The Impact of Imperfect One Bit Per Subcarrier Channel State Information Feedback on Adaptive OFDM Wireless Communication Systems

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Abstract— **If the channel state information (CSI) is available at the transmitter, adaptive techniques can be applied to mitigate deep fading in OFDM wireless communications. The performance of adaptive OFDM systems with average one bit per subcarrier CSI feedback transmitted through perfect feedback channel has been studied in [1]. However, in practical situations the assumption of perfect feedback channel may be unrealistic. In this paper, we study the impact of imperfect feedback channel to the performance of adaptive power allocation (APA) and adaptive modulation selection (AMS) techniques considered in [1]. We obtain that the one bit feedback-based APA technique is relatively robust to erroneous feedback as compared to the one bit feedback-based AMS approach, while the latter is relatively robust against feedback delays as compared to the former. It is also shown that by exploiting the knowledge of the feedback channel the performance of these two adaptive techniques can be improved.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) scheme is an efficient means to mitigate intersymbol interference [2], but it can suffer from fading that may affect some of subcarriers. This makes the reliable detection of the information-bearing symbols at these particular subcarriers very difficult. Therefore, the overall performance of the system may degrade in this case.

If some channel state information (CSI) is available at the transmitter, adaptive modulation and resource allocation techniques can be applied to mitigate fading [2]. In cellular communication systems, the transmitter CSI can be obtained through a feedback channel. However, the bandwidth consumed by the feedback channel is proportional to the rate of the feedback CSI. Therefore, it is important to study the performance of wireless communication system with a low-rate CSI feedback. In [1], the performance of adaptive OFDM system with average one bit per subcarrier CSI feedback has been studied under the assumption of a perfect feedback channel. However, in practice the feedback channel may be erroneous and may have a feedback delay. Therefore, the feedback CSI may be unreliable. In this paper, we study the impact of imperfect CSI feedback on the performance of the adaptive OFDM systems.

II. System Model

We consider the point-to-point cellular communication scenario, where both the transmitter and the receiver have one antenna. The wireless channel between the transmitter and the receiver is an Lth-order multipath channel with the channel gains h_l and delays τ_l $(l = 1, \cdots, L)$. The channel coefficients h_l $(l = 1, \cdots, L)$ are assumed to be independent but not necessarily identically distributed complex Gaussian random variables with the pdf $\mathcal{CN}(0, \sigma_l^2)$. For the sake of simplicity, we normalize the variance of the channel gain so that $\sum_{l=1}^{L} \sigma_l^2 = 1$. By employing the cyclic prefix (CP) whose length is longer than τ_L, the OFDM system with N subcarriers converts the frequency selective fading channel into N parallel flat fading channels [2]. Then the OFDM system model can be written as

$$\boldsymbol{r} = \boldsymbol{D}\boldsymbol{P}^{1/2}\boldsymbol{s} + \boldsymbol{v} \tag{1}$$

where $\boldsymbol{r} = [r(t), \cdots, r(t+N-1)]^T$ is the received block of symbols, $\boldsymbol{s} = [s(t), \cdots, s(t+N-1)]^T$ is the transmitted block of symbols, $\boldsymbol{P}$ is the diagonal matrix that allocates powers to all subcarriers, $\boldsymbol{v} = [v(t), \cdots, v(t+N-1)]^T$ is the vector of additive white Gaussian noise (AWGN), $\boldsymbol{D} = \mathrm{diag}(d_1, \cdots, d_N)$ is the diagonal matrix of channel gains at all subcarriers with

$$d_n = \sum_{l=1}^{L} h_l \exp\left(-\frac{j2\pi n \tau_l}{NT}\right), \quad n = 1, \cdots, N \tag{2}$$

and T is the sampling interval. It can be seen that $d_1, \cdots, d_N$ have identical complex Gaussian distribution with zero mean and unit variance. The absolute value of each d_n is Rayleigh distributed with the pdf

$$p(\alpha) = 2\alpha \exp(-\alpha^2). \tag{3}$$

III. The Impact of CSI Feedback Error to the Performance of OFDM Systems

The adaptive power allocation (APA) and adaptive modulation selection (AMS) approaches have been used to exploit the one bit per subcarrier CSI feedback [1]. The feedback is organized in the following fashion. At the receiver, the channel

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gain in each subcarrier is quantized into 2 states. If the channel gain is above a certain threshold κ, then 1 is sent back to the transmitter. Otherwise, 0 is sent. In the APA approach, if the transmitter receives 0, it allocates transmission power γ_1 to this subcarrier. Otherwise transmission power γ_2 is allocated. In the AMS approach, small size (e.g., BPSK) constellation and the power γ_1 are used if 0 is received in a certain subcarrier and, otherwise, larger size (e.g., 8-PSK) constellation and the other power γ_2 are used.

In this paper, we extend the results of [1] by considering two types of imperfect feedback channels. In particular, we consider the case of erroneous feedback channel as well as the case when the delay between the actual CSI and the CSI received by the transmitter through an outdated feedback channel is present.

A. Erroneous Feedback Channel

We use raw bit error rate (BER) as the criterion to evaluate the performance of the system. The exact symbol error rate (SER) in the case of M-PSK modulation can be calculated as [3]

$$P_s = \frac{1}{\pi}\int_0^{\frac{M-1}{M}\pi}\int_0^{\infty}\exp\left(-\frac{g_{\mathrm{PSK}}\alpha^2 E_s}{\sin^2\!\phi\ \sigma_v^2}\right)f(\alpha)\,d\alpha\,d\phi \qquad (4)$$

where σ_v^2 is the variance of AWGN, E_s is the transmission power, and $g_{\mathrm{PSK}} = \sin^2(\pi/M)$.

The feedback channel is modelled as a binary symmetric channel with the error probability p. Note that the SNR gain obtained from one bit CSI feedback decreases with increasing p, and if p is high enough, the erroneous CSI feedback can even worsen the system performance. Therefore, it is important to study the impact of erroneous CSI feedback on the performance of the APA technique. In particular, we aim to find what is the critical value of error probability p above which one bit per subcarrier feedback deteriorates the system performance.

1) Adaptive Power Allocation: If the feedback channel is perfect, the BER of the APA scheme using QPSK constellation and Gray mapping can be written as [1]

$$\begin{aligned} P_b^{APA}(\mathrm{QPSK},\kappa,\gamma_1,\gamma_2) &= \frac{1}{2\pi} \\ &\cdot\left[\int_0^{\frac{3}{4}\pi}\int_0^{\kappa}\exp\left(-\frac{\alpha^2\gamma_1 E_s}{2\sin^2\!\phi\ \sigma_v^2}\right)f(\alpha)\,d\alpha\,d\phi\right. \\ &\left.+\int_0^{\frac{3}{4}\pi}\int_{\kappa}^{\infty}\exp\left(-\frac{\alpha^2\gamma_2 E_s}{2\sin^2\!\phi\ \sigma_v^2}\right)f(\alpha)\,d\alpha\,d\phi\right]. \end{aligned} \qquad (5)$$

The optimal values of γ_1, γ_2 and κ have been found in [1]. It has been also shown that a substantial SNR gain can be obtained by the APA technique as compared to the case where no feedback is used. Here, we extend the results of [1] by considering the case of erroneous feedback channel.

Taking the feedback error into account, the BER can be calculated as

$$\begin{aligned} Q_b^{APA}(\mathrm{QPSK},\kappa,\gamma_1,\gamma_2;p) &= (1-p)P_b^{APA}(\mathrm{QPSK},\kappa,\gamma_1,\gamma_2) \\ &+ p\,P_b^{APA}(\mathrm{QPSK},\kappa,\gamma_2,\gamma_1). \end{aligned} \qquad (6)$$

TABLE I

CRITICAL PROBABILITY OF FEEDBACK ERROR OF CONVENTIONAL APA

SNR (dB)	0	5	10	15	20	25
p	0.0502	0.1235	0.3461	0.4942	0.5480	0.4769

TABLE II

OPTIMAL PARAMETERS OF APA WITH ERRONEOUS FEEDBACK CHANNEL

SNR (dB)		0	5	10	15	20	25
0.15	κ	0.1591	0.1591	0.5972	0.4031	0.2792	0.1591
	γ_1	4.9000	4.9000	1.7000	2.7000	4.7000	8.8000
	γ_2	0.9000	0.9000	0.7000	0.7000	0.7000	0.8000
0.4	κ	0.1591	0.1591	0.1591	0.1591	0.1591	0.1591
	γ_1	8.8000	4.9000	4.9000	4.9000	4.9000	4.9000
	γ_2	0.8000	0.9000	0.9000	0.9000	0.9000	0.9000

Inserting (5) into (6) we obtain the BER for the APA scheme considering CSI feedback error. The feedback in such an erroneous channel is meaningful if the following condition is satisfied

$$Q_b^{APA}(\mathrm{QPSK},\kappa,\gamma_1,\gamma_2;p) \le P_b(\mathrm{QPSK}). \qquad (7)$$

If (7) holds as equality, we obtain the critical value of p. The critical values of error probability p for different SNRs of the communication channel are listed in Table I. For calculating the critical values of p the optimal parameters from [1] have been used.

As can be seen from Table I, the critical error probability in the feedback channel depends on the SNR conditions of the communication channel, and the APA scheme can tolerate more errors if SNR is high rather than low. We can expect that for "bad" SNR conditions, the APA scheme can even worsen the performance of OFDM system with one bit per subcarrier feedback. Thus, in such a case it is recommended to use the conventional OFDM technique without feedback.

However, if the error probability p is known at the transmitter, we can find the optimal parameters κ, γ_1 and γ_2, which can improve the performance of the APA scheme even when the feedback channel contains errors. The optimal parameters γ_1, γ_2 and κ can be found in such a case as a solution of the following constrained optimization problem

$$\begin{aligned} \min_{\kappa,\gamma_1,\gamma_2}\quad & Q_b^{APA}(\mathrm{QPSK},\kappa,\gamma_1,\gamma_2;p) \\ \text{s.t.}\quad & \int_0^{\kappa}\gamma_1 f(\alpha)\,d\alpha + \int_{\kappa}^{\infty}\gamma_2 f(\alpha)\,d\alpha = 1 \\ & 0<\gamma_1<\gamma_M;\quad 0<\gamma_2<\gamma_M;\quad \kappa>0 \end{aligned} \qquad (8)$$

where γ_M denotes the normalized maximum transmission power which is determined by the base station transmitter peak power. The first constraint of (8) limits the normalized average transmitted power, while the second and third constraints of (8) limit the normalized peak transmitted powers.

Table II summarizes optimal parameters for the APA scheme with erroneous feedback channel when the probability of the feedback error is equal to 0.15 and 0.4, respectively.

TABLE III

CRITICAL PROBABILITY OF FEEDBACK ERROR OF AMS

SNR (dB)	7.5	10	15	20	25
p	0.0731	0.1975	0.2079	0.1277	0.0603

2) Adaptive Modulation Selection: To achieve the data rate of 2 bps per subcarrier, we can use the BPSK modulation at faded subcarriers and the 8PSK modulation at non-faded subcarriers. In this case, the threshold ξ of the channel gain that should be used to divide subcarriers into "faded" and "non-faded" groups can be found by solving the following data rate constraint equation

$$\int_0^{\xi} p(\alpha)\, d\alpha + 3\int_{\xi}^{\infty} p(\alpha)\, d\alpha = 2. \tag{9}$$

Using (3), we obtain from (9) that $\xi = \sqrt{\ln 2}$. Then, the BER for this particular AMS scheme can be written as

$$\begin{aligned} &P_b^{AMS}(\mathrm{BPSK}, 8\mathrm{PSK}, \gamma_1, \gamma_2) = \frac{1}{\pi} \\ &\cdot \left[\int_0^{\frac{\pi}{2}}\int_0^{\sqrt{\ln 2}} \exp\left(-\frac{\alpha^2\gamma_1 E_s}{\sin^2\phi\ \sigma_v^2}\right) p(\alpha)\, d\alpha\, d\phi \right. \\ &\left. +\frac{1}{3}\int_0^{\frac{7\pi}{8}}\int_{\sqrt{\ln 2}}^{\infty} \exp\left(-\frac{\sin^2(\pi/8)\alpha^2\gamma_2 E_s}{\sin^2\phi\ \sigma_v^2}\right) p(\alpha)\, d\alpha\, d\phi\right]. \end{aligned} \tag{10}$$

The optimal γ_1 and γ_2 have been found in [1].

For the AMS scheme with erroneous CSI feedback the BER can be calculated as

$$\begin{aligned} &Q_b^{AMS}(\mathrm{BPSK}, 8\mathrm{PSK}, \gamma_1, \gamma_2; p) \\ &= (1-p)P_b^{AMS}(\mathrm{BPSK}, 8\mathrm{PSK}, \gamma_1, \gamma_2) \\ &+p\ P_b^{AMS}(\mathrm{BPSK}, 8\mathrm{PSK}, \gamma_2, \gamma_1). \end{aligned} \tag{11}$$

Inserting (10) into (11), we obtain the BER for the AMS scheme in the presence of the CSI feedback error. The feedback in such an erroneous channel is meaningful if the following condition is satisfied

$$Q_b^{AMS}(\mathrm{BPSK}, 8\mathrm{PSK}, \gamma_1, \gamma_2; p) \le P_b(\mathrm{QPSK}). \tag{12}$$

If (12) holds as equality, we obtain the critical value of p. These values for different SNRs are listed in Table III. We can see from Table III that the error probability p in the feedback channel calculated for optimal parameters from [1] depends on the SNR conditions of the communication channel. Comparing Table III with Table I we can also see that the AMS scheme is more sensitive to feedback errors than the APA approach.

However, if the error probability p is known at the transmitter, we can find the optimal parameters γ_1 and γ_2, which can improve the performance of the AMS scheme used with erroneous feedback channel. These optimal parameters can be found as a solution to the following optimization problem

$$\begin{aligned} \min_{\gamma_1,\gamma_2}\ & Q_b^{AMS}(\mathrm{BPSK}, 8\mathrm{PSK}, \gamma_1, \gamma_2; p) \\ \text{s.t.}\quad & \gamma_1 + \gamma_2 = 2 \\ & 0 < \gamma_1, \gamma_2 < 2. \end{aligned} \tag{13}$$

TABLE IV

OPTIMAL PARAMETERS OF AMS WITH ERRONEOUS FEEDBACK CHANNEL

SNR (dB)	0	5	10	15	20	25
γ_1	1.3110	1.0596	0.9812	1.0628	1.0812	1.0653
γ_2	0.6890	0.9404	1.0188	0.9372	0.9188	0.9347

TABLE V

CRITICAL ρ OF CONVENTIONAL APA

SNR (dB)	0	5	10	15	20	25
ρ	0.8121	0.4518	0.6489	0.7556	0.8510	0.9404

Table IV shows the optimal values of the parameters γ_1 and γ_2 for the AMS scheme with erroneous feedback channel when the error probability p is equal 0.15.

B. Delayed Feedback Channel

The second source of imperfections in the feedback channel is the delay between the actual CSI and the CSI received by the transmitter. Therefore, it is also important to study the impact of CSI delay on the APA approach.

Let α_0 and α_τ be the channel gains at the time slot 0 and the time slot τ, respectively. It has been shown in [4] that the joint pdf of α_0^2 and α_τ^2 has the following form

$$f_{\alpha_0^2,\alpha_\tau^2}(x, y; \rho_\tau) = \frac{1}{1-\rho}\exp\left(-\frac{x+y}{1-\rho}\right) I_0\left(\frac{2\sqrt{\rho x y}}{1-\rho}\right) \tag{14}$$

where $I_0(\cdot)$ is the modified Bessel function of the first kind of order 0 and $\rho = \mathrm{cov}(x, y)/\sqrt{\mathrm{var}(x)\mathrm{var}(y)}$. The parameter ρ characterizes the feedback delay.

1) Adaptive Power Allocation: Using (14), we obtain that in the case of delayed one bit CSI feedback, QPSK constellation, and Gray mapping, the BER can be written as

$$\begin{aligned} &R_b^{APA}(\mathrm{QPSK}, \kappa, \gamma_1, \gamma_2; \rho) = \frac{1}{2\pi} \\ &\cdot\left[\int_0^{\kappa^2}\int_0^{\infty}\int_0^{\frac{3\pi}{4}} \exp\left(-\frac{xE_s\gamma_1}{2\sin^2\phi\ \sigma_v^2}\right) f_{\alpha_0^2,\alpha_\tau^2}(x, y; \rho)\, d\phi\, dx\, dy \right. \\ &\left. + \int_{\kappa^2}^{\infty}\int_0^{\infty}\int_0^{\frac{3\pi}{4}} \exp\left(-\frac{xE_s\gamma_2}{2\sin^2\phi\ \sigma_v^2}\right) f_{\alpha_0^2,\alpha_\tau^2}(x, y; \rho)\, d\phi\, dx\, dy\right]. \end{aligned} \tag{15}$$

It is important to note that with increasing delay τ, the coefficient ρ is decreasing, but the BER is increasing. Therefore, we can find the critical ρ below which the feedback CSI becomes meaningless. It can be done by solving the following equation

$$R_b^{APA}(\mathrm{QPSK}, \kappa, \gamma_1, \gamma_2; \rho) = P_b(\mathrm{QPSK}). \tag{16}$$

The critical values of the coefficient ρ for different SNRs are listed in Table V. As we can see from this table, for some values of SNR the critical values of the coefficient ρ can be quite large, thus, only very short feedback delay can be tolerated by the communication system. In such a case, the feedback may not provide any performance improvement and should not be used. Moreover, we can also see from

TABLE VI
OPTIMAL PARAMETERS OF APA WITH FEEDBACK DELAY

SNR (dB)	0	5	10	15	20	25
κ	0.5364	1.1774	0.8326	0.8326	0.8326	0.8326
γ_1	0.7000	1.1000	1.3000	1.5000	1.6000	1.6000
γ_2	1.1000	0.7000	0.7000	0.5000	0.4000	0.4000

TABLE VII
CRITICAL ρ OF AMS

SNR (dB)	10	15	17.5	20	22.5	25
ρ	0.7515	0.6725	0.7039	0.7455	0.7844	0.8172

TABLE VIII
OPTIMAL PARAMETERS FOR AMS WITH FEEDBACK DELAY

SNR (dB)	0	5	10	15	20	25
γ_1	1.3032	1.0568	0.9953	1.0811	1.2244	1.3412
γ_2	0.6968	0.9432	1.0047	0.9189	0.7756	0.6588

Table V that the dependence of the critical value of ρ on SNR is highly nonlinear. Thus, it is difficult to say which SNR region can tolerate longer feedback delay, and when the system performance can be possibly improved by using such a delayed feedback.

However, if ρ is known at the transmitter, we can find optimal parameters γ_1, γ_2 and κ, which can improve the performance of the APA scheme in the case when the feedback channel contains delay. In such a case, these parameters can be found by solving the following constrained optimization problem

$$\begin{aligned} \min_{\kappa,\gamma_1,\gamma_2} \quad & R_b^{APA}(\text{QPSK}, \kappa, \gamma_1, \gamma_2; \rho) \\ \text{s.t.} \quad & \int_0^{\kappa} \gamma_1 f(y)\, dy + \int_{\kappa}^{\infty} \gamma_2 f(y)\, dy = 1 \qquad (17) \\ & 0 < \gamma_1 < \gamma_M; \quad 0 < \gamma_2 < \gamma_M; \quad \kappa > 0. \end{aligned}$$

Table VI summarizes optimal parameters for the APA scheme with feedback delay when the coefficient ρ is equal to 0.8.

2) Adaptive Modulation Selection: We also study the performance of the AMS scheme when there is a delay between the actual CSI and the CSI received at the transmitter through an outdated feedback channel. Using joint pdf (14) and the expression (10), we obtain the BER of the AMS scheme in the case of delayed one bit CSI feedback

$$\begin{aligned} & R_b^{AMS}(\text{BPSK}, 8\text{PSK}, \gamma_1, \gamma_2; \rho) = \frac{1}{\pi} \\ & \cdot \left[\int_0^{\ln 2} \int_0^{\infty} \int_0^{\frac{\pi}{2}} \exp\Big(-\frac{x E_s \gamma_1}{\sin^2\phi\ \sigma_v^2}\Big) f_{\alpha_0^2,\alpha_\tau^2}(x, y; \rho)\, d\phi\, dx\, dy \right. \\ & + \frac{1}{3} \int_{\ln 2}^{\infty} \int_0^{\infty} \int_0^{\frac{7\pi}{8}} \exp\Big(-\frac{\sin^2(\pi/8) x E_s \gamma_2}{\sin^2\phi\ \sigma_v^2}\Big) \qquad (18) \\ & \left. \cdot f_{\alpha_0^2,\alpha_\tau^2}(x, y; \rho)\, d\phi\, dx\, dy \right]. \end{aligned}$$

Then, the critical value of ρ can be found by solving the following equation

$$R_b^{AMS}(\text{BPSK}, 8\text{PSK}, \gamma_1, \gamma_2; \rho) = P_b(\text{QPSK}). \qquad (19)$$

Table VII summarizes the critical values of the coefficient ρ calculated for different SNRs and for optimal parameters from [1]. Comparing Table VII with Table V, we can see that the AMS scheme is more robust to CSI feedback delay than the APA approach. Moreover, the performance of the AMS scheme can be improved if the coefficient ρ is known at the transmitter. In such a case, we can find the optimal parameters γ_1 and γ_2 by solving the following constrained optimization problem

$$\begin{aligned} \min_{\gamma_1,\gamma_2} \quad & R_b^{AMS}(\text{BPSK}, 8\text{PSK}, \gamma_1, \gamma_2; \rho) \qquad (20) \\ \text{s.t.} \quad & \gamma_1 + \gamma_2 = 2 \\ & 0 < \gamma_1, \gamma_2 < 2. \end{aligned}$$

Table VIII shows optimal values of the parameters γ_1 and γ_2 for the AMS scheme with delayed CSI feedback when the coefficient ρ is equal to 0.8.

IV. SIMULATIONS

The channel model used in our simulations is based on the ETSI "Vehicular A" channel environment [5]. In all examples, we assume that the base station (BS) transmits at the fixed data rate of $n_r = 128$ bps and the available number of subcarriers is $N = 64$. Throughout the simulations, we consider separately two sources of imperfections in the feedback channel as described in the previous section.

A. Erroneous Feedback Channel

Figure 1 displays the BER versus SNR for the APA and AMS schemes with erroneous feedback channel. The optimal parameters from [1] have been used for the APA and AMS approaches, respectively. We can see that the performance of both approaches degrades in the case of erroneous feedback channel compared to the case of perfect feedback channel. For the APA scheme, the performance degradation in terms of SNR is about 2 dB for the BER of 10^{-3}. However, the performance of the AMS scheme degrades more severely than the performance of the APA scheme. For example, for the BER of $3 \cdot 10^{-3}$, the performance degradation of the AMS approach with erroneous feedback channel amounts to 7.5 dB compared to the performance of the AMS approach with perfect feedback channel. Moreover, the APA scheme with erroneous CSI feedback performs better than the scheme without feedback, while the AMS scheme performs even worse in the high SNR region than the conventional OFDM technique.

As we can see from Figure 2, the performance of both schemes can be significantly improved if the error probability p is known at the transmitter. The "robust" optimal parameters from Table II and Table IV have been used to calculate the BER for the APA and AMS schemes, respectively. Figure 2 shows that the performance improvement for the APA scheme is more pronounced for higher values of the error probability

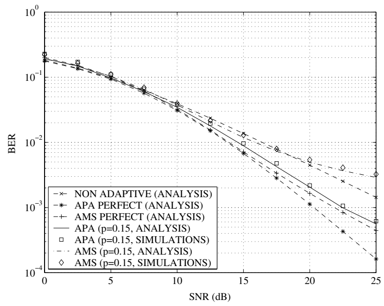

Fig. 1. BER versus SNR in the erroneous feedback channel case. APA and AMS schemes are compared.

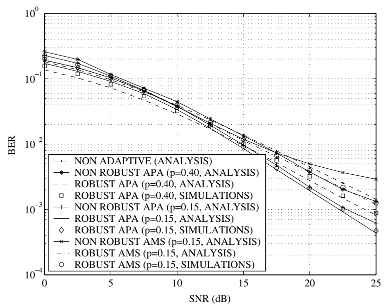

Fig. 2. BER versus SNR in the erroneous feedback channel case. APA and AMS schemes with robust parameters are compared.

p. However, the knowledge of p at the transmitter appears to be more helpful for the AMS approach.

B. Delayed Feedback Channel

Jakes' fading model is used to simulate the delayed feedback channel [6]. The maximal Doppler frequency of 67 Hz is used, which corresponds to the vehicular speed of 36 km/h at the carrier frequency of 2 GHz. We take $\rho = 0.8$, which corresponds to the feedback delay of 37 symbol durations in the IS-136 standard [7].

Simulation results for the delayed feedback channel using optimal parameters from [1] for the APA and AMS schemes are shown in Figure 3. Based on these results, we can see that the APA approach is more sensitive to the delay in the feedback channel as compared to the AMS approach. For example, for the BER of $2 \cdot 10^{-3}$, the performance degradation of the APA approach with delayed feedback channel compared to the APA approach with perfect feedback channel amounts to 7 dB, while the corresponding degradation of the AMS scheme is only 3 dB. Moreover, the APA scheme shows in such a case worse performance than the conventional OFDM technique.

Figure 4 shows the performance of the APA and AMS schemes with delayed feedback channel if the coefficient ρ is known at the transmitter. The "robust" optimal parameters from Tables VI and VIII have been used to calculate the BER for the APA and AMS schemes, respectively. It is easy to see that the performance of both approaches is improved if ρ is known at the transmitter. This improvement is more

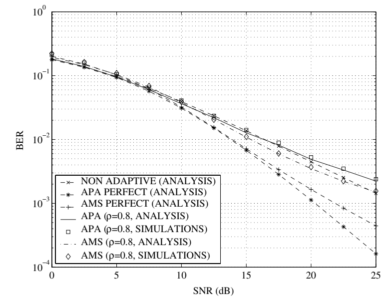

Fig. 3. BER versus SNR in the delayed feedback channel case. APA and AMS schemes are compared.

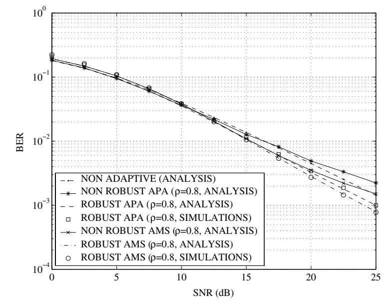

Fig. 4. BER versus SNR in the delayed feedback channel case. APA and AMS schemes with robust parameters are compared.

pronounced for the APA scheme as compared to the AMS scheme.

V. CONCLUSIONS

Under conditions of imperfect feedback channel, the performance of OFDM system with one bit per subcarrier feedback can be even worse than the performance of the conventional OFDM system without feedback. Interestingly, the APA scheme is relatively robust to the errors in the feedback channel, while the AMS approach is relatively robust to the delays in the feedback channel. Moreover, the performance of both the APA and AMS approaches can be improved by exploiting the knowledge of the type of imperfections in the feedback channel.

REFERENCES

[1] Y. Rong, S. A. Vorobyov, and A. B. Gershman, "On average one bit per subcarrier channel state information feedback in OFDM wireless communication systems," *Globecom'04*, submitted.

[2] T. Keller and L. Hanzo, "Adaptive multicarrier modulation: A convenient framework for time-frequency processing in wireless communications," *Proc. IEEE*, vol. 88, pp. 611-640, May 2000.

[3] M. K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels: A Unified Approach to Performance Analysis*, New York: John Wiley & Sons, 2000.

[4] S. Thoen, L. Van der Perre, B. Gyselinckx, and M. Engels, "Performance analysis of combined transmit-SC/receive-MRC," *IEEE Trans. Communications*, vol. 49, pp. 5-8, Jan. 2001.

[5] ETSI, "Universal mobile telecommunications system (UMTS); selection procedures for the choice of radio transmission technologies of the UMTS (UMTS 30.03 version 3.2.0)," ETSI, France, Tech. Rep. TR 101 112 V3.2.0, Apr. 1998.

[6] J. Proakis, *Digital Communications*, 4th Edition, McGraw Hill, 2001.

[7] A.F. Molisch, *Wideband Wireless Digital Communications*, Pearson Education, Inc., 2001.