (4) of STD+TCI is summarized in Tables 1 and 2 for different values of threshold ρ. The results for the TCI only scheme for a flat Rayleigh fading channel with unit power are also included in the tables for comparison. Note that from (2), the average power indicates the SNR loss that relative to BPSK over the AWGN channel. We observe significant throughput improvement of STD+TCI vs. STD given the same average power. With the assumption of perfect CSI at transmitter, the BER of STD + TCI is plotted in Figure 7 for various thresholds ρ. Note that STD+TCI significantly outperforms the STD only method, and reduces the BER to or below the level of the AWGN channel when ρ ≥ 0.3 (at a throughput of approximately 93%). This performance is achieved for ρ

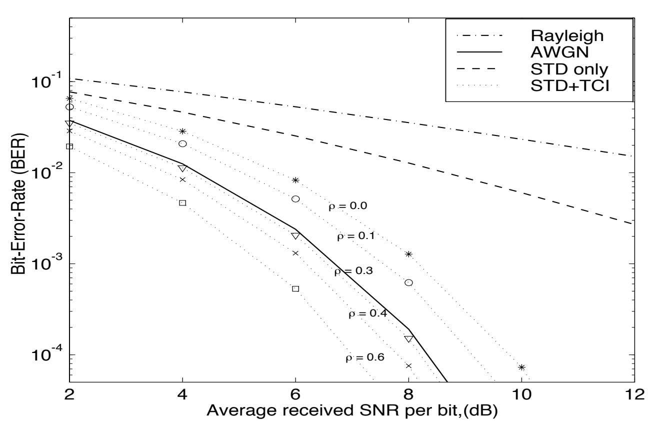

Figure 7 BER performance of STD+TCI with different thresholds for flat Rayleigh fading channel. BPSK with coherent detection. (Assume perfect CSI at transmitter)

= 0.4 by TCI only with a throughput of about 67%.

We compared the BER of STD+TCI for predicted and delayed CSI in Figure 8 using the same channel parameters as in Figures 2 and 3. For the LRP, the model order p =40 and the observation interval is 100 samples. In the simulation results, the transmitter antenna switching rate is 1.6 KHz. Interpolation is used to predict the channel coefficient at the data rate between two adjacent predicted low-rate samples. The TCI is operated at rate of 80kbps (data rate). In addition to the LRP, we considered the case when the actual channel coefficient is fed back to the transmitter with 0.625ms delay, and used it to select transmission antenna and also to adjust the transmitter power for all 50 data bits between the two lower sampling rate points. Simulation results indicate that our long range channel prediction algorithm provides accurate enough CSI for both antenna selection and power control of STD+TCI, and achieves significant performance gain over the case when delayed CSI is used.

3. CONCLUSION

We investigated Selective Transmit Diversity (STD) aided by long range prediction in the downlink of WCDMA, and combined STD with adaptive power control. A novel realistic channel model was used to validate performance of the LRP. It was demonstrated that adaptive transmission diversity and power control provide significant performance gains, and the LRP enables STD for fast vehicle speeds when enabled by accurate channel prediction.

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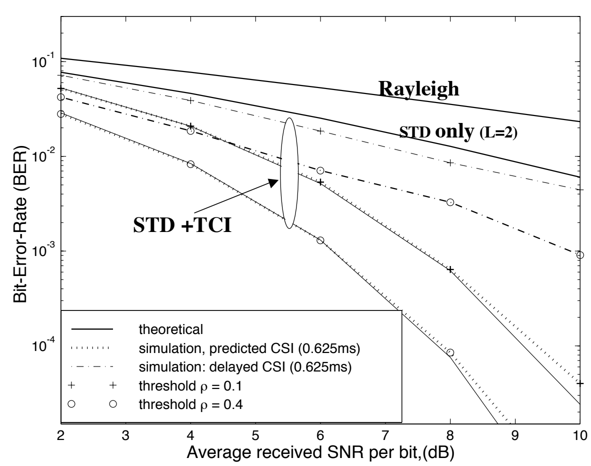

Figure 8 BER performance of STD+TCI with and without channel prediction for threshold 0.1 and 0.4. (9-oscillators Jakes model, f_{dm} = 200Hz)