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Rate-Optimal Multiuser Scheduling with Reduced Feedback Load and Analysis of Delay Effects

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We propose a feedback algorithm for wireless networks that always collects feedback from the user with the best channel conditions and has a significant reduction in feedback load compared to full feedback. The algorithm is based on a carrier-to-noise threshold, and closed-form expressions for the feedback load as well as the threshold value that minimizes the feedback load have been found. We analyze two delay scenarios. The first scenario is where the scheduling decision is based on outdated channel estimates, and the second scenario is where both the scheduling decision and the adaptive modulation are based on outdated channel estimates.

1. INTRODUCTION

In a wireless network, the signals transmitted between the base station and the mobile users most often have different channel fluctuation characteristics. This diversity that exists between users is called *multiuser diversity* (MUD) and can be exploited to enhance the capacity of wireless networks [1]. One way of exploiting MUD is by *opportunistic scheduling* of users, giving priority to users having good channel conditions [2, 3]. Ignoring the feedback loss, the scheduling algorithm, that maximizes the average system spectral efficiency among all time division multiplexing- (TDM-) based algorithms, is the one where the user with the highest carrier-to-noise ratio (CNR) is served in every time slot [2]. Here, we refer to this algorithm as *max CNR scheduling* (MCS).

To be able to take advantage of the MUD, a base station needs feedback from the mobile users. Ideally, the base station only wants feedback from the user with the best channel conditions, but unfortunately each user does not know the CNR of the other users. Therefore, in current systems like Qualcomm's high data rate (HDR) system, the base station collects feedback from all the users [4].

One way to reduce the number of users giving feedback is by using a *CNR threshold*. For the *selective multiuser diversity* (SMUD) algorithm, it is shown that the feedback load is reduced significantly by using such a threshold [5]. For this algorithm only the users that have a CNR above a CNR threshold should send feedback to the scheduler. If the scheduler does not receive a feedback, a random user is chosen. Because the best user is not chosen for every time slot, the SMUD algorithm however introduces a reduction in system spectral efficiency. In addition it can be hard to set the threshold value for this algorithm. Applying a high threshold value will lead to low feedback load, but will additionally reduce the MUD gain and hence the system spectral efficiency. Using a low threshold value will have the opposite effect: the feedback load reduction is reduced, but the spectral efficiency will be higher.

The feedback algorithm proposed here is inspired by the SMUD algorithm, in the sense that this new algorithm also employs a feedback threshold. However, if none of the users succeeds to exceed the CNR threshold, the scheduler requests full feedback, and selects the user with the highest CNR. Consequently, the MUD gain [1] is maximized, and still the feedback load is significantly reduced compared to the MCS algorithm. Another advantage with this novel algorithm is that for a specific set of system parameters it is possible to find a threshold value that minimizes the feedback load.

For the new feedback algorithm we choose to investigate two important issues, namely, (i) how the algorithm can be optimized, and (ii) the consequences of delay in the system. The first issue is important because it gives theoretical limits for how well the algorithm will perform. The second issue is important because the duration of the feedback collection process will often be significant and this will lead to a reduced performance of the opportunistic scheduling since the feedback information will be outdated. The consequences of delay are analyzed by looking separately at two different effects: (a) the system spectral efficiency degradation arising because the scheduler does not have access to instantaneous information about CNRs of the users, and (b) the bit error rate (BER) degradation arising when both the scheduler and the mobile users do not have access to instantaneous channel measurements.

Contributions

We develop closed-form expressions for the feedback load of the new feedback algorithm. The expression for the threshold value which minimizes the feedback load is also derived. In addition we obtain new closed-form expressions for the system spectral efficiency degradation due to the *scheduling delay*. Finally, closed-form expressions for the effects of *outdated channel estimates* are obtained. Parts of the results have previously been presented in [6].

Organization

The rest of this paper is organized as follows. In Section 2, we present the system model. The feedback load is analyzed in Section 3, while Sections 4 and 5 analyze the system spectral efficiency and BER, respectively. In Section 6 the effects of delay are discussed. Finally, Section 7 lists our conclusions.

2. SYSTEM MODEL

We consider a single cell in a wireless network where the base station exchanges information with a constant number N of mobile users which have identically and independently distributed (i.i.d.) CNRs with an average of $\overline{\gamma}$. The system considered is TDM-based, that is, the information transmitted in time slots with a fixed length. We assume flat-fading channels with a coherence time of one time slot, which means that the channel quality remains roughly the same over the whole time slot duration and that this channel quality is uncorrelated from one time slot to the next. The system uses adaptive coding and modulation, that is, the coding scheme, the modulation constellation, and the transmission power used depend on the CNR of the selected user [7]. This has two advantages. On one hand, the spectral efficiency for each user is increased. On the other hand, because the rate of the users is varied according to their channel conditions, it makes it possible to exploit MUD.

We will assume that the users always have data to send and that these user data are robust with respect to delay, that is, no real-time traffic is transmitted. Consequently, the base station only has to take the channel quality of the users into account when it is performing scheduling.

The proposed feedback algorithm is applicable in at least two different types of cellular systems. The first system model is a time-division duplex (TDD) scenario, where the same carrier frequency is used for both uplink and downlink. We can therefore assume a reciprocal channel for each user, that is, the CNR is the same for the uplink and the downlink for a given point in time. The system uses the first half of the time slot for downlink and the last half for uplink transmission. The users measure their channel for each downlink transmission and this measurement is fed back to the base station so that it can decide which user is going to be assigned the next time slot. The second system model is a system where different carriers are used for uplink and downlink. For the base station to be able to schedule the user with the best downlink channel quality, the users must measure their channel for each downlink transmission and feed back their CNR measurement. For both system models the users are notified about the scheduling decision in a short broadcast message from the base station between each time slot.

3. ANALYSIS OF THE FEEDBACK LOAD

The first step of the new feedback algorithm is to ask for feedback from the users that are above a CNR threshold value γ_{th}. The number of users n being above the threshold value γ_{th} is random and follow a *binomial distribution* given by

$$\Pr(n) = \binom{N}{n}\left(1 - P_{\gamma}(\gamma_{\text{th}})\right)^{n} P_{\gamma}^{N-n}(\gamma_{\text{th}}), \quad n = 1, 2, \ldots, N, \tag{1}$$

where $P_{\gamma}(\gamma)$ is the cumulative distribution function (CDF) of the CNR for a single user. The second step of the feedback algorithm is to collect full feedback. Full feedback is only needed if all users' CNRs fail to exceed the threshold value. The probability of this event is given by inserting $\gamma = \gamma_{\text{th}}$ into

$$P_{\gamma^*}(\gamma) = P_{\gamma}^{N}(\gamma), \tag{2}$$

where γ^* denotes the CNR of the user with the best channel quality.

We now define the *normalized feedback load* (NFL) to be the ratio between the average number of users transmitting feedback, and the total number of users. The NFL can be expressed as a the average of the ratio n/N, where n is the number of users giving feedback:

$$\begin{aligned}
\overline{F} &= \frac{N}{N} P_{\gamma}^{N}(\gamma_{\text{th}}) + \sum_{n=1}^{N} \frac{n}{N}\binom{N}{n}\left(1 - P_{\gamma}(\gamma_{\text{th}})\right)^{n} P_{\gamma}^{N-n}(\gamma_{\text{th}}) \\
&= P_{\gamma}^{N}(\gamma_{\text{th}}) + \left(1 - P_{\gamma}(\gamma_{\text{th}})\right) \sum_{n=1}^{N} \binom{N-1}{n-1} \\
&\quad \times \left(1 - P_{\gamma}(\gamma_{\text{th}})\right)^{n-1} P_{\gamma}^{N-n}(\gamma_{\text{th}}) = P_{\gamma}^{N}(\gamma_{\text{th}}) \\
&\quad + \left(1 - P_{\gamma}(\gamma_{\text{th}})\right) \sum_{k=0}^{N-1} \binom{N-1}{k}\left(1 - P_{\gamma}(\gamma_{\text{th}})\right)^{k} P_{\gamma}^{N-1-k}(\gamma_{\text{th}}) \\
&= 1 - P_{\gamma}(\gamma_{\text{th}}) + P_{\gamma}^{N}(\gamma_{\text{th}}), \quad N = 2, 3, 4, \ldots,
\end{aligned} \tag{3}$$

where the last equality is obtained by using binomial expansion [8, equation (1.111)]. For $N = 1$ full feedback is needed, and $\overline{F} = 1$. In that case the feedback is not useful for multiuser scheduling, but for being able to adapt the base station's modulation according to the channel quality in the reciprocal TDD system model described in the previous section.

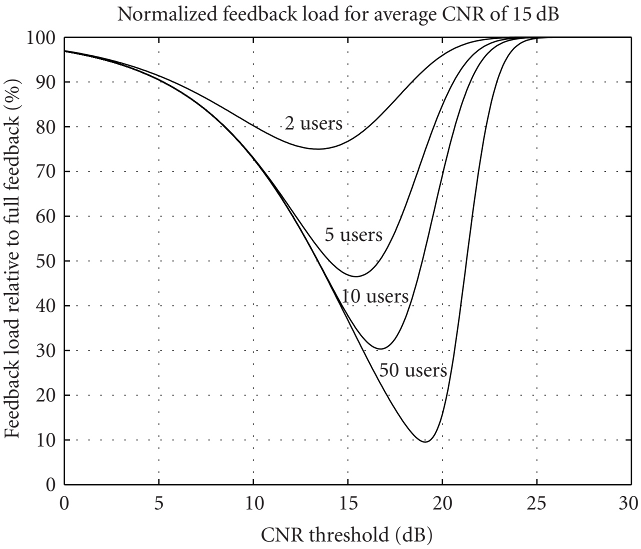

FIGURE 1: Normalized feedback load as a function of γ_{th} with $\overline{\gamma} = 15$ dB.

A plot of the feedback load as a function of γ_{th} is shown in Figure 1 for $\overline{\gamma}= 15$ dB. It can be observed that the new algorithm reduces the feedback significantly compared to a system with full feedback. It can also be observed that one threshold value will minimize the feedback load in the system for a given number of users.

The expression for the threshold value that minimizes the average feedback load can be found by differentiating (3) with respect to γ_{th} and setting the result equal to zero:

$$\gamma_{th}^{*} = P_{\gamma}^{-1}\left(\left(\frac{1}{N}\right)^{1/(N-1)}\right), \quad N = 2,3,4,\ldots, \tag{4}$$

where $P_{\gamma}^{-1}(\cdot)$ is the inverse CDF of the CNR. In particular, for a Rayleigh fading channel, with CDF $P_{\gamma}(\gamma) = 1 - e^{-\gamma/\overline{\gamma}}$, the optimum threshold can be found in a simple closed form as

$$\gamma_{th}^{*} = -\overline{\gamma}\ln\left(1-\left(\frac{1}{N}\right)^{1/(N-1)}\right), \quad N = 2,3,4,\ldots. \tag{5}$$

4. SYSTEM SPECTRAL EFFICIENCIES FOR DIFFERENT POWER AND RATE ADAPTATION TECHNIQUES

To be able to analyze the system spectral efficiency we choose to investigate the *maximum average system spectral efficiency* (MASSE) theoretically attainable. The MASSE (bit/s/Hz) is defined as the maximum average sum of spectral efficiency for a carrier with bandwidth W (Hz).

4.1. *Constant power and optimal rate adaptation*

Since the best user is always selected, the MASSE of the new algorithm is the same as for the MCS algorithm. To find the MASSE for such a scenario, the probability density function (pdf) of the highest CNR among all the users has to be found. This pdf can be obtained by differentiating (2) with respect to γ. Inserting the CDF and pdf for Rayleigh fading channels ($p_{\gamma}(\gamma) = (1/\overline{\gamma})e^{-\gamma/\overline{\gamma}}$), and using binomial expansion [8, equation (1.111)], we obtain

$$p_{\gamma^*}(\gamma) = \frac{N}{\overline{\gamma}}\sum_{n=0}^{N-1}\binom{N-1}{n}(-1)^n e^{-(1+n)\gamma/\overline{\gamma}}. \tag{6}$$

Inserting (6) into the expression for the spectral efficiency for optimal rate adaptation found in [9], the following expression for the MASSE can be obtained [10, equation (44)]:

$$\begin{aligned}\frac{\langle C\rangle_{\text{ora}}}{W} &= \int_0^{\infty}\log_2(1+\gamma)p_{\gamma^*}(\gamma)d\gamma \\ &= \frac{N}{\ln 2}\sum_{n=0}^{N-1}\binom{N-1}{n}(-1)^n\frac{e^{(1+n)/\overline{\gamma}}}{1+n}E_1\left(\frac{1+n}{\overline{\gamma}}\right),\end{aligned} \tag{7}$$

where ora denotes *optimal rate adaptation* and $E_1(\cdot)$ is the *first-order exponential integral function* [8].

4.2. *Optimal power and rate adaptation*

It has been shown that the MASSE for optimal power and rate adaptation can be obtained as [10, equation (27)]

$$\begin{aligned}\frac{\langle C\rangle_{\text{opra}}}{W} &= \int_0^{\infty}\log_2\left(\frac{\gamma}{\gamma_0}\right)p_{\gamma^*}(\gamma)d\gamma \\ &= \frac{N}{\ln 2}\sum_{n=0}^{N-1}\binom{N-1}{n}\frac{(-1)^n}{1+n}E_1\left(\frac{(1+n)\gamma_0}{\overline{\gamma}}\right),\end{aligned} \tag{8}$$

where opra denotes *optimal power and rate adaptation* and γ_0 is the optimal cutoff CNR level below which data transmission is suspended. This cutoff value must satisfy [9]

$$\int_{\gamma_0}^{\infty}\left(\frac{1}{\gamma_0}-\frac{1}{\gamma}\right)p_{\gamma^*}(\gamma)d\gamma = 1. \tag{9}$$

Inserting (6) into (9), it can subsequently be shown that the following cutoff value can be obtained for Rayleigh fading channels [10, equation (24)]:

$$\sum_{n=0}^{N-1}\binom{N-1}{n}(-1)^n\left(\frac{e^{-(1+n)\gamma_0/\overline{\gamma}}}{(1+n)\gamma_0/\overline{\gamma}} - E_1\left(\frac{(1+n)\gamma_0}{\overline{\gamma}}\right)\right) = \frac{\overline{\gamma}}{N}. \tag{10}$$

5. M-QAM BIT ERROR RATES

The BER of coherent M-ary quadrature amplitude modulation (M-QAM) with two-dimensional Gray coding over an additive white Gaussian noise (AWGN) channel can be approximated by [11]

$$\text{BER}(M,\gamma) \approx 0.2\exp\left(-\frac{3\gamma}{2(M-1)}\right). \tag{11}$$

The constant-power *adaptive continuous rate* (ACR) M-QAM scheme can always adapt the rate to the instantaneous CNR. From [12] we know that the constellation size for continuous-rate M-QAM can be approximated by $M \approx (1+3\gamma/2K_0)$, where $K_0 = -\ln(5\,\mathrm{BER}_0)$ and BER_0 is the target BER. Consequently, it can be easily shown that the theoretical constant-power ACR M-QAM scheme always operates at the target BER.

For physical systems only integer constellation sizes are practical, so now we restrict the constellation size M_k to 2^k, where k is a positive integer. This adaptation policy is called *adaptive discrete rate* (ADR) M-QAM, and the CNR range is divided into $K+1$ *fading regions* with constellation size M_k assigned to the kth fading region. Because of the discrete assignment of constellation sizes in ADR M-QAM, this scheme has to operate at a BER lower than the target. The average BER for ADR M-QAM using constant power can be calculated as [12]

$$\langle \mathrm{BER} \rangle_{\mathrm{adr}} = \frac{\sum_{k=1}^{K} k\overline{\mathrm{BER}}_k}{\sum_{k=1}^{K} k p_k}, \tag{12}$$

where

$$\overline{\mathrm{BER}}_k = \int_{\gamma_k}^{\gamma_{k+1}} \mathrm{BER}\,(M_k,\gamma)\, p_{\gamma^*}(\gamma) d\gamma, \tag{13}$$

$$p_k = \left(1-e^{-\gamma_{k+1}/\overline{\gamma}}\right)^N - \left(1-e^{-\gamma_k/\overline{\gamma}}\right)^N \tag{14}$$

is the probability that the scheduled user is in the fading region k for CNRs between γ_k and γ_{k+1}.

Inserting (11) and (6) into (13) we obtain the following expression for the average BER within a fading region:

$$\overline{\mathrm{BER}}_k = \frac{0.2N}{\overline{\gamma}} \sum_{n=0}^{N-1} \binom{N-1}{n} (-1)^n \frac{e^{-\gamma_k a_{k,n}} - e^{-\gamma_{k+1} a_{k,n}}}{a_{k,n}}, \tag{15}$$

where $a_{k,n}$ is given by

$$a_{k,n} = \frac{1+n}{\overline{\gamma}} + \frac{3}{2(M_k-1)}. \tag{16}$$

When power adaptation is applied, the BER approximation in (11) can be written as [11]

$$\mathrm{BER}_{\mathrm{pa}}(M,\gamma) \approx 0.2 \exp\left(-\frac{3\gamma}{2(M-1)} \frac{S_k(\gamma)}{S_{\mathrm{av}}}\right), \tag{17}$$

where $S_k(\gamma)$ is the power used in fading region k and S_{av} is the average transmit power. Inserting the continuous power adaptation policy given by [11, equation (29)] into (17) shows that the ADR M-QAM scheme using optimal power adaptation always operates at the target BER. Correspondingly, it can be shown that the continuous-power, continuous-rate M-QAM scheme always operates at the target BER.

6. CONSEQUENCES OF DELAY

In the previous sections, it has been assumed that there is no delay from the instant where the channel estimates are obtained and fed back to the scheduler, to the time when the optimal user is transmitting. For real-life systems, we have to take delay into consideration. We analyze, in what follows, two delay scenarios. In the first scenario, a *scheduling delay* arises because the scheduler receives channel estimates, takes a scheduling decision, and notifies the selected user. This user then transmits, but at a possibly different rate. The second scenario deals with *outdated channel estimates*, which leads to both a scheduling delay as well as suboptimal modulation constellations with increased BERs.

Outdated channel estimates have been treated to some extent in previous publications [12, 13]. However, the concept of scheduling delay has in most cases been analyzed for wire-line networks only [14, 15]. Although some previous work has been done on scheduling delay in wireless networks [16], scheduling delay has to the best of our knowledge not been looked into for cellular networks.

6.1. Impact of scheduling delay

In this section, we will assume that the scheduling decision is based on a perfect estimate of the channel at time t, whereas the data are sent over the channel at time $t+\tau$. We will assume that the link adaptation done at time $t+\tau$ is based on yet another channel estimate taken at $t+\tau$. To investigate the influence of this type of scheduling delay, we need to develop a pdf for the CNR at time $t+\tau$, conditioned on channel knowledge at time t. Let α and α_τ be the channel gains at times t and $t+\tau$, respectively. Assuming that the average power gain remains constant over the time delay τ for a slowly-varying Rayleigh channel (i.e., $\Omega = E[\alpha^2] = E[\alpha_\tau^2]$) and using the same approach as in [12] it can be shown that the conditional pdf $p_{\alpha_\tau|\alpha}(\alpha_\tau \mid \alpha)$ is given by

$$p_{\alpha_\tau|\alpha}(\alpha_\tau \mid \alpha) = \frac{2\alpha_\tau}{(1-\rho)\Omega} I_0\left(\frac{2\sqrt{\rho}\alpha\alpha_\tau}{(1-\rho)\Omega}\right) e^{-(\alpha_\tau^2+\rho\alpha^2)/(1-\rho)\Omega}, \tag{18}$$

where ρ is the correlation factor between α and α_τ and $I_0(\cdot)$ is the *zeroth-order modified Bessel function of the first kind* [8]. Assuming Jakes Doppler spectrum, the correlation coefficient can be expressed as $\rho = J_0^2(2\pi f_D \tau)$, where $J_0(\cdot)$ is the *zeroth-order Bessel function of the first kind* and f_D [Hz] is the maximum Doppler frequency shift [12]. Recognizing that (18) is similar to [17, equation (A-4)] gives the following pdf at time $t+\tau$ for the new feedback algorithm, expressed in terms of γ_τ and $\overline{\gamma}$ [17, equation (5)]:

$$p_{\gamma_\tau^*}(\gamma_\tau) = \sum_{n=0}^{N-1} \binom{N}{n+1} (-1)^n \frac{\exp\left(-\gamma_\tau/\overline{\gamma}\left(1-\rho(n/(n+1))\right)\right)}{\overline{\gamma}\left(1-\rho(n/(n+1))\right)}. \tag{19}$$

Note that for $\tau = 0$ ($\rho = 1$) this expression reduces to (6), as expected. When τ approaches infinity ($\rho = 0$) (19) reduces to the Rayleigh pdf for one user. This is logical since for large τs, the scheduler will have completely outdated and as such useless feedback information, and will end up selecting users independent of their CNRs.

Inserting (19) into the capacity expression for optimal rate adaptation in [9, equation (2)], then using binomial expansion, integration by parts, L'Hôpital's rule, and

[8, equation (3.352.2)], it can be shown that we get the following expression for the MASSE:

$$\frac{\langle C\rangle_{\text{ora}}}{W} = \int_0^\infty \log_2(1+\gamma_\tau)p_{\gamma_\tau^*}(\gamma_\tau)d\gamma_\tau = \frac{1}{\ln 2}\sum_{n=0}^{N-1}\binom{N}{n+1}(-1)^n e^{1/\overline{\gamma}(1-\rho(n/(n+1)))} \times E_1\left(\frac{1}{\overline{\gamma}(1-\rho(n/(n+1)))}\right). \tag{20}$$

Using a similar derivation as for the expression above it can furthermore be shown that we get the following expression for the MASSE using both optimal power and rate adaptation:

$$\frac{\langle C\rangle_{\text{opra}}}{W} = \int_0^\infty \log_2\left(\frac{\gamma_\tau}{\gamma_0}\right)p_{\gamma_\tau^*}(\gamma_\tau)d\gamma_\tau = \frac{1}{\ln 2}\sum_{n=0}^{N-1}\binom{N}{n+1}(-1)^n E_1\left(\frac{\gamma_0}{\overline{\gamma}(1-\rho(n/(n+1)))}\right), \tag{21}$$

with the following power constraint:

$$\sum_{n=0}^{N-1}\binom{N}{n+1}(-1)^n\left(\frac{e^{-1/\overline{\gamma}(1-\rho(n/(n+1)))}}{\gamma_0} - \frac{E_1(1/\overline{\gamma}(1-\rho(n/(n+1))))}{\overline{\gamma}(1-\rho(n/(n+1)))}\right) = 1. \tag{22}$$

Again, for zero time delay ($\rho = 1$), (20) reduces to (7), (21) reduces to (8), and (22) reduces to (10), as expected.

Figure 2 shows how scheduling delay affects the MASSE for 1, 2, 5, and 10 users. We see that both optimal power and rate adaptation and optimal rate adaptation are equally robust with regard to the scheduling delay. Independent of the number of users, we see that the system will be able to operate satisfactorily if the normalized delay is below the critical value of $2\cdot 10^{-2}$. For normalized time delays above this value, we see that the MASSE converges towards the MASSE for one user, as one may expect.

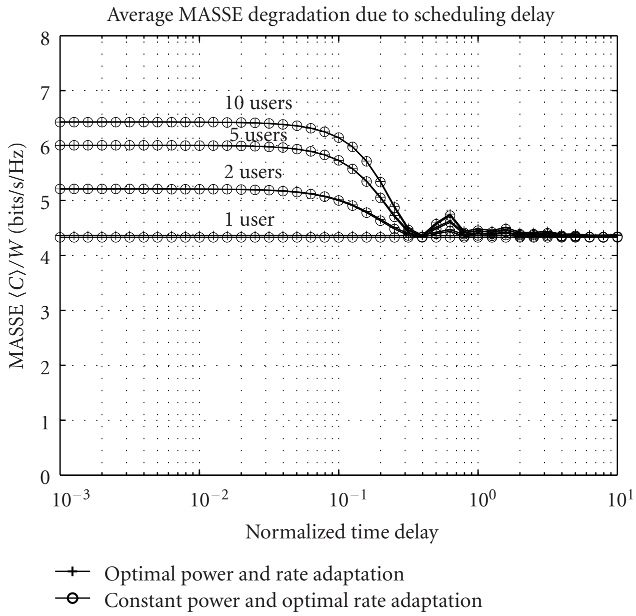

Figure 2: Average degradation in MASSE due to scheduling delay for (i) optimal power and rate adaptation and (ii) optimal rate adaptation.

6.2. Impact of outdated channel estimates

We will now assume that the transmitter does not have a perfect outdated channel estimate available at time $t+\tau$, but only at time t. Consequently, both the selection of a user and the decision of the constellation size have to be done at time t. This means that the channel estimates are outdated by the same amount of time as the scheduling delay. The constellation size is thus not dependent on γ_τ, and the time delay in this case does not affect the MASSE. However, now the BER will suffer from degradation because of the delay. It is shown in [12] that the average BER, conditioned on γ, is

$$\text{BER}(\gamma) = \frac{0.2\gamma}{\gamma+\overline{\gamma}(1-\rho)K_0}\cdot e^{-\rho K_0\gamma/(\gamma+\overline{\gamma}(1-\rho)K_0)}. \tag{23}$$

The average BER can be found by using the following equation:

$$\langle\text{BER}\rangle_{\text{acr}} = \int_0^\infty \text{BER}(\gamma)p_{\gamma^*}(\gamma)d\gamma. \tag{24}$$

For discrete rate adaptation with constant power, the BER can be expressed by (12), replacing $\overline{\text{BER}}_k$ with $\overline{\text{BER}}_k'$, where

$$\overline{\text{BER}}_k' = \int_{\gamma_k}^{\gamma_{k+1}}\int_0^\infty \text{BER}(M_k,\gamma_\tau)p_{\gamma_\tau|\gamma}(\gamma_\tau\mid\gamma)d\gamma_\tau p_{\gamma^*}(\gamma)d\gamma. \tag{25}$$

Inserting (6), (11), and (18) expressed in terms of γ_τ and γ into (25), we obtain the following expression for the average BER within a fading region:

$$\overline{\text{BER}}_k' = \frac{0.2N}{\overline{\gamma}}\sum_{n=0}^{N-1}\binom{N-1}{n}(-1)^n\frac{e^{-\gamma_k c_{k,n}} - e^{-\gamma_{k+1}c_{k,n}}}{d_{k,n}}, \tag{26}$$

where $c_{k,n}$ is given by

$$c_{k,n} = \frac{1+n}{\overline{\gamma}} + \frac{3\rho}{3\overline{\gamma}(1-\rho)+2(M_k-1)}, \tag{27}$$

and $d_{k,n}$ by

$$d_{k,n} = \frac{1+n}{\overline{\gamma}} + \frac{3(1+n-\rho n)}{2(M_k-1)}. \tag{28}$$

Note that for zero delay ($\rho = 1$), $c_{k,n} = d_{k,n} = a_{k,n}$, and (26) reduces to (15), as expected.

Because we are interested in the average BER only for the CNRs for which we have transmission, the average BER for

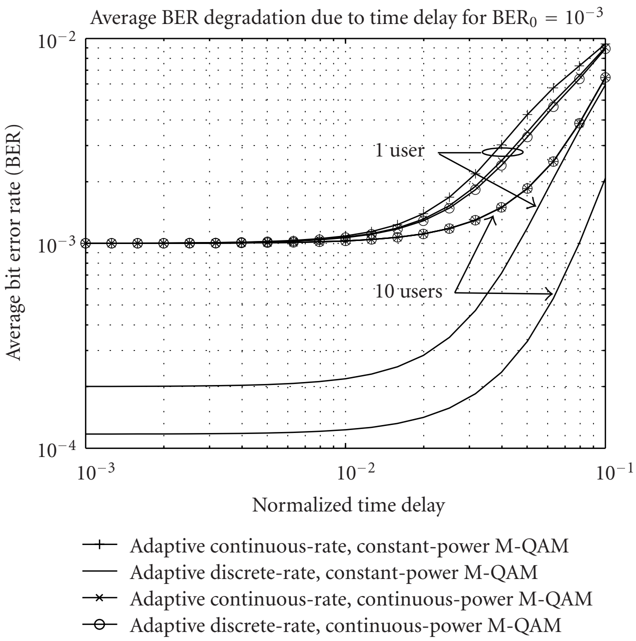

Figure 3: Average BER degradation due to time delay for M-QAM rate adaptation with $\overline{\gamma}$=15 dB, 5 fading regions, and $\text{BER}_0 = 10^{-3}$.

continuous-power, continuous-rate M-QAM is

$$\langle \text{BER} \rangle_{\text{acr,pa}} = \frac{\int_{\gamma_K}^{\infty} \text{BER}(\gamma) p_{\gamma^*}(\gamma) d\gamma}{\int_{\gamma_K}^{\infty} p_{\gamma^*}(\gamma) d\gamma}. \tag{29}$$

Correspondingly, the average BER for the continuous-power, discrete-rate M-QAM case is given by

$$\langle \text{BER} \rangle_{\text{adr,pa}} = \frac{\int_{\gamma_0^* M_1}^{\infty} \text{BER}(\gamma) p_{\gamma^*}(\gamma) d\gamma}{\int_{\gamma_0^* M_1}^{\infty} p_{\gamma^*}(\gamma) d\gamma}. \tag{30}$$

Figure 3 shows how outdated channel estimates affect the average BER for 1 and 10 users. We see that the average system BER is satisfactory as long as the normalized time delay again is below the critical value 10^{-2} for the adaptation schemes using continuous power and/or continuous rate. The constant-power, discrete-rate adaptation policy is more robust with regard to time delay.

7. CONCLUSION

We have analyzed a scheduling algorithm that has optimal spectral efficiency and reduced feedback compared with full feedback load. We obtain a closed-form expression for the CNR threshold that minimizes the feedback load for this algorithm. Both the impact of scheduling delay and outdated channel estimates are analytically and numerically described. For both delay scenarios plots show that the system will be able to operate satisfactorily with regard to BER when the normalized time delays are below certain critical values.

ACKNOWLEDGMENTS

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