Adaptive Modulation and Coding on Multipath Rayleigh Fading Channels Based on Channel Prediction

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Abstract— **Due to the time variant characteristic of wireless communication channels, channel-state-information (CSI) becomes out-of-date if we consider the CSI feedback delay. Thus, channel prediction is required to mitigate this phenomenon. In this paper, we propose an adaptive modulation and coding (AMC) scheme using channel prediction on multipath Rayleigh fading channels and evaluate the performance of the proposed scheme. For a given modulation and coding set (MCS), the average packet error rates are derived as functions of the predicted channel information and the prediction error variance. Based on CSI's, the required transmit power is obtained for each MCS option. simulation results show that the performance degradation due to feedback delay can be compensated by the proposed scheme.**

1. INTRODUCTION

As demand on high speed wireless data communication increases, high spectral efficiency is essential in modern wireless communication systems. Performance degradation is, however, inevitable due to fading channels. Using adaptive transmission techniques, we can mitigate the performance degradation and even enlarge the spectral efficiency. In most of earlier researches on adaptive transmission, it is assumed that there is no delay in channel-state-information (CSI) feedback. Since feedback delay cannot be ignored in mobile communication systems, the system performance of the earlier researches will be seriously degraded if the feedback delay is introduced. In order to mitigate such a phenomenon, channel prediction schemes are used [1][2]. In [1], an adaptive modulation technique on flat Rayleigh fading channels was proposed. In [2], the bit error rate (BER) performance of a adaptive wireless communication system on flat Rayleigh fading channels that uses multiple receive antennas by using the correlation coefficient between the true channel value and the predicted value.

In this paper, we propose an adaptive modulation and coding scheme on multipath Rayleigh fading channels based on channel prediction. In the proposed system, channel is predicted at a mobile station (MS) and reported to a base station (BS), and using the conditional probability of the true channel value given at the predicted value, adaptive transmission is performed at a base station. The results show that performance was enhanced compared to that of direct channel inversion. The proposed scheme can be considered as an extension of [1] and [2] to the multipath environment. The conditional pdf of the true channel value at given the predicted channel value for the multipath environment is derived. The proposed system can adopt users with different channel predictor and different channel states by exploiting both short-term CSI and long-term CSI.

2. SYSTEM MODEL

In this paper, an AMC scheme on multipath Rayleigh fading channels based on channel prediction is proposed. The overall system model is as shown in Fig. 1. The operation flow of the proposed system is as follows. At an MS, channel is estimated for each path by using pilot symbols transmitted from the BS, and the estimated values are forwarded to the channel predictor. The channel predictor keeps the forwarded channel values in buffers, whose lengths are determined by implementation specifics, for each path. Using the buffered values, channel values after a predetermined time constant is predicted and the channel-state-information (CSI) generator calculates predicted signal-to-noise ratio (SNR) after the maximal-ratio combining. The predicted SNR, called a short-term CSI, is then reported to BS. Here, we assume that an MS reports the short-term CSI in every slot (or packet) interval. Since the true SNR value can be obtained later, the prediction error variance can also be calculated and this value is reported to the BS as a long-term CSI (i.e. the report period is much longer than that of the short-term CSI). The CSI generator also reports the number of paths so that the BS can support MS's with channel states. Here, we assume that there is no error in the feedback channels.

Since we assumed a Rayleigh fading channel, the real and imaginary parts of each path are zero-mean Gaussian random variables with equal variance. Also it is assumed that each path is independent. The received signal-to-noise ratio after maximal-ratio combining is

$$\gamma = \frac{(\sum_{l=0}^{L-1} |h_l|^2) P_T}{\sigma^2}, \tag{1}$$

where L is the number of paths, h_l is the complex channel value of the lth path, P_T is the transmission power, and σ^2 is the noise variance.

3. CHANNEL-STATE-INFORMATION (CSI)

The CSI is comprised of two categories: the short-term CSI and the long-term CSI. The short-term CSI is reported

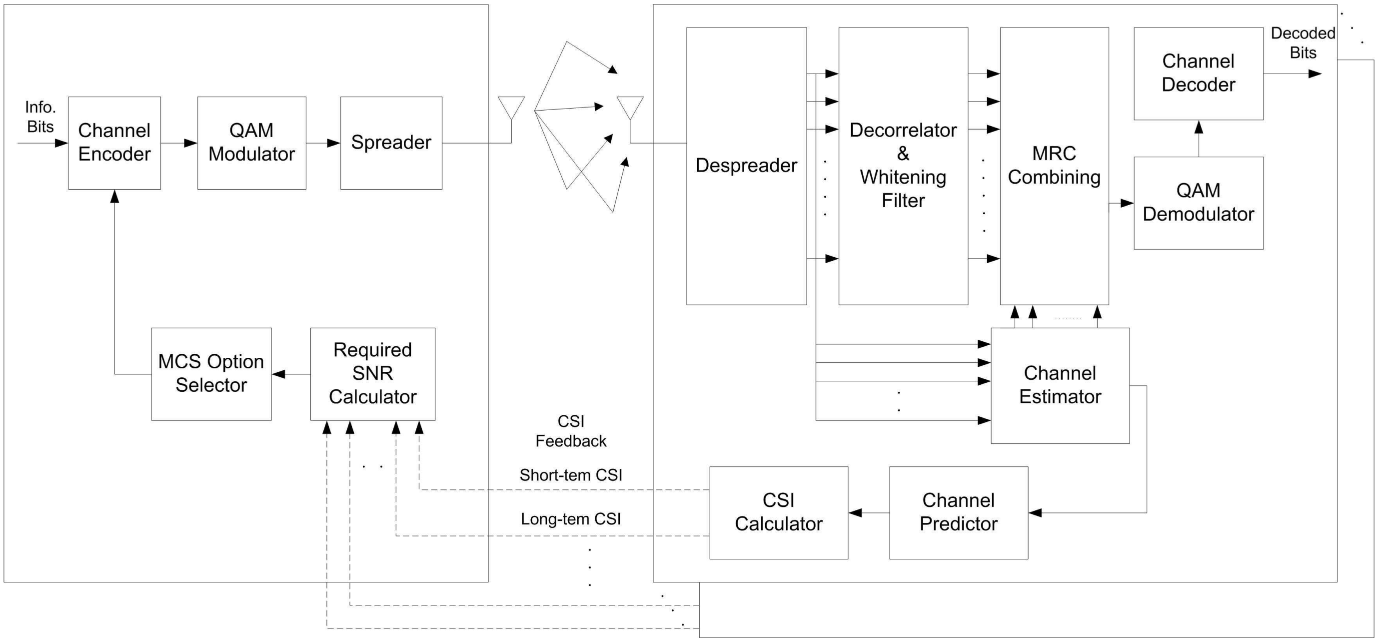

Fig. 1. System Model.

frequently so that the transmitter can track the fast Rayleigh fading channels and the long-term CSI is reported with much longer period since the statistical characteristic of the fading is slowly changed.

A. Short-Term CSI

The predicted SNR is reported from an MS to a BS as a short-term CSI. The prediction is done by exploiting present and past values of estimated channel values. First of all, we assume perfect channel estimation for simplicity. Let P_{pilot} be the pilot symbol power for each transmit antenna, then the estimated channel value of lth path is

$$\alpha_l = \sqrt{P_{pilot}}\, h_l. \tag{2}$$

For each channel path, a buffer is dedicated and the estimated values are stored. Here, we assume that the lengths of all buffers are equal to P, which implies the prediction order. In a linear predictor, the predicted value for the lth path is expressed as a linear combination of the present and the past values as

$$\hat{\alpha}_l[n+D] = \sum_{p=0}^{P-1} a_l[p]\alpha_l[n-p], \tag{3}$$

where n denotes the current time index, D is the amount of time the predictor looks ahead (i.e. prediction step), and $a_l[p]$, $0 \leq p \leq P-1$ is the prediction filter coefficients. It is known that the optimal linear predictor is the Wiener filter and the filter coefficients can be obtained by orthogonality principle [3] as

$$\mathbf{a}_l = \mathbf{R}_l^{-1}\mathbf{r}_l, \tag{4}$$

where $\mathbf{R}_l$ is the autocorrelation matrix of α_l, $\mathbf{a}_l = \left[a[0] \;\, a[1] \;\cdots\; a[P-1]\right]^T$ is the prediction filter coefficient vector, $\mathbf{r}_l = \left[R_l[D] \;\, R_l[D+1] \;\cdots\; R_l[D+P-1]\right]^T$ is the autocorrelation vector, and $R_l[k] = E\{\alpha_l[n]\alpha_l^*[n+k]\}$. In the sequel, we omit the time indices unless there is any ambiguity in expressions. Then, since the received signal is maximal-ratio combined, the overall predicted SNR is the sum of absolute square of all predicted values as

$$\tilde{\gamma} = \frac{\sum_{l=0}^{L-1} |\hat{\alpha}_l|^2}{\sigma^2}, \tag{5}$$

where σ^2 is the noise variance, in which the noise amplification due to the decorrelator is contained, is assumed to be perfectly estimated and we introduce the tilde since this predicted SNR is biased. The unbiased predictor is finally achieved by eliminating the bias as [1]

$$\hat{\gamma} = \tilde{\gamma} + E\{\gamma - \tilde{\gamma}\}. \tag{6}$$

B. Long-Term CSI

The long-term CSI contains two components: the number of paths, L, and the error variance of predicted SNR, $\sigma^2_{\epsilon,\hat{\gamma}}$. As will be discussed later, the number of paths is required for adaptive modulation and coding at the BS. The true SNR value corresponding to a predicted SNR can be obtained afterward. Therefore, we can calculate the error variance of the predicted SNR as

$$\sigma^2_{\epsilon,\hat{\gamma}} = E\{|\hat{\gamma} - \gamma|^2\}. \tag{7}$$

Note that there is no restriction on the prediction order. Thus, each MS can have its own predictor with different prediction order. Even the extreme case that the order is 1 (no prediction) is available. But the prediction step should be the same for all MS's.

4. ADAPTIVE MODULATION AND CODING (AMC)

The BS has modulation and coding set (MCS) in which each different modulation order and code rate are defined. By using the reported CSI of each MS, the BS determines the required transmit power of the MS that can meet the target error rate, which is predetermined, for each MCS option. Then, the adaptive loading scheme in [4] can be used for the active user and the corresponding MCS option selection. Let us consider this scheme in detail.

The packet error rate curve, which might be obtained by simulation for each MCS option, can be successfully approximated by an exponential function of the received SNR, γ, by curve fitting as

$$PER_i(\gamma) = \begin{cases} a_i \exp(-b_i\gamma) & \gamma \geq \gamma_{th,i}, \\ 1 & \gamma \leq \gamma_{th,i}, \end{cases} \tag{8}$$

where PER_i is the approximated packet error rate for ith MCS option when the SNR is γ, a_i and b_i are constants for ith MCS option determined by curve fitting, and $\gamma_{th,i}$ is the threshold value where the packet error rate becomes one as the SNR decreases. For a given predicted SNR, the true SNR value is distributed around the predicted value. Once the conditional probability distribution is determined, the average error probability, $PER_i(\hat{\gamma}, P_T)$, for each MCS option given the predicted SNR $\hat{\gamma}$ and the transmit power P_T can be obtained as

$$\begin{aligned} PER_i(\hat{\gamma}, P_T) &= E\{PER_i(\gamma)|\hat{\gamma}\} \\ &= \int_{-\infty}^{\infty} a_i \exp(-b_i \frac{\gamma P_T}{P_{pilot}}) f(\gamma|\hat{\gamma}) d\gamma, \end{aligned} \tag{9}$$

where $f(\gamma|\hat{\gamma})$ is the conditional probability of the true SNR value γ given the predicted SNR value $\hat{\gamma}$. Since each channel path h_l is assumed to be Gaussian distributed, α_l is also Gaussian distributed. Since $\hat{\alpha}_l$ is an output of the Wiener predictor, α_l can be expressed as

$$\alpha_l = \hat{\alpha}_l + \epsilon_l, \tag{10}$$

where ϵ_l is a zero-mean Gaussian random variable. The conditional distribution of α_l at a given $\hat{\alpha}_l$ is Gaussian with mean $\hat{\alpha}_l$ and variance $\sigma_\epsilon^2 \triangleq var\{\alpha_l|\hat{\alpha}_l\} = R_l[0] - \mathbf{a}_l^H \mathbf{r}_l$. Therefore the moment generating function of the maximal-ratio combined SNR at given the predicted value is given as

$$\Phi(s) = \prod_{l=0}^{L/2-1} \frac{\exp(-s\hat{\alpha_l^2}/(1+2s\sigma_{\epsilon,l}^2))}{1+2s\sigma_{\epsilon,l}^2}. \tag{11}$$

TABLE 1. MCS used in simulation

No.	Mod. Order	Code Rate	Data Rate (kbps)
0	No Tx	No Tx	0
1	QPSK	0.19	384
2	QPSK	0.36	768
3	QPSK	0.70	1536
4	16QAM	0.52	2304
5	16QAM	0.70	3072
6	16QAM	0.87	3840
7	64QAM	0.69	4224
8	64QAM	0.81	4992

By using this moment generating function, the conditional pdf of the true SNR at given the predicted SNR can be derived. Since the resulting formula is very complicated, however, we assume that the variance of each path, $\sigma_{\epsilon,l}^2$, is identical for all paths as $\sigma_\epsilon^2 = (1/L)\sum_{l=0}^{L-1} \sigma_{\epsilon,l}^2$ for simplification. Then the conditional pdf becomes as

$$\begin{aligned} f(\gamma|\hat{\gamma}) = {} & \frac{1}{\rho}\left(\frac{\gamma}{\hat{\gamma}-L\rho}\right)^{\frac{L-1}{2}} \\ & \cdot \exp\left(-\frac{\gamma+(\hat{\gamma}-L\rho)}{\rho}\right) I_{L-1}\left(\frac{2\sqrt{\gamma(\hat{\gamma}-L\rho)}}{\rho}\right), \end{aligned} \tag{12}$$

where $\rho = \sigma_\epsilon^2/\sigma^2$, $I_{L-1}(\cdot)$ is the modified Bessel function of order $L-1$. Substituting (12) into (9) and calculating the integral, we get the average packet error rate of the ith MCS option as a function of transmit power, P_T, and the CSI vector $\mathbf{c} = [c_L \ c_S], \ c_L = (\sigma_{\epsilon,\hat{\gamma}}^2, L), \ c_S = \hat{\gamma}$ as

$$\begin{aligned} PER_i(P_T, \mathbf{c}) = {} & \left[1 - Q_L\left(\sqrt{2\hat{\gamma}\rho - L}, \sqrt{2\frac{\gamma_{th,i}}{L\rho}}\right)\right] \\ & + a_i \left(\frac{1}{1+b_i\rho\Delta P_T}\right)^L e^{\left(-\frac{b_i\Delta P_T(\hat{\gamma}-L\rho)}{1+b_i\rho\Delta P_T}\right)} \\ & \cdot Q_L\left(\sqrt{2\frac{\frac{\hat{\gamma}}{\rho\Delta P_T}-L}{1+b_i\rho\Delta P_T}}, \sqrt{\frac{2\gamma_{th,i}(1+b_i\rho\Delta P_T)}{\rho}}\right), \end{aligned} \tag{13}$$

where $\Delta P_T = P_T/P_{pilot}$ and $Q_L(\cdot)$ is the generalized Q-function [5]. Here, $\rho = \sigma_\epsilon^2/\sigma^2$ can be obtained from the CSI as

$$\rho = \frac{\sigma_\epsilon^2}{\sigma^2} = \frac{\hat{\gamma} - \sqrt{\hat{\gamma}^2 - L\sigma_{\epsilon,\hat{\gamma}}^2}}{L}. \tag{14}$$

Using the reported CSI and the target error rate, the required transmit power of the ith MCS option at a given CSI vector $\mathbf{c}$ can be calculated inversely from (13). Since $PER_i(P_T, \mathbf{c})$ is a monotonically decreasing function of P_T, a simple binary search with proper initial condition or a table lookup method can be used.

5. SIMULATION RESULTS

In the following simulation, we used MCS shown in Table 1. First, packet-error rate of each MCS option is obtained by computer simulation and is approximated to the exponential function. It is seen from Fig. 2 that the exponential approximation is successful.

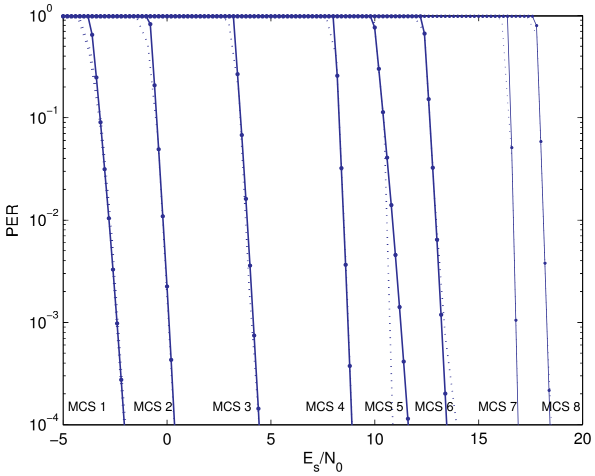

Fig. 2. PER approximation. Solid lines and dotted lines denote the original PER and its approximation using (8), respectively.

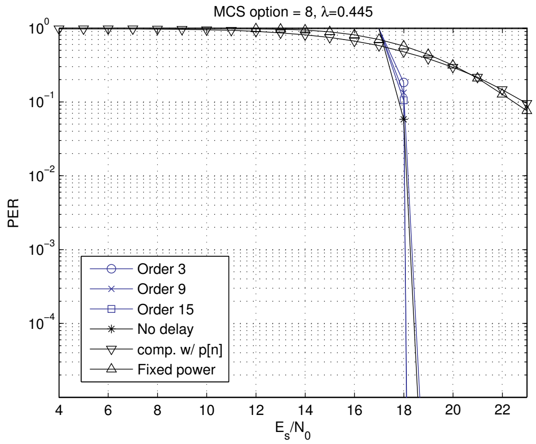

Fig. 3. PER performance in 6-path equal-gain channel.

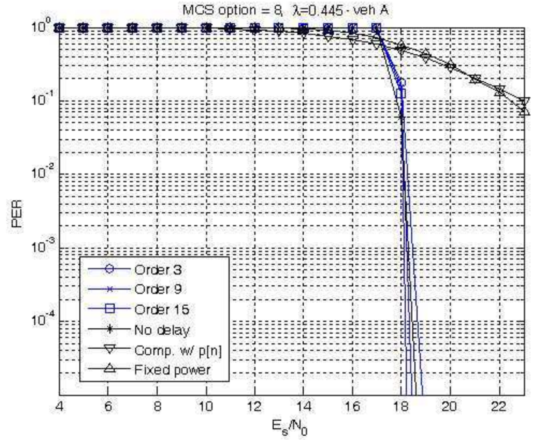

Fig. 4. PER performance in ITU-R vehicular A channel.

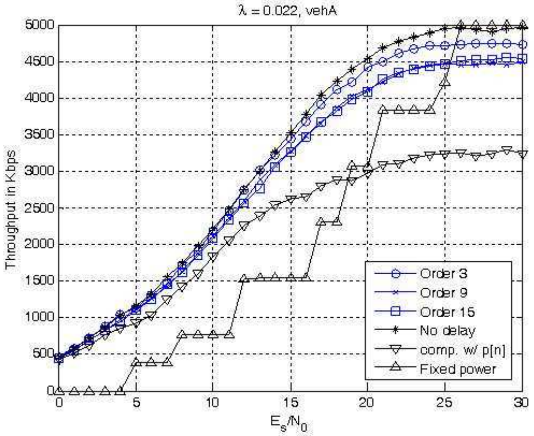

Fig. 5. Throughput performance when $\lambda = 0.022$.

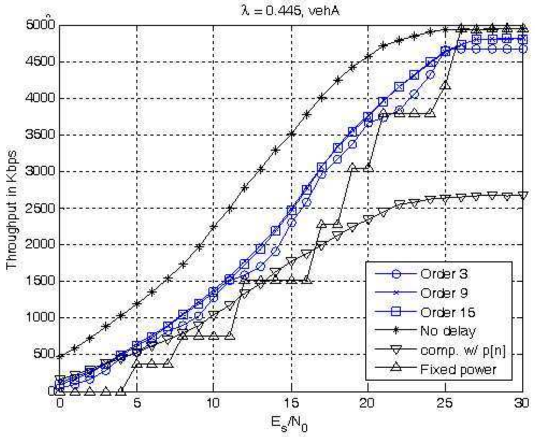

Fig. 6. Throughput performance when $\lambda = 0.445$.

A. PER performance

Since we adjust the transmit power of each MS to meet the target PER, the average PER performance should be the same as that in AWGN channel (i.e., non-fading channel). Fig. 3 shows the PER performance for the 8th MCS option when the variance of each path $\sigma^2_{\epsilon,l}$ is identical for all paths as we assumed and $\lambda = 0.445$, where λ is the maximum Doppler frequency multiplied by the prediction interval. The 8th MCS option is selected because this option has the highest data rate and thus is most sensitive to fading. The required transmit power is determined by using the long-term and the short-term CSI's and the PER obtained by transmitting with the determined power (the lines with a circle, x, and a rectangle mark) is almost same to the PER in AWGN channel (the line with asterisk mark). Thus, it can be seen that the proposed scheme works as intended.

Also in Fig. 4 which shows the PER performance of the 8th MCS option on ITU-R vehicular A channel (i.e., the channel model is different from the assumption), it can be seen that the proposed scheme has nearly no performance degradation.

B. Throughput performance

Using the reported CSI, the required transmit power for each MCS option is calculated. Among the MCS options whose required transmit power is available, one with the maximum data rate is chosen. Figs. 5-6 show the throughput performance of the proposed system for single-user case when λ is 0.022 and 0.445, respectively. Here, 'No delay', 'Fixed power', and 'Delay' denote the case of perfect prediction (i.e. there is no delay in feedback), the case of fixed power AMC, and the case of using the D-step outdated CSI, respectively. For the fixed transmit power case, the required transmit power for each MCS option to meet the target PER in the fading channel is pre-calculated and used. The performance of the proposed scheme is also shown when the prediction order is 3, 9, and 15. It is seen that the performance of the proposed system lies between the perfect prediction case and the fixed-power case and is much better than the system using outdated CSI. When the mobility of the MS is low, the performance is near the 'No delay' case. As the mobility increases, the performance of the proposed system approaches the fixed-power case. Also the performance is improved as the prediction order is increased.

6. CONCLUSION

In this paper, an adaptive modulation and coding scheme on downlink multipath Rayleigh fading channels based on channel prediction. The proposed scheme adaptively allocates transmit power by using both short-term and long-term CSI's. It was seen that the throughput performance lies between that of the no-delay case and the fixed-power AMC case. The throughput performance degrades as the prediction order decreases or the mobility of MS increases. Also, it was seen that the proposed method gives good performance when the channel model is different from the assumption on the channel. A detailed evaluation of the performance in multiuser environment will be performed.

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