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Signal Processing 88 (2008) 2095–2107

SIGNAL PROCESSING

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Multiuser adaptive transmission technique for time-varying frequency-selective fading channels

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Received 8 August 2007; received in revised form 21 February 2008; accepted 24 February 2008
Available online 4 March 2008

Abstract

This paper proposes an efficient multiuser adaptive modulation and coding (AMC) scheme that considers inevitable feedback delay by employing short-term and long-term channel state information (CSI) in time-varying frequency-selective fading channels. By taking the statistic of the true signal-to-noise ratio (SNR) at a given predicted SNR value into account, the required transmit power to meet the target packet-error-rate (PER) can be obtained and used for user selection, power allocation, and modulation and coding set (MCS) selection. In addition, a simple and useful approximation method of obtaining the required transmit power is proposed. The performance of the proposed scheme is shown to be much better than that of conventional schemes without considering the feedback delay or the prediction error. The proposed scheme can also reduce the feedback resource while maintaining the system throughput by allocating different feedback resources to different users according to their prediction error variances.

Keywords: Multiuser AMC; Channel prediction; MIMO

1. Introduction

To exploit the time-varying property of wireless channels, various adaptive transmission techniques have been widely investigated. In [1], a variable-rate variable-power M-QAM system was proposed and it was shown that the proposed adaptive transmission with a restricted set of constellations gives a spectral efficiency within 1 dB of the efficiency without the restriction. However, it did not consider the inevitable feedback delay (the time delay between the channel measurement and the actual transmission) and the performance could be degraded with the presence of mobility. To mitigate the feedback delay problem, an adaptive transmission technique that considers the statistical characteristic of the current channel at a given outdated fading estimate was proposed in [2], and it was shown that the feedback delay problem could be alleviated. On the other hand, a channel prediction scheme was employed in [3–5] for an adaptive modulation using outdated channel estimates to overcome the feedback delay problem, and it was shown that a prediction-aided adaptive transmission can perform well in a moderate mobile speed range. However, the prediction error was not considered in [3–5] and it can seriously degrade the performance of an adaptive transmission with a

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0165-1684/$ - see front matter
doi:10.1016/j.sigpro.2008.02.014

channel prediction scheme as the mobile speed increases. To remedy this, prediction-based adaptive transmission techniques were proposed by considering the statistic of the prediction error in [6,7] and it was shown that the performance degradation due to the prediction error can be significantly mitigated. Although the prediction-based adaptive transmission techniques provide efficient solutions for adaptive transmission in time-varying fading channels, the results were restricted to a point-to-point communication in a flat fading channel and have not been generalized either to multiuser or to frequency-selective fading environments. In this paper, a multiuser adaptive modulation and coding (AMC) scheme with power allocation is proposed in frequency-selective fading channels with multiple antenna diversity such as in [8,9]. The initial results of this work were presented in [10], and an efficient method of obtaining the required transmit power in the proposed multiuser AMC scheme, which is very useful for practical implementation, is also proposed in this paper. Furthermore, a scheme for adaptively allocating the feedback resource is proposed to reduce the feedback resource while maintaining the system performance. This paper can be considered an extension of [6,7] to multiuser and multipath environments with multiple antenna diversity. The remaining part of this paper is constructed as follows. In Section 2, the system model considered in this paper is shown. In Section 3, the proposed multiuser adaptive transmission scheme with power allocation and the proposed adaptive feedback resource allocation scheme are presented. The performance of each proposed scheme is evaluated using computer simulation in Section 4, and a concluding remarks are given in Section 5.

2. System model

In this paper, the downlink of a frequency division duplexing (FDD) cellular system is considered. The physical layer frame structure considered in this paper is as follows: there are a number of time slots in a frame and each time slot is composed of a number of sub-channels that are orthogonal to each other. It is assumed that the channel quality of all the sub-channels in a time slot are the same and mainly determined from the maximal-ratio combined signal-to-noise ratio (SNR) of each signal path. The overall system structure is shown in Fig. 1. At the receiver, the channel gain of each signal path is estimated using pilot symbols for demodulation at the MRC combiner. The received pilot symbols are also used to predict the channel at the channel predictor after pilot pattern compensation. Here, each receiver can employ a predictor with a different order (even without any predictor). The CSI calculator calculates the predicted SNR after the maximal-ratio combining and reports it as short-term CSI in every time slot. Since the predicted SNR is not sufficient for power control to meet the target packet-error-rate (PER), its statistic is parameterized and reported as well.

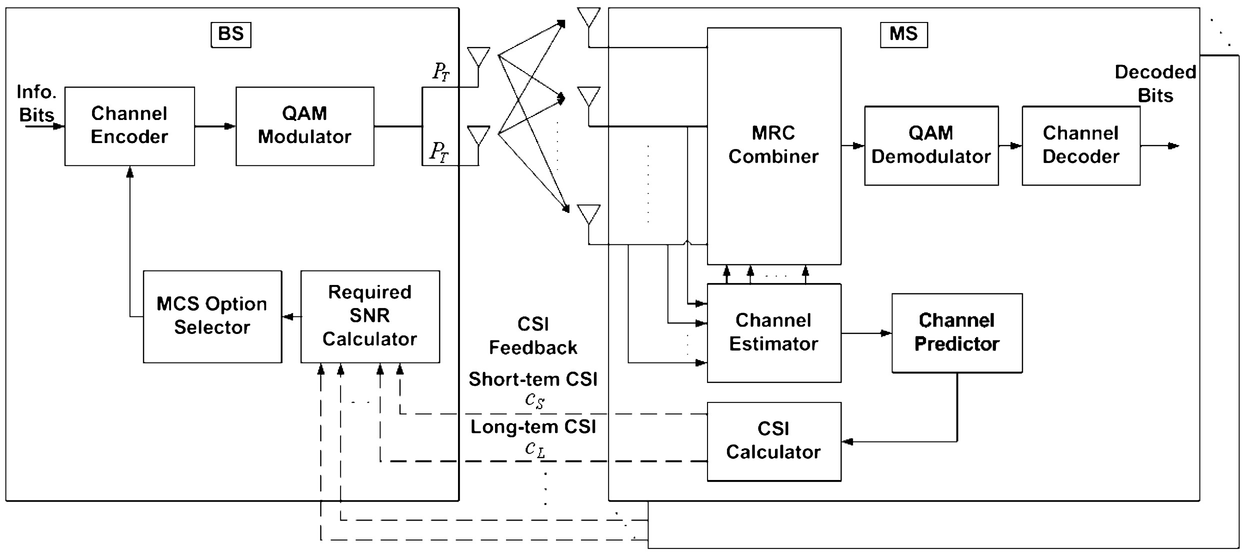

Fig. 1. The system model.

Here, the average prediction-error-to-noise-power-ratio (PENR) and the total number of signal paths are reported as long-term CSI with a much longer feedback period than the short-term CSI (typically, hundreds to thousands of times longer). With the two CSIs, the transmitter selects active users with corresponding modulation and coding sets (MCSs) and transmit powers. The information bits of each selected user are then encoded and modulated according to the selected MCS of the user and transmitted with the determined transmit power of the user. As depicted in Fig. 1, an MIMO antenna environment can be adopted in which each channel between a transmit antenna and a receive antenna is a frequency-selective Rayleigh fading channel (i.e., the channel gain of each path is independent complex Gaussian). In this paper, the full-diversity space–time codes such as in [8,9,13] are considered, the performance of which is determined by the maximally combined SNR, as mentioned earlier. It is straightforward to extend the results of this paper, however, to a general transmit diversity scheme as long as the performance is determined by the combined SNR.

As mentioned earlier, orthogonal sub-channels with identical channel qualities, determined by maximal-ratio combined SNR, were assumed in a time slot. This assumption can be directly applied to an orthogonal frequency division multiple access (OFDMA) system with well-interleaved sub-channels (as in [11]). Note that the quality of one sub-channel is almost identical with that of the others and determined by the average SNR over all the sub-carriers, which is the same as the maximal-ratio combined SNR of each signal path according to Parseval's theorem. A code division multiple access (CDMA) system employed with a decorrelator followed by the maximal-ratio combiner can be another example. In this case, the effective SNR of each signal path is given by the eigenvalues of the channel covariance matrix multiplied by a matrix related to the noise whitening filter. Then the performance is determined by the maximal-ratio combined SNR of the effective SNR of each signal path [12].

3. Adaptive transmission scheme

3.1. Channel-state-information

Let P_{pi} be the pilot symbol power for each transmit antenna. The channel estimate for the kth path is thus $\alpha_k = h_k\sqrt{P_{\mathrm{pi}}}$, where h_k is the complex channel gain of the kth path. Here, it is assumed that we can obtain a noiseless observation of α_k for simplicity. Then, the predicted SNR, $\tilde{\gamma}$, is given by

$$\tilde{\gamma} = \frac{\sum_{k=1}^{K}|\hat{\alpha}_k|^2}{\sigma_w^2}, \tag{1}$$

where K is the total number of signal paths, $\hat{\alpha}_k$ is the predicted value of α_k using the Wiener predictor [14], and σ_w^2 is the variance of the background complex additive white Gaussian noise (AWGN). If it is assumed that the number of multipaths is the same for all antenna pairs, K is given as MNq, where M is the number of transmit antennas, N is the number of receive antennas, and q is the number of multipaths for each antenna pair. Finally, by eliminating the bias as in [15], the unbiased predicted SNR, $\hat{\gamma}$, is given by

$$\begin{aligned}\hat{\gamma} &= \tilde{\gamma} + E\{\gamma - \tilde{\gamma}\} \\ &= \tilde{\gamma} + E\left\{\frac{\sum_{k=1}^{K}|\alpha_k - \hat{\alpha}_k|^2}{\sigma_w^2}\right\}.\end{aligned} \tag{2}$$

The long-term CSI has two components: the number of signal paths, K, and the average PENR, ρ, given as

$$\begin{aligned}\rho &= \frac{\sum_{k=1}^{K}E\{|\alpha_k - \hat{\alpha}_k|^2\}}{K\sigma_w^2} \\ &= \frac{\sum_{k=1}^{K}E\{|\varepsilon_k|^2\}}{K\sigma_w^2}.\end{aligned} \tag{3}$$

Since the true SNR can be obtained afterwards and the channel is assumed to be ergodic, the bias and the PENR can be easily calculated by time-averaging $\gamma - \tilde{\gamma}$ and $\sum_{k=1}^{K}|\alpha_k - \hat{\alpha}_k|^2$ at each mobile station, respectively. In summary, the CSI vector, $\mathbf{c}$, is defined as

$$\mathbf{c} = [c_{\mathrm{L}}\ c_{\mathrm{S}}], \tag{4}$$

where $c_{\mathrm{L}} = (\rho, K)$ is the long-term CSI and $c_{\mathrm{S}} = \hat{\gamma}$ is the short-term CSI.

3.2. Calculation of the required transmit power

Using the reported CSI of each user, the transmitter determines the required transmit power that can meet the predetermined target PER for each MCS option. Then, the adaptive power allocation scheme in [16] can be adopted for the selection of active users and the determination of the corresponding MCS option with power allocation. The PER curve of the ith MCS option in an AWGN channel, $\mathrm{Pr}_{e,i}(\gamma)$, which can be obtained using computer simulation, can be successfully approximated as in [4]:

$$\mathrm{Pr}_{e,i}(\gamma) = \begin{cases} a_i \exp(-b_i\gamma), & \gamma \geqslant \gamma_i, \\ 1, & \gamma < \gamma_i, \end{cases} \tag{5}$$

where a_i, b_i, and γ_i are constants for the ith MCS option determined through curve fitting. Once the conditional distribution of the true SNR at a given predicted SNR is determined, the average PER of the ith MCS option, $\overline{\mathrm{Pr}}_{e,i}(P_{\mathrm{T}}, \mathbf{c})$, at a given CSI $\mathbf{c}$, and the transmit power P_{T} (for each transmit antenna), can be obtained similarly to [7], as follows:

$$\overline{\mathrm{Pr}}_{e,i}(P_{\mathrm{T}}, \mathbf{c}) = \int_0^{\infty} \mathrm{Pr}_{e,i}\left(\frac{\gamma P_{\mathrm{T}}}{P_{\mathrm{pi}}}\right) f(\gamma|\mathbf{c})\, \mathrm{d}\gamma, \tag{6}$$

where $f(\gamma|\mathbf{c})$ is the conditional pdf of the true SNR value γ at the given predicted SNR value $\hat{\gamma}$ and the long-term CSI $c_{\mathrm{L}} = (\rho, K)$. The conditional distribution of α_k at the given $\hat{\alpha}_k$ is Gaussian with a mean $\hat{\alpha}_k$ and a variance $\sigma_\varepsilon^2 \triangleq \mathrm{var}\{\alpha_k|\hat{\alpha}_k\}$. Here, it is assumed that $\{\alpha_k\}_{k=1}^K$ is independent and identically distributed (i.i.d.) for simplicity. Then, the maximal-ratio combined SNR becomes a non-central χ^2 random variable, and its conditional pdf is given as in [17]:

$$f(\gamma|\mathbf{c}) = \frac{1}{\rho}\left(\frac{\gamma}{v}\right)^{(K-1)/2} \exp\left(-\frac{\gamma + v}{\rho}\right) I_{K-1}\left(\frac{2\sqrt{\gamma v}}{\rho}\right), \tag{7}$$

where the PENR $\rho = \sigma_\varepsilon^2/\sigma_w^2$ due to the i.i.d. assumption, $v = \hat{\gamma} - K\rho$, and $I_K(\cdot)$ is the Kth order modified Bessel function. Substituting (7) into (6), the average PER of the ith MCS option is obtained as follows:

$$\begin{aligned} \overline{\mathrm{Pr}}_{e,i}(P_{\mathrm{T}}, \mathbf{c}) &= \int_0^{\infty} \mathrm{Pr}_{e,i}\left(\frac{\gamma P_{\mathrm{T}}}{P_{\mathrm{pi}}}\right) f(\gamma|\mathbf{c})\, \mathrm{d}\gamma \\ &= \int_0^{\gamma_i} f(\gamma|\mathbf{c})\, \mathrm{d}\gamma + \int_{\gamma_i}^{\infty} \mathrm{Pr}_{e,i}\left(\frac{\gamma P_{\mathrm{T}}}{P_{\mathrm{pi}}}\right) f(\gamma|\mathbf{c})\, \mathrm{d}\gamma \\ &= \mathscr{I}_1 + \mathscr{I}_2. \end{aligned} \tag{8}$$

In (8), $\mathscr{I}_1$ is just a cumulative distribution function (cdf) value of a non-central χ^2 random variable, given in [17] as

$$\mathscr{I}_1 = 1 - Q_K\left(\sqrt{\frac{2v}{\rho}}, \sqrt{\frac{2\gamma_i}{\rho K}}\right), \tag{9}$$

where $Q_K(\cdot)$ is the generalized Q-function [17]. Also, $\mathscr{I}_2$ can be rewritten as

$$\begin{aligned} \mathscr{I}_2 &= a_i \int_{\gamma_i}^{\infty} \frac{1}{\rho}\left(\frac{\gamma}{v}\right)^{(K-1)/2} \mathrm{e}^{-(A\gamma+v)/\rho} I_{K-1}\left(\frac{2}{\rho}\sqrt{\gamma v}\right) \mathrm{d}\gamma \\ &= \frac{a_i}{A^K} \mathrm{e}^{-b_i \Delta P_{\mathrm{T}} v/A} \int_{A\gamma_i}^{\infty} \frac{1}{\rho}\left(\frac{A\gamma'}{v}\right)^{(K-1)/2} \\ &\quad \times \mathrm{e}^{-(\gamma' + v/A)/\rho} I_{K-1}\left(\frac{2}{\rho}\sqrt{\frac{\gamma' v}{A}}\right) \mathrm{d}\gamma' \\ &= \frac{a_i}{A^K} \mathrm{e}^{-b_i \Delta P_{\mathrm{T}} v/A} Q_K\left(\sqrt{\frac{2}{A}\left(\frac{\hat{\gamma} - \rho K}{\Delta P_{\mathrm{T}} \rho}\right)}, \sqrt{\frac{2\gamma_i A}{\rho}}\right), \end{aligned} \tag{10}$$

where $\Delta P_{\mathrm{T}} = P_{\mathrm{T}}/P_{\mathrm{pi}}$, $A = 1 + b_i\rho\Delta P_{\mathrm{T}}$, and $\gamma' = (1 + b_i\rho\Delta P_{\mathrm{T}})\gamma$. Finally, the required transmit power for the ith MCS option at a given CSI vector $\mathbf{c}$ and the target PER, P_{target}, from $\overline{\mathrm{Pr}}_{e,i}(P_{\mathrm{T}}, \mathbf{c}) = P_{\mathrm{target}}$ are obtained, where

$$\begin{aligned} &\overline{\mathrm{Pr}}_{e,i}(P_{\mathrm{T}}, \mathbf{c}) \\ &\quad = 1 - Q_K\left(\sqrt{\frac{2v}{\rho}}, \sqrt{\frac{2\gamma_i}{\rho K}}\right) \\ &\qquad + \frac{a_i}{A^K} \mathrm{e}^{-b_i \Delta P_{\mathrm{T}} v/A} Q_K\left(\sqrt{\frac{2}{A}\left(\frac{\hat{\gamma} - \rho K}{\Delta P_{\mathrm{T}} \rho}\right)}, \sqrt{\frac{2\gamma_i A}{\rho}}\right). \end{aligned} \tag{11}$$

Note that the required transmit power calculated from (11) can be quite large. In a point-to-point communication system with only power control, a truncated power control, such as in [1], should be applied so as not to waste power. However, the proposed system is a multiuser system that employs AMC and the AMC algorithm (shown in Section 3.4) determines the actual user selection and power allocation. Thus, such a power-wasting problem does not exist.

In this sub-section, two assumptions were made, the noiseless observation of pilot symbols and the i.i.d. channels, which can be considered impractical assumptions. It will be shown later in Section 4, however, by simulation, that the results of the i.i.d. channel assumption work well in practical channels such as the ITU-R channel models. Also, the effect of a noisy pilot does not abruptly cause the deterioration of the proposed scheme. In this case, the prediction is performed with the noisy observation $\tilde{\alpha}_k = \alpha_k + n_k$, where n_k is the background

AWGN with variance σ_w^2. Then the PENR increases because the prediction filter output contains two independent error terms: the prediction error in the noiseless case and the error term due to the background noise. Since a larger PENR implies a less accurate prediction, the required transmit power would be overestimated, which would lead to the waste of transmission power. Thus, the performance would be degraded. Such performance degradation would not be abrupt, however, since the effect is similar to the effect of increased mobile speed (the impact of the effect increases as SNR decreases), which will be confirmed later in Section 4 from the simulation results.

3.3. Efficient calculation method for the required transmit power

Since (11) is a monotonically decreasing function of P_T, the required transmit power, P_T, can be obtained using the binary search algorithm (within several iterations with appropriate initial value and search range) using (11). However, a much simpler calculation method is required in practice since the evaluation of (11) requires the calculation of the generalized Q function, which is not appropriate for a real-time operation at each reporting time of the short-term CSI. Thus, an efficient method of calculating the required transmit power is proposed. To develop this efficient calculation method, it was first observed that the predicted SNR, $\hat{\gamma} = \tilde{\gamma} + E\{\gamma - \tilde{\gamma}\}$, is composed of the predicted term $\tilde{\gamma}$ and the bias $E\{\gamma - \tilde{\gamma}\}$. Then the two extreme cases are considered: (i) the very low mobility case: the prediction is almost perfect so that $\rho \approx 0$ and the bias is almost zero (i.e., $\varepsilon_k \approx 0$ for all k in (3)) and (ii) the very high mobility case: $\tilde{\gamma} \approx 0$ (i.e., $\hat{\alpha}_k \approx 0$ for all k) so that $\hat{\gamma} \approx E\{\gamma\}$ and $\rho \approx \sum_{k=1}^{K} E\{|\alpha_k|^2\}/K\sigma_w^2 = E\{\gamma\}/K$. Note that the instantaneous received SNR determines the performance in the former case, whereas the average received SNR determines the performance in the latter case. However, the required transmit power is determined through simple channel inversion, since the predicted SNR, $\hat{\gamma}$, is the instantaneous SNR in the former case and the average SNR in the latter case. The required transmit power for the MCS option 8, which has the highest rate, is shown as a function of the predicted SNR for the two extreme cases in Fig. 2, wherein the almost linear relationship between P_T and $\hat{\gamma}$ in the dB scale can be confirmed. For the range of ρ between the two extreme cases,

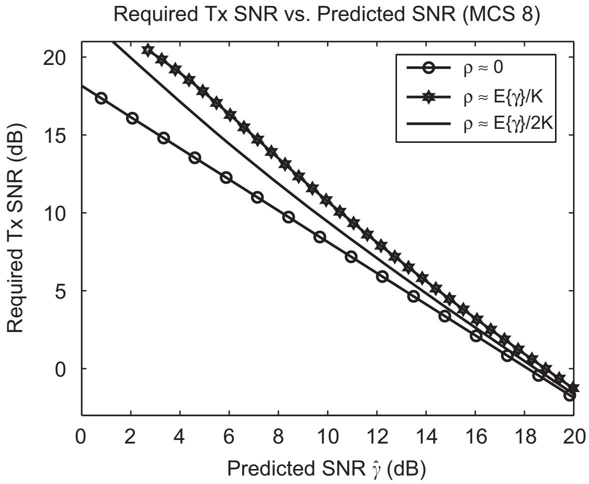

Fig. 2. The required transmit power for various values of ρ.

the linear relationship does not hold, as shown in Fig. 2. A linear approximation is expected to be a good solution, though. A linear approximation method of calculating the required transmit power is proposed as follows. For an appropriate range of K and quantized values of ρ, the two points, $(\hat{\gamma}_1(\mathbf{c}_L), P_{T,1}(\mathbf{c}_L))$ and $(\hat{\gamma}_2(\mathbf{c}_L), P_{T,2}(\mathbf{c}_L))$, $(\hat{\gamma}_1(\mathbf{c}_L) < \hat{\gamma}_2(\mathbf{c}_L))$, are obtained from (11) using the binary search algorithm. From the two points, the transmit power $P_T(\hat{\gamma}, \mathbf{c}_L)$ as a function of the CSI vector can be linearly approximated as

$$P_T(\hat{\gamma}, \mathbf{c}_L) \cong m_i(\mathbf{c}_L)\hat{\gamma} + n_i(\mathbf{c}_L) \text{ (dB)}, \tag{12}$$

where i is the MCS option index

$$m_i(\mathbf{c}_L) \triangleq \frac{\hat{\gamma}_2(\mathbf{c}_L) - \hat{\gamma}_1(\mathbf{c}_L)}{P_{T,2}(\mathbf{c}_L) - P_{T,1}(\mathbf{c}_L)} \tag{13}$$

and

$$n_i(\mathbf{c}_L) \triangleq -m_i(\mathbf{c}_L)P_{T,1}(\mathbf{c}_L) + \hat{\gamma}_1(\mathbf{c}_L). \tag{14}$$

Here, $\hat{\gamma}_1(\mathbf{c}_L)$ and $\hat{\gamma}_2(\mathbf{c}_L)$ can be selected arbitrarily. The approximation error depends on the selection. Although $\hat{\gamma}$ is distributed over $(K\rho, \infty)$, it occurs with a very low probability that $\hat{\gamma}$ is near $K\rho$ or is very large. Also, in a practical system, the selection can be quite straightforward since the short-term feedback is quantized. In this case, $\hat{\gamma}_1(\mathbf{c}_L)$ and $\hat{\gamma}_2(\mathbf{c}_L)$ may be set to the smallest quantized level exceeding $K\rho$ and to the maximum quantized level, respectively. Note that $m_i(\mathbf{c}_L)$ and $n_i(\mathbf{c}_L)$ depend only on the long-term CSI and the required transmit power can be calculated simply using (12) at each change of the short-term CSI, $\hat{\gamma}$. There are two possible ways to implement the proposed method: (i) for a possible range of K and appropriately quantized values of ρ, $m_i(\mathbf{c}_L)$ and $n_i(\mathbf{c}_L)$ are predetermined and tabulated in a base-station and (ii) $m_i(\mathbf{c}_L)$ and $n_i(\mathbf{c}_L)$ are calculated for each user when the long-term CSI of the user changes. For the first method, the size of the table is the number of MCS options multiplied by the number of possible values of K and ρ, which is not quite a burden for a practical implementation. For the second method, since the long-term CSI varies quite slowly, a real-time calculation of $m_i(\mathbf{c}_L)$ and $n_i(\mathbf{c}_L)$ can be easily implemented.

Fig. 3 shows the error of the linear approximation (the difference between the exact required transmit power obtained using (11) and the approximated transmit power obtained using (12)) when $K = 6$. Since the required transmit power is determined using the three parameters of the CSI, the error is shown as a function of the two remaining parameters ($\hat{\gamma}$ and ρ). From the results, it can be seen that the maximum error does not exceed 0.2 dB, which is much less than a reasonable resolution of power quantization in practical systems. Although the error becomes negative when $K\rho$ is quite close to $E\{\gamma\}$, which means the required power is underestimated, it does not cause a serious problem, since the probability density of $\hat{\gamma}$ approaches a delta function, $\delta(\hat{\gamma} - K\rho)$.

3.4. Adaptive modulation and coding

Let I, J, S, and P_A denote the number of MCS options, the number of users, the number of sub-channels in a time slot, and the total power available at the transmitter for data channels, respectively. Each user reports its CSI, $\mathbf{c}_j = [c_{L,j}, c_{S,j}]$, where j denotes the user index. Here, $c_{L,j} = (\rho_j, K_j)$ is the long-term CSI, and $c_{S,j} = \hat{\gamma}_j$ is the short-term CSI, where $\hat{\gamma}_j$, ρ_j, and K_j are the predicted SNR, the average PENR, and the total number of signal paths of the jth user, respectively. Using the reported CSIs, the required transmit power of each MCS option for the jth user is obtained using (11) or (12). Once the required transmit power of each user for each MCS option is determined, the user selection and power allocation algorithm proposed in [16], which can be considered as a sub-optimal maximum throughput scheduler, is used. Initially, an equally divided power, $P_S = P_A/S$, is allocated to each sub-channel. Then, the highest available MCS option for each user is determined as in [16]:

$$i(j) = \arg\max_i r(i) \quad \text{subject to } P_T(i,j) \leqslant P_A/S, \quad (15)$$

where $i(j)$ is the selected MCS option for the jth user and $r(i)$ is the data rate of the ith MCS option. Then, the active user set $\{j^*(s)|s = 1, \ldots, S\}$ is selected in the descending order of the corresponding

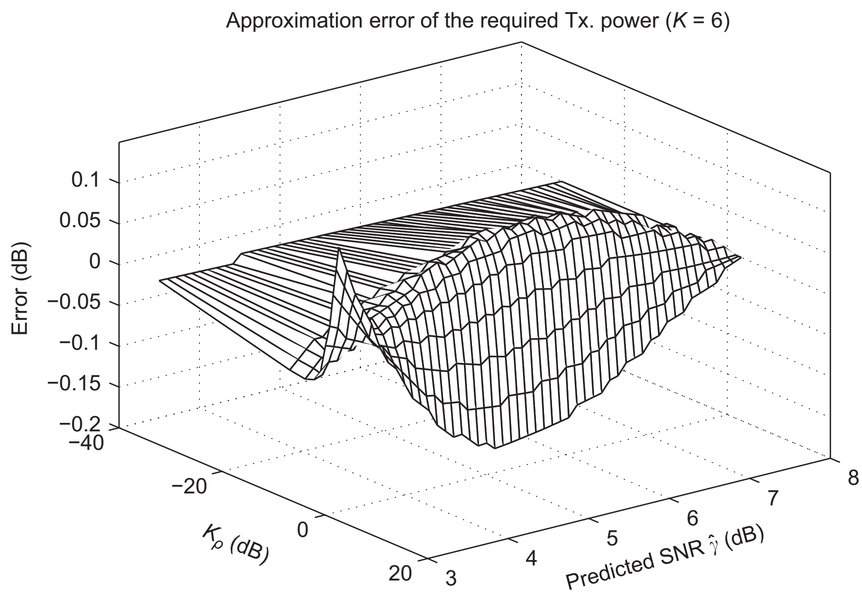

Fig. 3. Approximation error in the required transmit power.

MCS option index (i.e., the descending order of the corresponding data rate). After the initial allocation, further modification is performed iteratively, wherein in each iteration, the allocation is modified when the throughput can be increased with the additional power that is less than the remaining power or when the remaining power can be increased without loss of the throughput [16].

3.5. Feedback resource allocation strategy

As the mobility increases, the predicted SNR (before the bias elimination), $\tilde{\gamma}$, approaches zero, since the input to the predictor becomes almost a white noise process. Also, $K\rho$ approaches the average received SNR, $E\{\gamma\}$, as discussed earlier. Then, the conditional pdf in (7) becomes a central χ^2 pdf, given as

$$f(\gamma|\mathbf{c}) = f(\gamma|\mathbf{c}_\mathrm{L}) = \frac{\gamma^{K-1}\mathrm{e}^{-\gamma/\rho}}{(K-1)!\rho}. \tag{16}$$

The performance of the proposed scheme approaches that of the conventional fixed power transmission scheme based only on the long-term CSI (denoted as 'fixed power'), which will be confirmed in Section 4. Note that the conventional fixed power transmission scheme needs only the long-term CSI, $\mathbf{c}_\mathrm{L} = (\rho, K)$, and the required transmit power for each MCS option is determined from

$$\begin{aligned}\overline{\mathrm{Pr}}_{e,i}(P_\mathrm{T}, \mathbf{c}_\mathrm{L}) &= \int_0^{\gamma_i} f(\gamma|\mathbf{c}_\mathrm{L})\,\mathrm{d}\gamma + \int_{\gamma_i}^{\infty} \mathrm{Pr}_{e,i}(\gamma) f(\gamma|\mathbf{c}_\mathrm{L})\,\mathrm{d}\gamma \\ &= \left[1 - \mathrm{e}^{\gamma_i/K\rho\Delta P_\mathrm{T}} \sum_{k=0}^{K-1} \frac{1}{K}\left(\frac{\gamma_i}{K\rho\Delta P_\mathrm{T}}\right)^k\right] \\ &\quad + a_i \left(\frac{1}{1+A'}\right)^k \mathrm{e}^{\gamma_i A'/K\rho\Delta P_\mathrm{T}} \sum_{k=0}^{K-1} \frac{1}{k!}\left(\frac{\gamma_i A'}{K\rho\Delta P_\mathrm{T}}\right)^k,\end{aligned} \tag{17}$$

where $A' = 1 + b_i K\rho\Delta P_\mathrm{T}$. Therefore, when the mobility is high (when ρ is high), the 'fixed power' scheme must be used since it does not require the short-term CSI. Let the normalized PENR, η, be defined as

$$\eta = \frac{K\rho}{E\{\gamma\}} \tag{18}$$

and let the long-term CSI be added to it. The long-term CSI in the feedback resource allocation strategy is now redefined as $\mathbf{c}_{\mathrm{L},j} = (\rho_j, K_j, \eta_j)$. Then, the users with the normalized PENRs larger than a pre-determined threshold, δ, will be classified as in a *bad* state and the others will be classified as in a *good* state. Users in the *good* state are serviced with the proposed scheme using both the long-term and the short-term CSIs, whereas users in the *bad* state are serviced with the 'fixed power' scheme with only the long-term CSI. Since the long-term CSI has a negligible feedback overhead compared with the short-term CSI, the reduced portion of the feedback resource, f_red can be written as

$$f_\mathrm{red} = \frac{\text{No. of users in the bad state}}{\text{No. of users}}. \tag{19}$$

Let the distribution of mobility among users be $f_X(x)$. Then, f_red can be rewritten as

$$f_\mathrm{red} = \Pr\{\eta > \delta\} = \sum_{(x_{1,i}, x_{2,i}) \in U} \int_{x_{1,i}}^{x_{2,i}} f_X(x)\,\mathrm{d}x, \tag{20}$$

where U is the set of all disjoint intervals in which η is larger than δ. Note that η may not be a strictly monotonic function of mobility.

4. Simulation results

Through the simulation, the $I = 9$ MCS options shown in Table 1 are used. The carrier frequency, the slot period, and the prediction step are set at 2 GHz, 1 ms, and 4 (slots), respectively. Fig. 4 shows the PER performance for the ninth MCS option (the highest data rate) when $\lambda = 0.445$ (60 km/h), where λ is the maximum Doppler frequency multiplied by the prediction interval. Here, the 'order x,' 'perfect SNR,' 'Inv. w/o pred.,' and 'Inv. w/pred.' denote the performance of the proposed scheme with the predictor order of x, the performance of the ideal scheme that perfectly meets the target instantaneous received SNR, the conventional scheme that uses direct inversion without prediction (without considering the feedback delay as in [1]), and the conventional scheme that uses inversion with the predicted SNR (without considering the prediction error as in [3]), respectively, in a frequency-selective Rayleigh fading channel with six equal-gain signal paths. For comparison, the same AMC algorithm described in Section 3.4 is applied to all methods with different required power calculations. Note that the results should be identical for any combination of (M, N, q) as long as $K = MNq = 6$ and the i.i.d. assumption on the channel gains holds. Here, the abscissa denotes the

Table 1
MCS used in simulation

No.	Mod. order	Code rate	Data rate (kbps)	a_i	b_i	γ_i (dB)
0	No Tx	No Tx	0	–	–	–
1	QPSK	0.19	384	4.95×10^{8}	46.8	−3.7
2	QPSK	0.36	768	4.05×10^{12}	35.1	−0.8
3	QPSK	0.70	1536	1.18×10^{12}	13.3	3.2
4	16QAM	0.52	2304	3.88×10^{18}	6.7	8.1
5	16QAM	0.70	3072	3.07×10^{8}	2.0	10.0
6	16QAM	0.87	3840	2.70×10^{13}	1.8	12.4
7	64QAM	0.69	4224	3.57×10^{34}	1.8	16.5
8	64QAM	0.81	4992	1.01×10^{24}	0.9	17.8

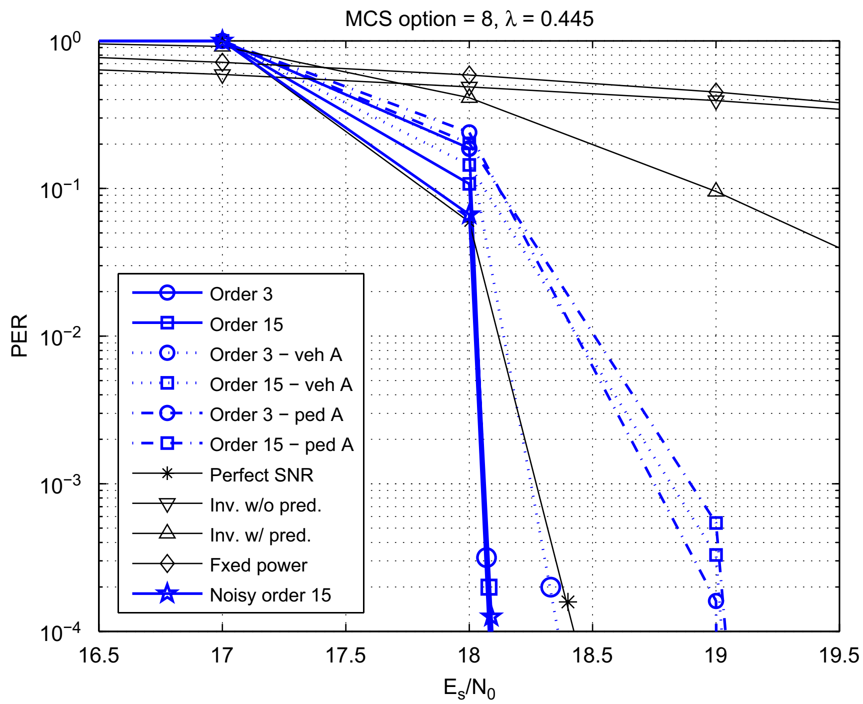

Fig. 4. PER performance of the proposed scheme.

instantaneous received SNR in the 'perfect SNR' scheme and the average received SNR in the 'fixed power' scheme. For other schemes, the transmit power is determined as providing the same PER (but without considering both the feedback delay and the prediction error in the 'Inv. w/o pred.' scheme and without considering the prediction error in the 'Inv. w/ pred.' scheme) as the 'perfect SNR' scheme. Fig. 4 shows that the proposed scheme can guarantee the target PER, whereas the conventional schemes are not acceptable. Also, 'order x—veh. A' and 'order x—ped. A' denote the performance of the proposed scheme in the vehicular A channel and the pedestrian A channel (i.e., different channel gains for different signal paths), in which the i.i.d. assumption does not hold. In this case, the definition of σ_ε^2 is modified as

$$\sigma_\varepsilon^2 = \frac{1}{K}\sum_{k=1}^{K} \mathrm{var}\{\alpha_k|\hat{\alpha_k}\}. \tag{21}$$

The results show that the performance degradation is less than 1 dB over the PER range of $10^{-2}-10^{-4}$, which is the practical range of the target PER. For the PER of 10^{-2}, which is the target PER of the proposed system, the performance degradation is only around 0.5 dB. Also, 'noisy order 15' denotes the performance of the proposed scheme with the predictor order x, considering the noise in the pilot observation. Although not shown explicitly, more power is needed to meet the same PER compared to the noiseless case. It can be seen, however, that the proposed scheme works well with the noisy pilot observations as mentioned earlier.

Figs. 5–7 show the multiuser throughput performance of the proposed scheme with various values of mobile speed when the target PER is 10^{-2}. Here, the average SNR is set as equal for all users. (In real systems, the average SNR of users can differ, and the concept of the proportional fair scheduling in the proposed AMC scheme may be adopted.) The prediction order, K, J, and S are set to 15, 6, 20, and 12, respectively. Here, 'low mobility,' 'mid mobility,' and 'high mobility' denote the cases when all the users are with $\lambda = 0.022$, 0.222, and 0.667, respectively. Also, 'Prop.' and 'Prop.—linear approx.' denote the performance of the proposed scheme when the exact required transmit power using (11) and the approximated required transmit power using (12) are used, respectively. The results show that the proposed scheme is much better than conventional schemes in all cases. As the mobility increases, the performance of the proposed scheme is gracefully degraded to that of the 'fixed power' case, as discussed in Section 3.5, whereas the performance of the conventional schemes is severely degraded. Also, the proposed linear approximation method shows almost no performance degradation, since the approximation error is small enough, as seen in Fig. 3. In Fig. 5, the performance of the proposed scheme with the noisy pilot observation case is included for comparison. When the SNR is low, the performance is close to that of the 'fixed power' case (or high mobility, as seen in Fig. 7) due to the effect of noise. As the SNR increases, however, the performance approaches that of the noiseless case, which is an expected result from the discussion in Section 2.

Fig. 8 shows the performance when users have different mobile speeds. There are four users of the mobility $\lambda = 0.022$ (3 km/h), four users of the mobility $\lambda = 0.222$ (30 km/h), three users of the mobility $\lambda = 0.445$ (60 km/h), three users of the mobility 0.667 (90 km/h), three users of the mobility 0.890 (120 km/h), and three users of the mobility 1.853 (250 km/h). Here, the dotted line marked with the star symbol denotes the performance when the proposed adaptive feedback

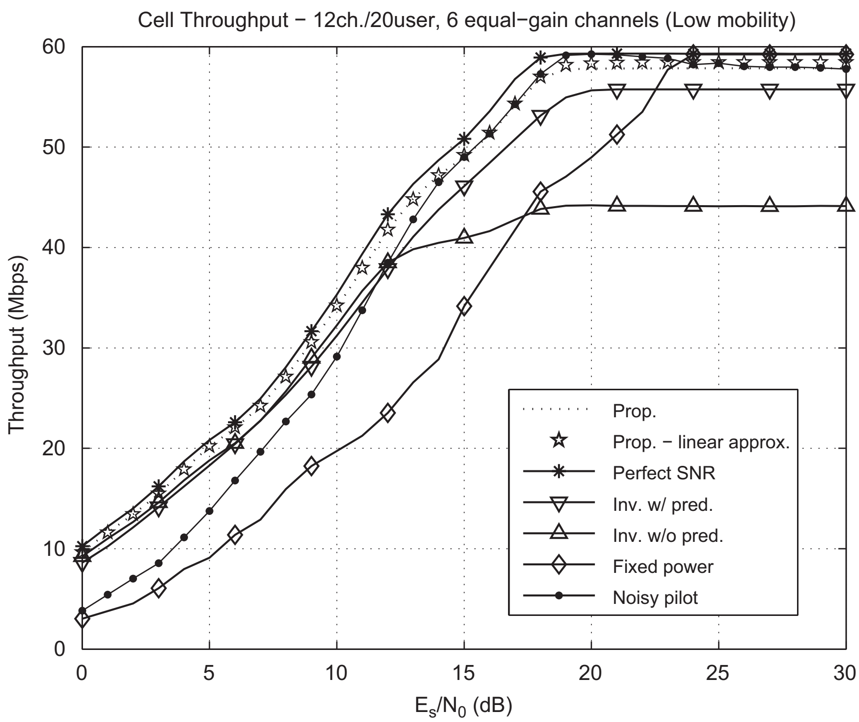

Fig. 5. Cell throughput of the proposed scheme when $\lambda = 0.022$ (low mobility).

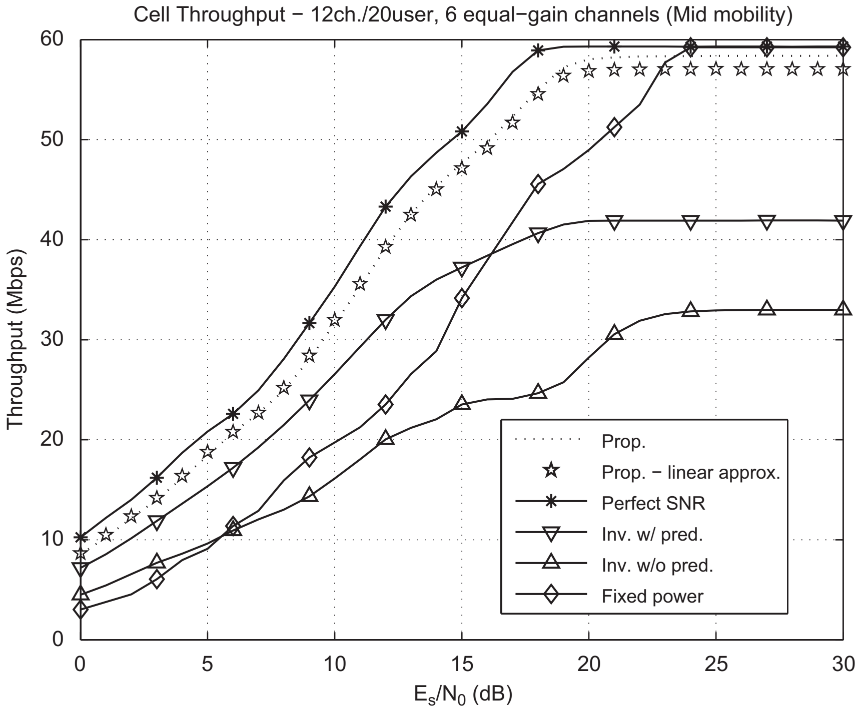

Fig. 6. Cell throughput of the proposed scheme when $\lambda = 0.222$ (mid mobility).

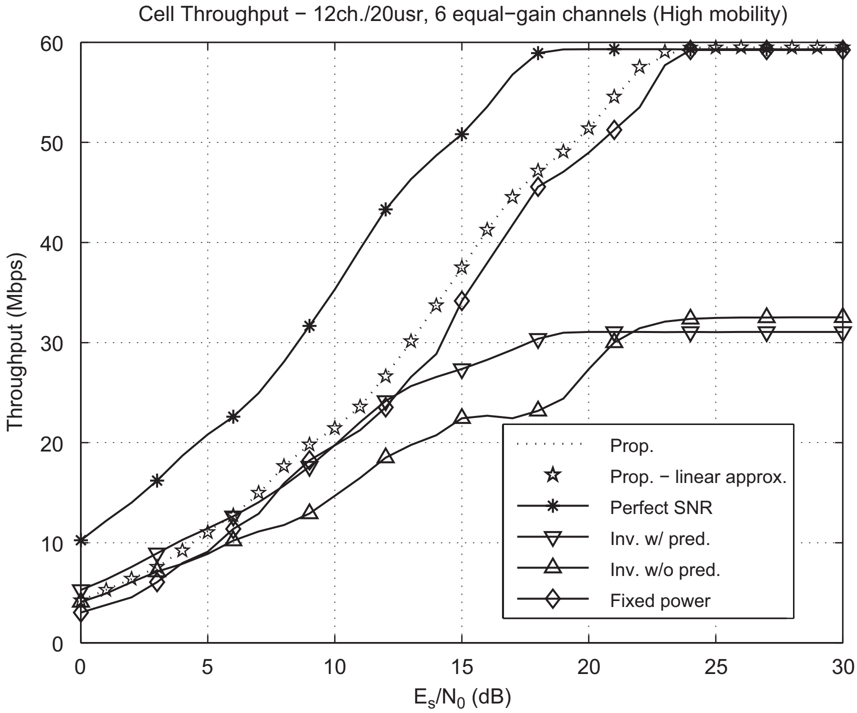

Fig. 7. Cell throughput of the proposed scheme when $\lambda = 0.667$ (high mobility).

resource allocation scheme is applied to this situation with $\delta = 0.4$ (i.e., the 'fixed power' scheme for users with $\lambda > 0.445$). In this case, 60% of the feedback resource can be reduced without performance degradation. As a numerical example, the amount of the feedback resource reduction is

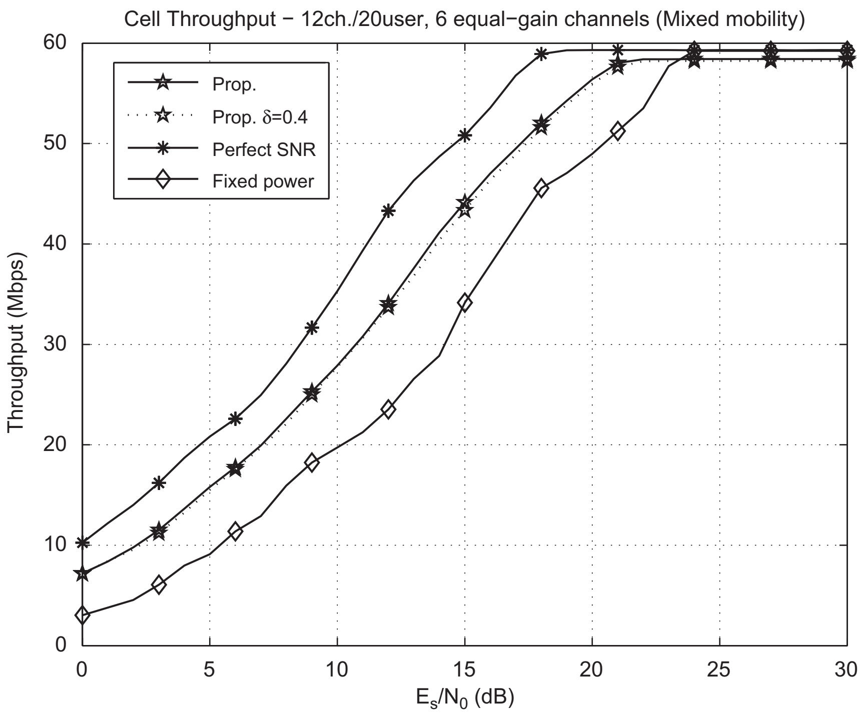

Fig. 8. Cell throughput of the proposed scheme (mixed mobility).

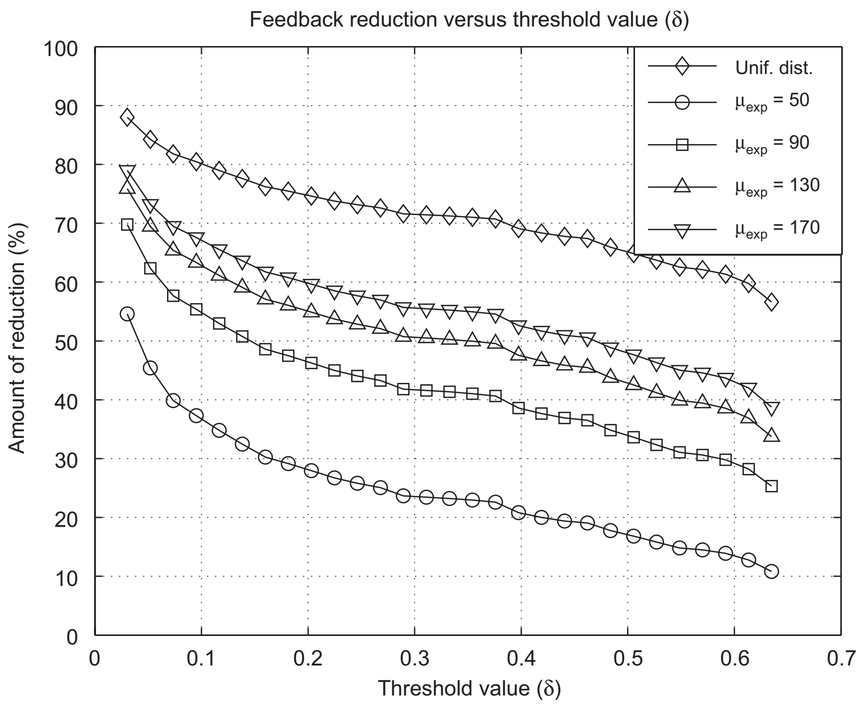

Fig. 9. Amount of reduced feedback overhead in the proposed adaptive feedback resource allocation scheme.

plotted using (20) in Fig. 9 for the cases in which the mobility distribution is a uniform distribution over [0,250 km/h], i.e.,

$$f_X(x) = \frac{1}{250}, \quad 0 \leqslant x \leqslant 250, \tag{22}$$

and a truncated exponential distribution over [0,250 km/h], i.e.,

$$f_X(x) = \frac{\exp(-x/\mu_{\exp})/\mu_{\exp}}{(1-\exp(-250/\mu_{\exp}))}, \quad 0 \leqslant x \leqslant 250. \tag{23}$$

From Fig. 9, it can be easily seen that the proposed scheme can significantly reduce the amount of the feedback resource (by up to 70% at $\delta = 0.4$) without performance loss.

5. Conclusion

In this paper, an efficient multiuser AMC scheme that employs short-term and long-term CSIs was proposed for time-varying frequency-selective fading channels. Taking into account the statistical characteristic of the predicted SNR, the required transmit power, which meets the target PER, can be obtained, and then used for user selection, power allocation, and MCS selection. Also, a computationally efficient method of determining the required transmit power was proposed. It is appropriate for a practical system, since the computational complexity is greatly reduced at the expense of negligible performance degradation.

The computer simulation results showed that the proposed scheme is much better than the conventional systems without considering the feedback delay or the prediction error. It was also seen that the performance of the proposed scheme is gracefully degraded as the mobility increases. From this observation, an adaptive feedback resource allocation scheme was proposed in which the long-term CSI is allocated to every user but the short-term CSI is allocated only to users with good long-term CSI. By adaptively allocating the feedback resource, the feedback overhead can be significantly reduced without performance loss. Therefore, the proposed scheme can be a good option for practical cellular systems since (i) the proposed scheme allows a different order of prediction for each user, including no prediction at all, (ii) the performance degradation due to mobility increase is very graceful (always better than the 'fixed power' scheme), and (iii) the proposed adaptive feedback resource allocation scheme can significantly reduce the feedback overhead with negligible performance degradation.

Acknowledgements

This research was supported by the Ministry of Knowledge Economy, Korea, under the Information Technology Research Center support program supervised by the Institute of Information Technology Advancement (IITA-2008-C1090-0801-0003).

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