Adaptive Modulation for Transmitter Antenna Diversity Mobile Radio Systems[1]

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Abstract - Development of novel signal processing and communication techniques for 3G wireless systems is motivated by high data-rate service requirements. These techniques include adaptive modulation and transmitter antenna diversity. In rapidly time variant channels, these methods need the knowledge of future fading conditions. Thus, they require accurate long range fading prediction. We investigate three combined adaptive modulation and transmitter diversity schemes in conjunction with our previously proposed long-range channel prediction (LRP) algorithm. It is demonstrated that the novel combined schemes can achieve higher data rates than the conventional adaptive modulation methods when aided by the LRP. In addition to utilizing the Jakes fading model to test the proposed methods, we validate long-range prediction for antenna diversity systems using a novel realistic fading channel model.

I. Introduction

New adaptive transmission techniques such as adaptive modulation were proposed recently to satisfy the tremendous growth in demand for wireless communications capacity. Adaptive modulation is a useful approach to achieve bandwidth efficient transmission by adapting the modulation parameters (e.g., constellation size, transmitted signal power, symbol rate, etc.) to current fading conditions. In this paper, we investigate combined adaptive modulation and antenna diversity. It is well known that diversity improves channel capacity [1], and as the number of diversity branches increases, the capacity of the fading channel converges to that of the Gaussian channel [2]. In [2], Alouini and Goldsmith investigate the Rayleigh fading channel capacity for space diversity with Maximal Ratio Combining (MRC) and selection combining (SC) *at the receiver* under three adaptive transmission policies. Theoretical results in [2] show that diversity yields large capacity gains for adaptive transmission schemes and indicate that selection combining provides less diversity gain than MRC. However, the design of the combined adaptive modulation and diversity system was not addressed in [2]. Moreover, the implementation of space diversity at the mobile is usually difficult due to the limitations in the cost, size and power of remote units. Therefore, it is of interest to consider combined adaptive modulation and *transmitter diversity* system.

The combined adaptive modulation and transmitter diversity methods depend on accurate channel state information, but the rapid variation of the fading channel makes feedback of the current channel estimate insufficient. To implement these combined schemes in practice, *channel state information* (CSI) for a future block of tens to hundreds of data symbols [3] must be available at the transmitter. CSI can be estimated at the receiver and sent to the transmitter via a feedback channel. Thus, feedback delay and overhead, processing delay and practical constraints on modulation have to be taken into account in the performance analysis of combined adaptive modulation and transmitter methods. For very slowly fading channels (pedestrian or low vehicle speeds), *outdated* CSI is sufficient for reliable adaptive system design. However, for faster fading that corresponds to realistic mobile speeds, even small delay will cause significant degradation of performance since channel variation due to large Doppler shifts usually results in a different channel at the time of transmission than at the time of channel estimation. To realize the potential of adaptive transmission methods, these channel variations have to be *reliably predicted* at least several milliseconds ahead.

Recently, we have investigated a *novel adaptive long range fading channel prediction algorithm* in [4 - 8]. This algorithm characterizes the fading channel using an autoregressive (AR) model and computes the Minimum Mean Squared Error (MMSE) estimate of a future fading coefficient sample based on a number of past observations. The superior performance of this algorithm relative to conventional methods is due to its *longer memory span* that permits prediction much further into the future. Given *fixed model order*, the long memory span is achieved by using *low sampling rate* (on the order of twice the maximum Doppler shift and much lower than the data rate) [6, 7]. The prediction method is enhanced by an *adaptive tracking* method [6, 7] that increases accuracy, reduces the effect of noise and maintains the robustness of long-range prediction as the physical channel parameters vary.

In [5 – 9], we applied the long-range prediction in adaptive power control, adaptive modulation and transmitter diversity for wideband Code Division Multiple Access systems (WCDMA). It was demonstrated that LRP enables

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these adaptive transmission techniques for high vehicle speeds and realistic feedback delays.

In this paper and [19], we extend the application of long range channel prediction to our proposed combined adaptive modulation and transmitter diversity schemes. We concentrate on the study of the following three combined schemes: combined adaptive modulation (AM) +Selective Transmitter Diversity (STD); (2) combined adaptive modulation (AM) + Transmit Adaptive Array (TxAA); and (3) adaptive space-time modulation[2] (AM + STTD). We analyze performance of these techniques for perfect CSI and demonstrate that LRP enables their performance for rapid vehicle speeds using the Jakes fading channel model. In addition, we describe a realistic physical model that captures variation of channel parameters associated with the reflectors that contribute to the channel for an antenna array system. Performance of selective diversity with LRP is investigated for this model.

II. Combined Adaptive Modulation and Transmitter Diversity

In the following study, we consider the case of two transmitter antennas and one receiver antenna. The same analytical approach can be extended to the case of any number of transmitter antennas. Here, we only consider modulation level-controlled adaptive modulation scheme [3, 10, 11]. We restrict the constellation size M of square M-QAM to 0, 2, 4, 16 and 64, and choose the target BER as 10^{-3}.

First, consider operation of modulation level-controlled adaptive modulation over a single antenna flat Raleigh fading channel with the gain $\alpha(t)$ and additive white Gaussian noise. The basic idea is to vary the constellation size according to the instantaneous channel condition, which can be measured as either the instantaneous signal-to-noise (SNR) ratio $\gamma(t)$ or the fading gain $\alpha(t)$. Throughout this paper, we characterize the channel condition as $\alpha(t)$. Given fixed transmitter power E_s (or the average Signal-to-Noise Ratio (SNR) level $\bar{\gamma} = E_s/N_0$), to maintain a target BER, we need to adjust the modulation size M according to the instantaneous channel gain $\alpha(t)$. In other words, the adaptive modulation scheme can be specified by the threshold values α^i, i = 1, …, 4, defined as: when $\alpha(t) \geq \alpha^{i,}$ M_i-QAM is employed, where $M_1 = 2$, $M_i = 2^{2(i-1)}$, i > 1. When perfect CSI $\alpha(t)$ is available, these thresholds can be directly calculated from the BER bound of MQAM for the Additive White Gaussian Noise (AWGN) channel [3]:

$BER_M \leq 0.2 \exp(-1.5\gamma(t)/(M-1))$ for M>2, and

$$BER_2 = Q(\sqrt{2\gamma}) , \quad (1)$$

where $\gamma(t)= \alpha^2(t)\bar{\gamma}$ is the instantaneous received SNR. The modulation switching thresholds calculation for predicted CSI was studied in [8, 9, 12]. However, we found that when LRP is used, modification of thresholds is not necessary for stationary Rayleigh fading channels and realistic feedback delays and vehicle speeds. The CSI is predicted accurately enough that thresholds chosen for perfect CSI can be used.

Now, consider combined adaptive modulation and transmitter antenna diversity. The 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. The transmitter antennas are combined according to the chosen diversity scheme. Additive white Gaussian noise is present at the receiver. Assume accurate CSI is available at the transmitter. When we combine adaptive modulation and transmitter diversity, the modulation switching threshold values are not affected, since they depends only on the target BER_{tg} and average SNR $\bar{\gamma}$ (1). However, the modulation level selection rule and the performance depends on the transmission diversity scheme and fading channel conditions for both antennas. Thus, we can find a function of $\alpha_1(t)$ and $\alpha_2(t)$ for each combining scheme, say $g(\alpha_1, \alpha_2)$, so that M_i is selected based on $g(\alpha_1, \alpha_2)$, using the thresholds calculated from eq. (1). In the following sections, we discuss the function $g(\alpha_1, \alpha_2)$ for each combined adaptive modulation and transmitter diversity scheme, and derive the data rates, bit error rates (BER) and outage probabilities. In our theoretical analysis, we assume the perfect CSI is available at the transmitter. The threshold calculation using predicted CSI for combined schemes is much more complicated than for AM only case since it depends on the statistical model of the prediction error $g(\alpha_1,\alpha_2)/g(\hat{\alpha}_1,\hat{\alpha}_2)$. We examine the performance of combined schemes aided by long range prediction through simulations in section III.

(1) *Combined Adaptive Modulation (AM) and Selective Transmitter Diversity (STD) Scheme.*

An AM+ STD scheme for two transmitter antennas is illustrated in Figure 1. The received signal r(t) is given by:

$$r(t) = \alpha_{SC}(t)\, s(t) + n(t), \quad (2)$$

where s(t) is the transmitted signal, n(t) is white Gaussian noise, and $\alpha_{SC}(t) = \max(\alpha_1(t), \alpha_2(t))$. Then the instantaneous SNR can be calculated as: $\gamma(t) = \bar{\gamma}\alpha_{SC}^2(t)$. Thus, we can identify the AM+STD scheme with a single transmission antenna system with the channel:

$$g_{AM+STD}(\alpha_1, \alpha_2) = \max(\alpha_1, \alpha_2) \quad (3)$$

Then, the constellation size of AM+STD scheme can be selected based on $\max(\alpha_1, \alpha_2)$. Now, let us analyze the performance of AM+STD. The pdf of the channel $g_{AM+STD}(\alpha_1, \alpha_2) = \max(\alpha_1, \alpha_2)$ can be derived as:

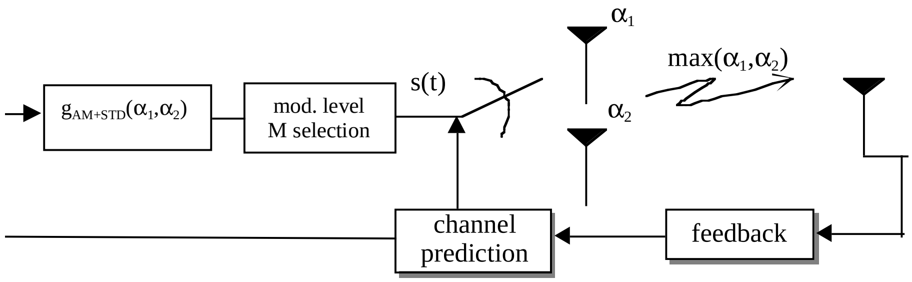

Figure 1. Driving configuration of AM+STD scheme

[2] Here we only consider Alamouti space-time code [13].

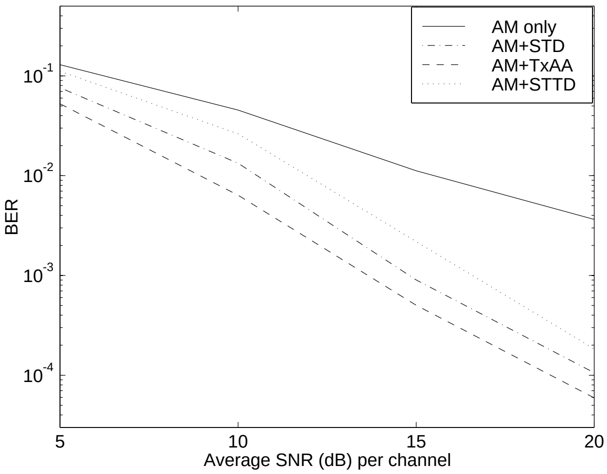

Figure 2. BER comparison for different adaptive transmission schemes. (All schemes achieve bit rate of 2.7 bits/symbol)

$$f_{AM+STD}(x) = \frac{2x}{\sigma^2}(1-e^{\frac{-x^2}{2\sigma^2}})e^{\frac{-x^2}{2\sigma^2}}, \quad (4)$$

where σ^2 is the average power of the fading channels. From [11], the data rate performance of combined AM+STD scheme for ideal CSI is given by:

$$R_{AM+STD} = \sum_{i=1}^{4} \log_2 M_i \int_{\alpha^i}^{\alpha^{i+1}} f_{AM+STD}(x)dx. \quad (5)$$

According to modulation switching policy, we know that the transmission will be interrupted when the fading gain α falls below the threshold α^1. Thus AM+STD scheme suffers the outage probability

$$P_{AM+STD}^{out} = \int_0^{\alpha^1} f_{AM+STD}(x)dx = (1-e^{-\frac{\alpha^{1^2}}{2\sigma^2}})^2 \quad (6)$$

(2) Combined Adaptive Modulation (AM) and Transmit Adaptive Array (TxAA) Scheme

For the TxAA scheme [14], the signals are transmitted coherently with the same data and code at each transmission antenna, but with antenna-specific amplitude and phase weighting, say w_1 and w_2. These complex values, w_1 and w_2 (array weights), are selected to maximize the received power at the mobile, and the same diversity gain as receiver diversity with MRC can be achieved. For the flat fading channel, the weights w_1 and w_2 are given as [14]:

$$w_1 = c_1^*/\sqrt{\alpha_1^2+\alpha_2^2} \quad (7)$$

$$w_2 = c_2^*/\sqrt{\alpha_1^2+\alpha_2^2} \quad (8)$$

where the normalization is necessary to maintain the total transmit power at a constant level. Given these weights, the received signal is:

$$r(t) = s(t)\sqrt{\alpha_1^2+\alpha_2^2} + n(t) \quad (9)$$

Then the instantaneous SNR is $\gamma(t)=\bar{\gamma}(\alpha_1^2(t)+\alpha_2^2(t))$. Thus the AM+TxAA scheme is equivalent to a single transmission antenna system but with the channel:

$$g_{AM+TxAA}(\alpha_1, \alpha_2) = \sqrt{\alpha_1^2+\alpha_2^2} \quad (10)$$

Therefore, the constellation size of AM+TxAA scheme can be selected based on $\sqrt{\alpha_1^2+\alpha_2^2}$. The pdf of the channel $g_{AM+TxAA}(\alpha_1, \alpha_2) = \sqrt{\alpha_1^2+\alpha_2^2}$ can be derived as:

$$f_{AM+TxAA}(x) = \frac{1}{2\sigma^4}x^3\exp(-\frac{x^2}{2\sigma^2}) \quad (11)$$

As in (5), the data rate performance of combined AM+TxAA scheme for ideal CSI is given by:

$$R_{AM+TxAA} = \sum_{i=1}^{4} \log_2 M_i \int_{\alpha^i}^{\alpha^{i+1}} f_{AM+TxAA}(x)dx \quad (12)$$

The probability of outage of AM+TxAA is

$$P_{AM+TxAA}^{out} = \int_0^{\alpha^1} f_{AM+TxAA}(x)dx = 1-e^{-\frac{\alpha^{1^2}}{2\sigma^2}} - \frac{1}{2}e^{-\frac{\alpha^{1^2}}{2\sigma^2}}\frac{\alpha^{1^2}}{\sigma^2} \quad (13)$$

(3) Adaptive Space-Time Modulation (AM+STTD):

In the two-branch adaptive space-time transmit diversity (AM+STTD) scheme two signals are simultaneously transmitted from the two antennas, say antenna 1 and antenna 2 at a given symbol period. During the first symbol interval, signal s_1 is transmitted from antenna 1 and s_2 is transmitted from antenna 2. During the second symbol period, signal $-s^*_2$ is transmitted from antenna 1 and s_1^* is transmitted antenna 2, where * represents the conjugate operation. The signal transmission matrix for STTD [13] is given by:

$$\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \quad (14)$$

Since in (14) the encoding is done in both space and time, it is an example of the *space-time coding* method. Assuming that fading is constant across two consecutive symbols, we can express the received signals as:

$$r_1=r(t)=c_1s_1+c_2s_2+n_1 \quad (15)$$

$$r_2=r(t+T)=-c_1s_2^*+c_2s_1^*+n_2 \quad (16)$$

where T is the symbol interval, r_1 and r_2 are the received signals at times t and t+T, and n_1 and n_2 are white Gaussian noise samples. The maximum likelihood detector is based on the variables [13]

$$\tilde{s}_1 = c^*_1 r_1 + c_2 r^*_2 \quad (17)$$

$$\tilde{s}_2 = c^*_2 r_1 - c_2 r^*_2 \quad (18)$$

Substituting (15) and (16) into (17) and (18) we get:

$$\begin{aligned} s_1 &= (\alpha_1^2 + \alpha_2^2)s_1 + c_1^* n_1 + c_2 n_2 \\ s_2 &= (\alpha_1^2 + \alpha_2^2)s_2 - c_1 n_2^* + c_2^* n_1 \end{aligned} \quad (19)$$

Now let us calculate the instantaneous SNR for the STTD scheme. If we denote the noise term $n' = c^*_1n_1 + c_2n_2$ for symbol s_1, and $n'' = c_1n^*_2 + c^*_2n_1$ for s_2, then variances of n' and n'' are given by:

$$Var(n') = Var(n'') = (\alpha_1^2 + \alpha_2^2)\frac{N_0}{2} \quad (20)$$

Here we assume $\mathrm{Var}(n_1) = \mathrm{Var}(n_2) = \frac{N_0}{2}$. In order to make a fair comparison of performance with AM+STD and AM+TxAA schemes, the total radiated power of STTD , say E_s, has to be same as for STD and TxAA. Thus, each antenna radiates half of the total power, i.e., $E\{|s_1|^2\} = E\{|s_2|^2\} = E_s/2$. Therefore, the instantaneous SNR is given by:

$$\gamma(t) = \frac{(E_s/2)(\alpha_1^2+\alpha_2^2)^2}{N_0(\alpha_1^2+\alpha_2^2)} = \frac{E_s}{N_0}\frac{\alpha_1^2+\alpha_2^2}{2}$$

$$= \bar{\gamma}\frac{\alpha_1^2+\alpha_2^2}{2} \tag{21}$$

Thus, AM+STTD is equivalent to a single transmission antenna system with the channel:

$$g_{AM+STTD}(\alpha_1, \alpha_2) = \sqrt{(\alpha_1^2+\alpha_2^2)/2}\,. \tag{22}$$

Therefore, the constellation size of AM+STTD scheme is selected based on $\sqrt{(\alpha_1^2+\alpha_2^2)/2}$

The pdf of the channel $g_{AM+STTD}(\alpha_1, \alpha_2)$ is

$$f_{AM+STTD}(x) = \sqrt{2}\, f_{TxAA}(\sqrt{2}\, x) = \frac{\sqrt{2}}{\sigma^4}x^3\exp(-\frac{x^2}{\sigma^2}) \tag{23}$$

The data rate performance of combined AM+STTD scheme for ideal CSI is given by:

$$R_{AM+STTD} = \sum_{i=1}^{4}\log_2 M_i \int_{\alpha_i}^{\alpha_{i+1}} f_{AM+STTD}(x)dx \tag{24}$$

The probability of outage of AM+STTD, $P^{out}_{AM+STTD}$, is:

$$P^{out}_{AM+STTD} = \int_0^{\alpha^1} f_{AM+STTD}(x)dx = 1 - e^{-\frac{(\alpha^1)^2}{\sigma^2}} - e^{-\frac{(\alpha^1)^2}{\sigma^2}}\frac{(\alpha^1)^2}{\sigma^2} \tag{25}$$

III. Performance of Combined Adaptive Modulation and Transmitter Diversity Schemes.

In the simulations, the Jakes model [17] with 9 oscillators was used to generate fading channel coefficients. Assume Maximum Doppler shift f_{dm} = 100Hz. All methods are compared on the basis of SNR per channel, and average power for each channel is normalized to unity. Alternatively, one can compare them based on receives SNR per symbol, thus measuring the diversity gain directly [16]. While the relative gains will be reduced in the latter case, the ranking of the diversity methods will not be affected. First, we compare the BER performance of three combined schemes and AM only in Figure 2. In this comparison, we consider the adaptive modulation that selects either 4-QAM or 16-QAM constellation. We assume that perfect CSI is available at the transmitter. All four schemes achieve the same bit rate of 2.7 bits/symbol by using the appropriate switching thresholds (Throughout the paper, the thresholds are calculated in terms of the channel gain given by $\alpha(t)$ for AM only, and $g(\alpha_1,\alpha_2)$ for the combined schemes. In Fig. 2, the thresholds are: 1.02 for AM only, 1.28 for AM+STD scheme, 1.49 for AM+TxAA, and 1.05 for AM+STTD.) From Figure 2, we observe that all of the three combined schemes significantly outperform the AM only case for the moderate to high SNR (SNR > 10dB). The reduction of performance gain of the combined schemes over AM only case at low SNR is due to the domination of noise in signal detection. Furthermore, by comparing the performance of the three combined schemes, we found that AM+TxAA achieves the best performance. This agrees with the fact that the TxAA is the optimal diversity method as was discussed in [14]. Of course, AM+TxAA is the most complex method among the three schemes.

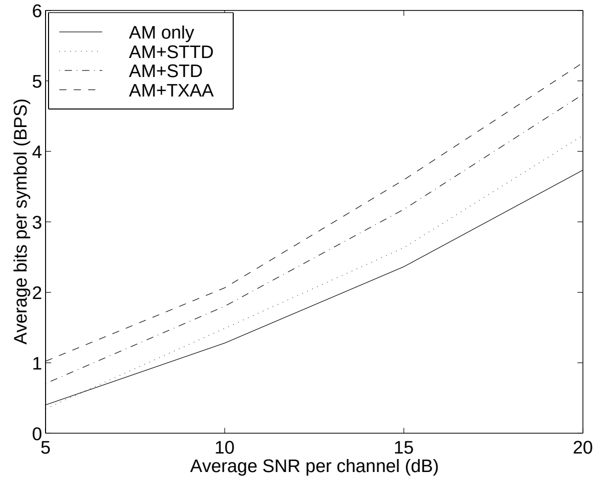

Figure 3. Comparison of average bit rate performance for different adaptive transmission schemes. ($BER_{tg} = 10^{-3}$)

Second, we compare the data rate performance in Figure 3 for the combined schemes and AM only case. Constellation sizes of M-QAM in the set of {0, 2, 4, 16, 32} are used in the Figure 3 (and in the rest of the paper). Here we assume perfect CSI is available at the transmitter and the thresholds are calculated based on eq. (1) for the target $BER_{tg} = 10^{-3}$. The ideal data rate performance for AM only, AM+STTD, AM+STD and AM+TxAA schemes based on (11) in [9], (5), (12) and (24) are shown in Figure 3. We observe that all combined schemes achieve higher data rate than adaptive modulation only case, and AM+TxAA achieves the best data rate performance.

The BER performance comparison of three combined schemes for delayed and predicted CSI is shown in Figure 4. We use our previously proposed long-range channel prediction method [4 ~ 8] to forecast future values of the fading coefficients. In this method, the linear MMSE prediction of the future channel sample $\hat{c}_n$ based on p previous samples $c_{n-1}...c_{n-p}$ is given by [4 ~ 8]:

$$\hat{c}_n = \sum_{j=1}^{p} d_j c_{n-j} \tag{26}$$

where the coefficients d_j are determined by the orthogonality principle. The channel sampling rate is 500Hz, and p = 50. We assume the receiver continuously monitors the channel conditions for both transmitter antennas, and feeds back the channel observations to the transmitter, which employs the channel prediction based on the observed samples for each transmitter antenna. We further assume the symbol rate of 25Ksymbols/s, and both the modulation switching rate and the antenna switching rate in STD are the same as the symbol

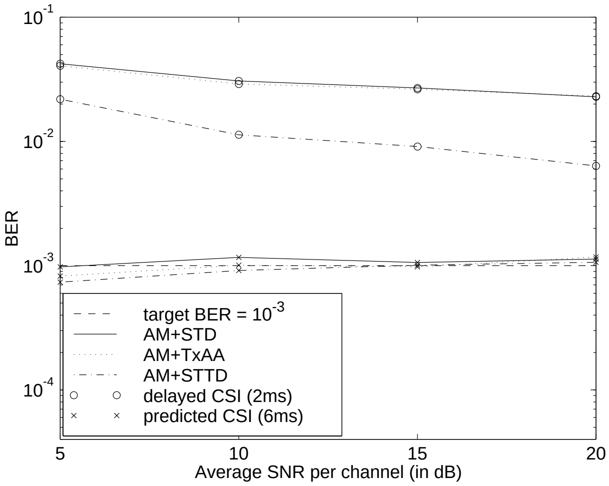

Figure 4. Comparison of BER performance for different combined adaptive modulation and transmitter diversity schemes with and without channel prediction. 9-oscillator Jakes model. f_{dm} = 100Hz.

rate. In addition, the modulation switching thresholds calculated based on the perfect CSI are used in the simulation. The target BER is set to 10^{-3}. We compared results for 3-step (6ms) ahead prediction with those for 2ms-delayed CSI without prediction. In AM+STD, the predicted CSI is used for both transmission antenna and constellation size selection. In AM+TxAA, the predicted CSI is used for specifying antenna weights and selecting the modulation level. Since STTD itself doesn't require CSI, the channel prediction is only used to aid modulation level switching. The simulation results in Figure 4 indicate that the long-range channel prediction provides sufficient CSI for the combined adaptive modulation and transmitter diversity schemes to maintain the target BER. This implies that the combined schemes can achieve the data rate performance of the ideal case with the aid of channel prediction algorithm. However, when delayed CSI is used, the BER of all three schemes significantly departs from the target BER. Note that AM+STTD is less sensitive to the feedback delay since STTD doesn't require CSI at the transmitter.

Finally, the comparison of outage probabilities for AM only and 3 combined schemes is shown in Figure 5.

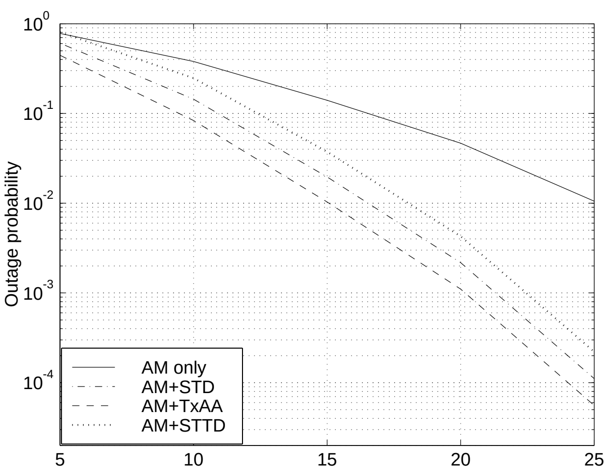

Figure 5. Comparison of outage probability for different adaptive transmission methods.

Expressions (5.33) in [8], (6), (13) and (25) are used to calculate performance of different methods. The thresholds were computed based on the perfect CSI and BERtg = 10^{-3}. Results in Figure 5 indicate that the outage probability of adaptive modulation can be greatly reduced by combining it with diversity techniques.

IV. Realistic Physical Modeling for Transmitter Antenna Diversity

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 [7,8,18]. This model includes the variation of parameters associated with individual reflectors as the mobile moves past them. The configuration shown in Figure 6 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 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 6 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.

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 the model order p=30 and assumed the observation samples had high SNR. In Figure 7, 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 [7]); (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 is within 2 dB of the BER

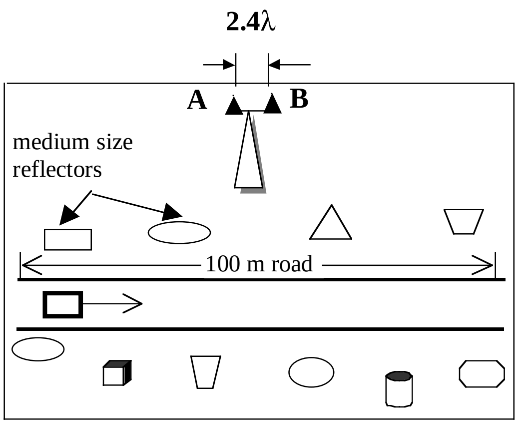

Figure 6 Generation of realistic physical model for selective transmitter diversity (STD).

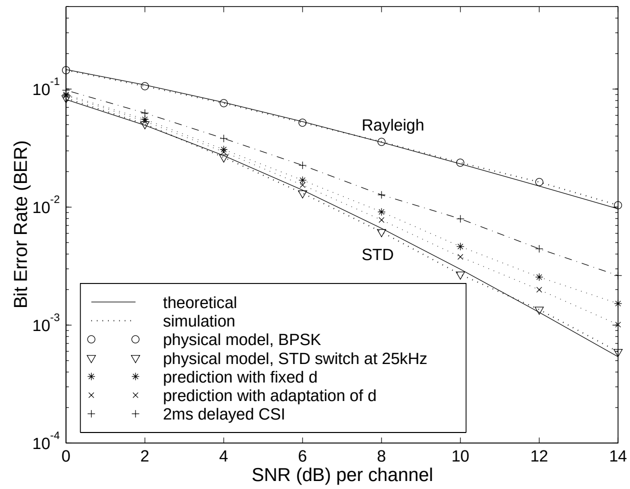

Figure 7. BER performance over generated physical model data.

performance for 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. Using this physical modeling approach, we have also shown in [9] that adaptive modulation can be implemented reliably for realistic mobile channels and high vehicle speeds when aided by LRP. Moreover, we have incorporated prediction reliability function into the adaptive modulation method. The investigations presented in this section and in [9] indicate that the combined adaptive modulation and transmitter diversity techniques with LRP are feasible for realistic mobile radio channels.

V. Conclusions

We investigated three combined adaptive modulation and transmitter diversity schemes. Both theoretical and simulation results show that the BER and the bit rate performance of adaptive modulation is improved when it is combined with transmitter antenna diversity. Also, using the Jakes model and a novel realistic physical model, we demonstrate that accurate long-range prediction of the fading channel makes these combined adaptive transmission schemes feasible for rapidly time-varying mobile radio channels.

References

[1] W. C. Y. Lee, "Estimate of Channel Capacity in Rayleigh Fading Environment," IEEE Trans. Veh. Technol., Vol. 39, pp. 187 – 190, Aug. 1990.

[2] M. S. Alouini, and A. J. Goldsmith, "Capacity of Rayleigh Fading Channels Under Different Adaptive Transmission and Diversity-Combining Techniques," *IEEE Trans. Veh. Technol*., Vol. 48, No. 4, July 1999, pp. 1165 – 1181.

[3] A. J. Goldsmith and S. G. Chua, "Variable-Rate Variable-power MQAM for Fading Channels", *IEEE Trans. Comm.*, vol. 45, No. 10, pp. 1218 - 1230, Oct. 1997.

[4] T. Eyceoz, A. Duel-Hallen, and H. Hallen, "Deterministic Channel Modeling and Long Range Prediction of Fast Fading Mobile radio Channels", *IEEE Comm. Letters*, Vol. 2, No. 9, pp. 254 – 256, Sept. 1998.

[5] T. Eyceoz, S. Hu, A. Duel-Hallen, and H. Hallen "Adaptive Prediction, Tracking and Power Adjustment for Frequency Non-Selective Fast Fading Channels", Proc. of the *Eighth Communication Theory Mini Conference (CTMC'99, ICC'99),* June 1999, pp.1 - 5.

[6] T. Eyceoz, S. Hu, A. Duel-Hallen, "Performance Analysis of Long range Prediction for Fast fading Channels," Proceedings of the *33rd Annual Conference on Information Sciences and Systems (CISS'99*), March 1999, Volume II, pp.656-661.

[7] A. Duel-Hallen, S. Hu, H. Hallen, "Long-range Prediction of Fading Signals: Enabling Adaptive Transmission for Mobile Radio Channels", *IEEE Signal Processing Magazine,* Vol. 17, No.3, May 2000, pp.62-75.

[8] S. Hu, *Realizing the potential of Adaptive Transmission Techniques Through Long Range Prediction for Rapidly Time-Varying Fading Mobile Radio Channels,* Ph.D. thesis, North Carolina State University, Raleigh, June 2000.

[9] S. Hu, A. Duel-Hallen, H. Hallen, "Long Range Prediction Makes Adaptive Modulation Feasible for Realistic Mobile Radio Channels," *Proc. of 34rd Annual Conf. on Inform. Sciences and Systems CISS'2000*, March 2000, Volume I, pp.WP4-7 ~ WP4-13.

[10] D. L. Goeckel, "Adaptive Coding for Time-Varying Channels Using Outdated Fading Estimates, " *IEEE Trans. on. Communi*., Vol. 47, No. 6, pp. 844- 855, June 1999.

[11] T. Ue, S. Sampei, N. Morihiko, and K. Hamaguchi, "Symbol Rate and Modulation Level–Controlled Adaptive Modulation/TDMA/TDD System for High–Bit–Rate Wireless Data Transmission," *IEEE Trans. on Vehicular Techn.*, Vol. 47, No. 4, pp. 1134 – 1147, Nov. 1998.

[12] S. Hu, A. Duel-Hallen, H. Hallen, "Adaptive Modulation using Long Range Prediction for Fast Flat Fading Channels," Proc. of *IEEE Int. Symp. On Inform. Theory, ISIT'2000, p 159* .

[13] S. M. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications," *IEEE Journal on Select Areas in Communi.*, Vol. 16, No. 8, Oct. 1998, pp. 1451 – 1458.

[14] K. Rohani, M. Harrison, K. Kuchi, "A Comparison of Base Station Transmitter Diversity Methods for Third Generation Cellular Standards," *Proceedings of VTC*, 1999, Vol. 1, pp. 351-355.

[15] S. Hu, T. Eyceoz, A. Duel-Hallen, H. Hallen, "Transmitter Antenna Diversity and Adaptive Signaling Using Long Range Prediction For fast fading DS/CDMA Mobile radio Channels," *Proc. of IEEE Wireless Commun. and Networking Conf. WCNC'99*, Vol. 2, 1999, pp. 824 – 828.

[16] S. Guncavdi, A. Duel-Hallen, "A Space-Time Pre-RAKE Transmitter Diversity Method for W-CDMA Using Long Range Prediction," Proceedings of 35th Annual Conference on Information Sciences and Systems, *CISS'01*, March 2001.

[17] W.C. Jakes, *Microwave Mobile Communications*, IEEE Press, 1993

[18] H. Hallen, S. Hu, M. Lei, and A. Duel-Hallen, "A physical model for wireless channels to understand and test long range prediction of flat fading," *Proc. Of Wireless 2001*, Calgary, Alberta, Canada, July 9-11, 2001.

[19] S. Hu, A. Duel-Hallen, "Combined Adaptive Modulation and Transmitter Diversity Using Long Range Prediction for Flat Fading Mobile Radio Channels," Proceedings of IEEE Globecom'01, San Antonio, Texas, Nov. 25-29.