MAXIMIZING THROUGPUT WITH ADAPTIVE M-QAM BASED ON IMPERFECT CHANNEL PREDICTIONS

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Abstract— **Uncoded adaptive M-QAM transmission over flat Rayleigh fading channels is here optimized in a novel way in the presence of channel prediction errors. The modulation rate is determined based on the predicted channel state. The modulation rate limits are adjusted by maximizing the throughput in error-free link-level frames, averaged over the pdf of the true channel state. No bit error rate constraint is imposed. This approach is appropriate when fast link-level retransmissions can be used to attain required error levels. The resulting scheme is evaluated analytically in a multiuser environment where predictive link adaptation is used in combination with a scheduling strategy that provides multiuser diversity gain. Prediction errors typical of prediction 1/3 wavelength ahead in space will then result in only 8% - 12% reduction in the spectral efficiency, as compared to a case with perfectly known channels. The resulting performance is very robust with respect to the prediction error variance assumed when optimizing the rate adaptation scheme.**

I. INTRODUCTION

A promising way of improving the spectral efficiency of radio interfaces beyond 3G is by performing fast adaptation of the transmission. For example, we may envision the downlink of an adaptive OFDM system. For each terminal, the signal-to-interference and noise ratio (SINR) of different subcarriers is measured and this information is then reported to a scheduler at the base station. This information is used by the scheduler to allocate time-frequency resources to different users, using link adaptation to maximize the throughput [1],[2].

Due to the delays involved in this feedback loop, allocation decisions would be based on outdated channel estimates. This becomes a major complication if such a system is intended to be used also by vehicular users. A feedback delay on the scale of milliseconds will then correspond to a significant fraction of the wavelength. The use of channel *predictions* instead of outdated estimates can reduce, but not eliminate, the estimation errors [3], [4], [5]. Erroneous channel power predictions may still lead to a large performance degradation [6]. It thus becomes important to quantify this performance loss, and to study how it could be minimized. This is the topic of the present paper.

The statistics of the prediction errors can be taken into account in the optimization of an adaptive modulation system, in which the modulation rate is selected based on the predicted channel SINR. This has been done for uncoded adaptive M-QAM in [7] and for Trellis-coded modulation in [8]. In both cases, single-user systems with flat Rayleigh fading channels were assumed and the optimizations were performed under bit error rate constraints. It was then found that the optimal SINR intervals for using a given modulation rate are raised significantly in fading dips (when the instantaneous SINR is below the average SINR). An adaptive modulation system optimized under a bit error rate constraint is there forced to act cautiously: It has to use lower order modulation than if the channel was exactly known, to attain the bit error rate constraint. This behavior reduces the spectral efficiency.

The present paper will address shared links with multiple users and will also present a new approach to optimizing link adaptation in the presence of channel prediction errors. A key observation is that placing bit-error rate constraints on the adaptive modulation scheme is unnecessary in packet data systems that include fast link-level retransmissions. The retransmission mechanism can be used to attain a residual bit error rate consistent with the required quality of service.

In Section IV, we therefore *maximize the expected value of the throughput in correct link-level frames*, without introducing any BER constraints. This is done based on the error statistics of the unbiased quadratic power predictor [5], presented in Section III, that was derived in [9]. It then turns out that the optimal modulation rate limits depend only weakly on the prediction uncertainty and on the average SINR. In fact, very little performance is lost by simply using the rate limits that would be optimal for perfect channel predictions. This simplifies the design considerably.

The adaptive modulation is combined with a scheduler which allocates the frame to the terminal that predicts the highest SINR relative to its own average. For Rayleigh fading channels, this gives all users equal chance to deliver frames, independent of their average SINR's and positions. Users with high average SINR's obtain higher throughput, since the link adaptation will on average deliver more bits per frame to them.

The resulting performance is evaluated analytically in Section VI for a situation with K active users who all have flat Rayleigh fading channels with the same average SINR. In particular, we investigate the improvement in spectral efficiency that is obtained by giving the channel to the user with the best predicted instantaneous SINR. (The scheduler reduces to this strategy when all users have the same average SINR). The case with perfect channel prediction was investigated in [2], where the multiuser diversity effect resulted in a strong increase of the spectral efficiency. Here, only a small loss of performance ($8\% - 12\%$) is encountered for prediction errors typical when predicting 1/3 wavelength ahead. At velocities of 100 km/h and 1900 MHz carriers, such prediction horizons correspond to 2 ms, which is a reasonable adaptation feedback delay.

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II. THE SYSTEM

Either uplink or downlink transmission is considered in a cell of an adaptive OFDM system containing K active users (terminals) [1]. For each terminal, the signal- to-interference and noise ratio (SINR) of different subcarriers is measured and this information is utilized by a scheduler at the base station. In one resource allocation round, a set of time-frequency bins (link-level frames) that each contains n_s payload symbols, are allocated exclusively to active users, normally to different users for different bins.

The bins are so small that the channel to user u in bin ℓ, $h_{u,\ell}$, can be assumed constant within the bin. The fading is assumed to be independent between different users u, but there may be correlation between the channels in different bins ℓ for the same user u. The received complex signal is given by

$$y_n = h_{u,\ell} s_n + v_n \quad , \tag{1}$$

where $n = 1, \ldots, n_s$ is a payload symbol position index within the bin. The noise and interference v_n will be assumed zero mean and Gaussian, with possibly bin-varying and user-dependent variance $\sigma^2_{v,u,\ell}$. This variance is in the following assumed known.

Above, s_n represents the transmitted symbol. For all signal constellations, the average symbol energy will be assumed constant and given by $E_s|s_n|^2 = \bar{S}$, where $E_s(\cdot)$ represents averaging over the constellation points. The symbols s_n are chosen among the constellations BPSK, 4-QAM, 8-Cross-QAM, 16-QAM, 32-Cross-QAM, 64-QAM, 128-Cross-QAM and 256-QAM. The rates, i.e. the corresponding numbers of bits per symbol, are denoted by $c_{u,\ell}$. All payload symbols within a bin use the same modulation format.

Coherent detection of payload symbols is assumed to be performed by the receiver, based on perfect channel estimates. This simplification is motivated since channel estimators can be constructed for adaptive OFDM systems which result in estimation error variances much smaller than the noise variance, see e.g. [10]. Thus, the error probability will mainly be determined by the SINR, not by the estimation error variance. The effect of channel estimation errors on adaptive M-QAM has been studied separately, see e.g. [11].

The instantaneous SINR for user u in bin ℓ and the corresponding average SINR are defined by

$$\gamma_{u,\ell} = \frac{|h_{u,\ell}|^2 \bar{S}}{\sigma^2_{v,u,\ell}} \quad ; \quad \bar{\gamma}_{u,\ell} = \frac{E_h|h_{u,\ell}|^2 \bar{S}}{\sigma^2_{v,u,\ell}} = \frac{\sigma^2_h \bar{S}}{\sigma^2_{v,u,\ell}} \; , \tag{2}$$

respectively, where σ^2_h is the average channel power gain and where the average symbol energy $\bar{S}$ has been used in both definitions. Above, $E_h(\cdot)$ denotes an average over the statistics of the short-term variability of $h_{u,\ell}$. It is assumed that $\bar{\gamma}_{u,\ell}$ is known for all u and all ℓ.

III. THE PREDICTOR

The channel power gains $p_{u,\ell} = |h_{u,\ell}|^2$ are assumed to be predicted by unbiased quadratic power predictors [5],

$$\hat{p}_{u,\ell} = |\hat{h}_{u,\ell}(t|t-L)|^2 + \sigma^2_h - \sigma^2_{\hat{h}} \quad . \tag{3}$$

Here, $\hat{h}_{u,\ell}(t|t-L)$ is a linear prediction of the complex channel $h_{u,\ell}$ with prediction horizon L, based on the measurements up to time $t-L$, and $\sigma^2_{\hat{h}} = E|\hat{h}_{u,\ell}(t|t-L)|^2$. The properties of this predictor that are relevant for the present purpose are summarized below.

When $\hat{h}_{u,\ell}$ is a linear MMSE prediction of $h_{u,\ell}$, the squared magnitude of the predicted complex tap will constitute a biased (under-estimated) prediction of the power [9]. The term $\sigma^2_h - \sigma^2_{\hat{h}}$ in (3) compensates for this bias and reduces the MSE. Since the noise and interference powers $\sigma^2_{v,u,\ell}$ are here assumed known, the predictions $\hat{p}_{u,\ell}$ then provide unbiased SINR predictions $\hat{\gamma}_{u,\ell} = \hat{p}_{u,\ell}\bar{S}/\sigma^2_{v,u,\ell}$ of $\gamma_{u,\ell}$.

Introduce the prediction error MSE of the complex channel, the corresponding normalized prediction error variance and the power prediction error MSE as

$$\begin{aligned} \sigma^2_{\epsilon_c} &= E_h|h_{u,\ell} - \hat{h}_{u,\ell}(t|t-L)|^2 \; , & (4) \\ \tilde{\sigma}^2 &= \sigma^2_{\epsilon_c}/\sigma^2_h \; , & (5) \\ \sigma^2_{\epsilon_p} &= E_h|p_{u,\ell} - \hat{p}_{u,\ell}(t|t-L)|^2 \; . & (6) \end{aligned}$$

When MMSE-optimally adjusted linear predictors $\hat{h}_{u,\ell}(t|t-L)$ are used in (3), it can be shown [9] that

$$\sigma^2_{\epsilon_p} = \sigma^2_{\epsilon_c}[2\sigma^2_h - \sigma^2_{\epsilon_c}] \quad . \tag{7}$$

For a Rayleigh fading channel, with $h_{u,\ell}$ complex Gaussian, $E_h|h_{u,\ell}|^4 = 2(\sigma^2_h)^2$. The normalized mean square SINR prediction error (NMSE), defined as

$$\sigma^2_{\Delta\gamma/\gamma} = \frac{E_h|\gamma_{u,\ell} - \hat{\gamma}_{u,\ell}|^2}{E_h|\gamma_{u,\ell}|^2} \quad , \tag{8}$$

is then by (2),(7) and (5) given by

$$\sigma^2_{\Delta\gamma/\gamma} = \frac{\sigma^2_{\epsilon_p}}{E_h|h_{u,\ell}|^4} = \frac{\sigma^2_{\epsilon_c}[2\sigma^2_h - \sigma^2_{\epsilon_c}]}{2(\sigma^2_h)^2} = \tilde{\sigma}^2(1 - 0.5\tilde{\sigma}^2). \tag{9}$$

Use of $\hat{\gamma}_{u,\ell} = \bar{\gamma}_{u,\ell}$ would give $\tilde{\sigma}^2 = 1$ and $\sigma^2_{\Delta\gamma/\gamma} = 0.5$. The prediction NMSE grows with the prediction horizon. In oversampled channels that allow efficient noise reduction, the level $\sigma^2_{\Delta\gamma/\gamma} = 0.10$ will for flat Rayleigh fading channels correspond to prediction 0.33 wavelengths ahead [5]. At carrier frequency 1900 MHz, this corresponds to a prediction horizon of 2 ms if the vehicle travels at 100 km/h. A velocity of 50 km/h would for the same horizon in time correspond to 0.16 wavelength. The attainable prediction error NMSE is then much better, around 0.02. We will however use the rather extreme case of all users having NMSE=0.1 in the evaluation.

When using the unbiased predictor (3) on a Rayleigh fading channel, it can be shown ([9], eq. (8.10)) that the pdf of the SINR prediction is for $\tilde{\sigma}^2 < 1$ given by

$$f_{\hat{\gamma}}(\hat{\gamma}_{u,\ell}) = \frac{U((\hat{\gamma}/\bar{\gamma}) - \tilde{\sigma}^2)}{\bar{\gamma}(1 - \tilde{\sigma}^2)} \exp\left[-\frac{(\hat{\gamma}/\bar{\gamma}) - \tilde{\sigma}^2}{1 - \tilde{\sigma}^2}\right] \quad , \tag{10}$$

where $U(x)$ is Heaviside's step function. Due to the bias compensation, the power prediction has a lower limit $\hat{\gamma}/\bar{\gamma} \geq \tilde{\sigma}^2$. The indexes u, ℓ were omitted in this expressions, as will also be done below, when not needed for clarity.

Furthermore, the pdf of $\gamma_{u,\ell}$ conditioned on the prediction $\hat{\gamma}_{u,\ell}(t|t-L)$ will be given by ([9], eq. (8.8))

$$f_\gamma(\gamma|\hat{\gamma}) = \frac{U(\gamma)U((\hat{\gamma}/\bar{\gamma}) - \bar{\sigma}^2)}{\bar{\gamma}\,\bar{\sigma}^2} \exp\left[-\frac{(\gamma/\bar{\gamma}) + (\hat{\gamma}/\bar{\gamma}) - \bar{\sigma}^2}{\bar{\sigma}^2}\right] \times \mathrm{I}_0\left(\frac{2}{\bar{\sigma}^2}\sqrt{\frac{\gamma}{\bar{\gamma}}\left(\frac{\hat{\gamma}}{\bar{\gamma}} - \bar{\sigma}^2\right)}\right) , \quad (11)$$

where $\mathrm{I}_0(\cdot)$ is the modified Bessel function of order zero.

IV. Adaptive Modulation

We strive towards a simple solution in which the resource allocation problem is solved in two steps. First, the SINR of each bin ℓ is predicted for each user u and a corresponding capacity measure $b_{u,\ell}$ is reported to the scheduler. The scheduler then allocates bins based on this information.

A. The Bin Capacity

Modulation rates $c_{u,\ell}$ are to be selected for each user u for potential use in each bin ℓ. These choices are to be made based on channel SINR predictions $\hat{\gamma}_{u,\ell}$ and the related statistics of the channel variability and the prediction errors.

A possible criterion could be to maximize the spectral efficiency under a bit error rate constraint, as explored in e.g. [12] for single-user systems. However, in most proposed wireless systems for packet data, erroneous link-level frames are detected with high probability and link-level retransmissions are performed. It is then not at all obvious what BER level is appropriate. It seems simpler and more efficient to instead maximize the throughput in correct bins. (Correct bits in bins that contain errors will be discarded together with the whole bin, and will have to be retransmitted.) The bin rejection probability, or frame rejection probability $p_f(c_{u,\ell}, \gamma_{u,\ell})$ will depend on the utilized modulation rate $c_{u,\ell}$ and on the encountered SINR $\gamma_{u,\ell}$. The modulation rate is determined based on the prediction $\hat{\gamma}_{u,\ell}$ and its statistics, and the true $\gamma_{u,\ell}$ may of course differ from $\hat{\gamma}_{u,\ell}$. The *bin capacities* $b_{u,\ell}$ will be defined as the *average number of accepted bits per symbol*:

$$b_{u,\ell} = E_\gamma[c_{u,\ell}(1 - p_f(c_{u,\ell}, \gamma))] , \quad (12)$$

where $E_\gamma(\cdot)$ represents an average over the true (unknown) SINR $\gamma_{u,\ell}$. In the following, we assume that the symbol errors are *independent*, due to that the Gaussian noise is here assumed white and that the channel has earlier been assumed constant within bins. With symbol error probability $p_s(c_{u,\ell}, \gamma)$, the frame rejection probability for bins with n_s symbols is then

$$p_f(c_{u,\ell}, \gamma) = 1 - (1 - p_s(c_{u,\ell}, \gamma))^{n_s} . \quad (13)$$

Thus,

$$b_{u,\ell} = c_{u,\ell} E_\gamma[(1 - p_s(c_{u,\ell}, \gamma))^{n_s}] \quad \text{[bits/symbol]} . \quad (14)$$

Maximizing the throughput within correct bins will always maximize the throughput of accepted bits for any link-level retransmission scheme. For example, if an infinite number of retransmissions is allowed, payload frames that are unsuccessfully transmitted will always be successfully transmitted at a later stage. Assuming that p_f is constant, it can then be shown that the fraction $1 - p_f$ of frames will be used for new bits, while the fraction p_f will be utilized for retransmissions.

B. Optimization of Rate Limits

Assume that uncoded BPSK or uncoded M-QAM is used. With the interference v_n in (1) assumed to be Gaussian, the symbol error probability $p_s(c_{u,\ell}, \gamma)$ will, for $M = 2^{c_{u,\ell}}$, be given by ([13], Chapter 4)

$$p_s = \begin{cases} 0.5\,\mathrm{erfc}(\sqrt{\gamma}) & c_{u,\ell} = 1 \\ 1 - \left[1 - \left(1 - \frac{1}{\sqrt{M}}\right)\mathrm{erfc}\left(\sqrt{\frac{3\gamma}{2(M-1)}}\right)\right]^2 & c_{u,\ell} = 2,4,6,8 \\ 1 - \left[1 - \mathrm{erfc}\left(\sqrt{\frac{3\gamma}{2(M-1)}}\right)\right]^2 & c_{u,\ell} = 3,5,7 \end{cases} . \quad (15)$$

The first and second expressions are exact, while the third is a tight upper bound.

The *switching levels* $\hat{\gamma}_i$, can now be adjusted to maximize $b_{u,\ell}$. They are the SINR thresholds for using the modulation rate $c_{u,\ell} = i + 1$, $i = 0, \ldots, 7$ in the interval $\hat{\gamma}_i < \hat{\gamma} \leq \hat{\gamma}_{i+1}$, with $\hat{\gamma}_8 = \infty$, A switching level is characterized by the property that the gain in $b_{u,\ell}$ obtained with a higher modulation rate $c_{u,\ell} + 1$ would be exactly balanced by the loss due to a lower frame acceptance rate $E_\gamma(1 - p_f) = E_\gamma(1 - p_s)^{n_s}$.

i	Modulation	$c_{u,\ell}$	NMSE 0 $\hat{\gamma}_i$ (dB)	NMSE 0.1 $\hat{\gamma}_i$ (dB)
0	BPSK	1	$-\infty$	(6.23)
1	4-QAM	2	8.70	8.39
2	8 Cross-QAM	3	13.53	14.39
3	16-QAM	4	16.88	17.61
4	32 Cross-QAM	5	20.46	21.03
5	64-QAM	6	23.39	23.91
6	128 Cross-QAM	7	26.86	27.07
7	256-QAM	8	29.94	30.05

TABLE I

Optimized switching levels $\hat{\gamma}_i$ for the lowest SINR per symbol and receiver antenna for using modulation with $c_{u,\ell}$ bits per symbol. Optimized for $n_s = 108$ symbols per bin, for the case of perfect prediction and for power prediction NMSE 0.1 at average SINR 16 dB.

Let us first consider the case with perfect predictions. The averaging $E_\gamma(\cdot)$ then becomes superfluous in (14) and the balance equation at $\hat{\gamma}_i = \gamma_i$ is given by

$$c_{u,\ell}(1 - p_s(c_{u,\ell}, \gamma_i))^{n_s} = (c_{u,\ell} + 1)(1 - p_s(c_{u,\ell} + 1, \gamma_i))^{n_s} . \quad (16)$$

When the SINR prediction is uncertain, the average over the true γ is taken in (14), using the conditional pdf

$$b_{u,\ell} = c_{u,\ell} \int_0^\infty [1 - p_s(c_{u,\ell}, \gamma)]^{n_s} f_\gamma(\gamma|\hat{\gamma})\, d\gamma . \quad (17)$$

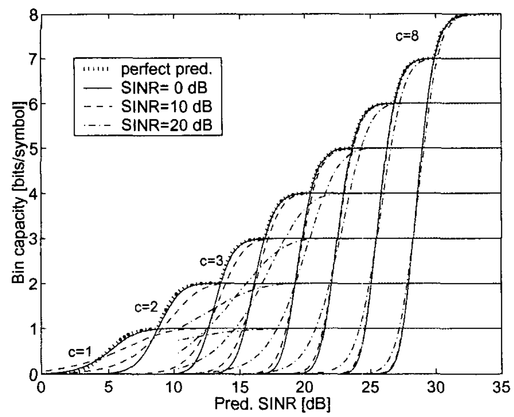

Fig. 1. Bin capacity $b_{u,\ell}$ by (17) as a function of the instantaneous SINR for SINR prediction NMSE 0.1 and $n_s = 108$, at modulation rates $c_{u,\ell} \in [1,\ldots,8]$, for average SINR 0 dB (solid), 10 dB (dashed) and 20 dB (dash-dotted). Compare to perfect prediction (dotted).

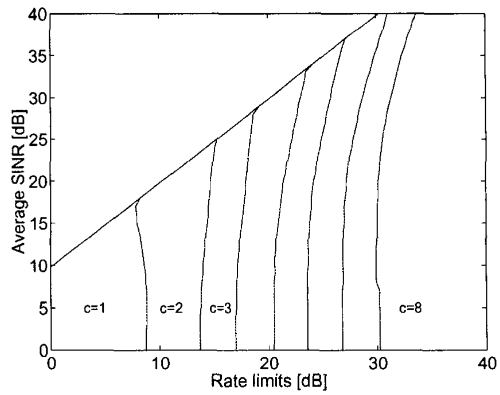

Fig. 2. Optimized modulation rate limits for modulation rates $c_{u,\ell} \in [1,\ldots,8]$ as a function of the average SINR when the SINR prediction NMSE is 0.1. The diagonal line represents the lower limit $\hat{\gamma}/\bar{\gamma} \geq \tilde{\sigma}^2$ for predicted SINR's obtained by the unbiased predictor.

With uncertain predictions, the balance equation (16) for determining the switching levels $\hat{\gamma}_i$ is modified to

$$c_{u,\ell}\int_0^\infty [1-p_s(c_{u,\ell},\gamma)]^{n_s} f_\gamma(\gamma|\hat{\gamma}=\hat{\gamma}_i)\,d\gamma$$
$$=(c_{u,\ell}+1)\int_0^\infty [1-p_s(c_{u,\ell}+1,\gamma)]^{n_s} f_\gamma(\gamma|\hat{\gamma}=\hat{\gamma}_i)\,d\gamma. \quad (18)$$

We in the following evaluate the design for $n_s = 108$ payload symbols per bin, as in the proposed system of [1], [2]. Rayleigh fading statistics of $\gamma_{u,\ell}$ and the use of the predictor (3) is assumed, so we use the expression (11) for $f_\gamma(\gamma|\hat{\gamma})$ in (17),(18). The resulting SINR thresholds are presented in Table 1. The function (17) is illustrated for different rates and different instantaneous predicted SINR's in Fig. 1.

The variation of the rate limits with the average SINR $\bar{\gamma}$ is illustrated in Fig. 2 for NMSE 0.1. It is evident that the rate limits that are active in fading dips $\hat{\gamma}_i < \bar{\gamma}$ are raised somewhat, but that this effect is rather small.

V. Scheduling

Opportunistic scheduling is designed to in some way utilize the variability of the channel to increase the total throughput. The here considered scheduler selects the user who has the highest normalized predicted SINR, i.e the highest SINR *relative to its own average*,

$$\tilde{\gamma}_m = \max_u \tilde{\gamma}_{u,\ell} = \max_u \frac{\hat{\gamma}_{u,\ell}}{\bar{\gamma}_{u,\ell}} \quad . \quad (19)$$

We will here assume that all users have Rayleigh fading statistics and have the same normalized prediction error variance $\tilde{\sigma}^2$ defined by (5). The pdf of $\tilde{\gamma}_{u,\ell}$ will then be equal for all users u. The scheduling rule $\max_u \tilde{\gamma}_{u,\ell}$ will then maximize the capacity allocated to each user, under the constraint that users are given equal chance to obtain bins. The rule is related to the proportional fair scheduler discussed in [14], which normalizes $\hat{\gamma}_{u,\ell}$ by the windowed throughput of user u.

The pdf of $\tilde{\gamma}_m = \max_u \tilde{\gamma}_{u,\ell}$ determines the resulting spectral efficiency. By (10), the CDF of $\tilde{\gamma}_{u,\ell}$ is

$$C(\tilde{\gamma}_{u,\ell}) = U(\tilde{\gamma}-\tilde{\sigma}^2)\left(1-\exp\left[\frac{-\tilde{\gamma}+\tilde{\sigma}^2}{1-\tilde{\sigma}^2}\right]\right) \quad . \quad (20)$$

Since the channels to the K users are assumed independently fading with equal cdf's (20), the cdf of $\tilde{\gamma}_m$ will be

$$C_m(\tilde{\gamma}_m) = (C(\tilde{\gamma}_m))^K = U(\tilde{\gamma}_m-\tilde{\sigma}^2)\left(1-\exp\left[\frac{-\tilde{\gamma}_m+\tilde{\sigma}^2}{1-\tilde{\sigma}^2}\right]\right)^K . \quad (21)$$

The pdf of $\tilde{\gamma}_m$ is then obtained by differentiating (21) with respect to $\tilde{\gamma}_m$, and it is given by $c_m(\tilde{\gamma}_m) =$

$$\frac{U(\tilde{\gamma}_m-\tilde{\sigma}^2)}{1-\tilde{\sigma}^2}K\left(1-\exp\left[\frac{-\tilde{\gamma}_m+\tilde{\sigma}^2}{1-\tilde{\sigma}^2}\right]\right)^{K-1}\exp\left[\frac{-\tilde{\gamma}_m+\tilde{\sigma}^2}{1-\tilde{\sigma}^2}\right]. \quad (22)$$

The spectral efficiency is obtained as

$$\bar{\eta} = \sum_{i=0}^{7}(1+i)\int_{\hat{\gamma}_i}^{\hat{\gamma}_{i+1}} E_\gamma[(1-p_s(c_{\kappa(\ell),\ell},\gamma))^{n_s}] f_{\hat{\gamma}}(\hat{\gamma}_m)\,d\hat{\gamma}_m, \quad (23)$$

where $\hat{\gamma}_m$ is the SINR's of the selected users. If all potential users have the same average SINR $\bar{\gamma}$, the pdf $f_{\hat{\gamma}}(\hat{\gamma}_m)$ required in (23) can be obtained from (22) as $f_{\hat{\gamma}}(\hat{\gamma}_m) = (1/\bar{\gamma})c_m(\hat{\gamma}_m/\bar{\gamma})$.

VI. Sum Capacity for K Users with Equal SINR

We here consider the adaptive modulation of Section IV used together with the opportunistic scheduler of Section V in a situation where all users have the same average SINR $\bar{\gamma}$. Fig. 3 shows $\bar{\eta}$ as a function of $\bar{\gamma}$ for different levels of prediction uncertainty when using optimized switching levels. The capacity is reduced by only 12% for $K = 1$ and by 8% for $K = 20$ users at NMSE 0.1. Fig. 4 shows the corresponding frame error rates. Fig. 5 illustrates several interesting properties at $\bar{\gamma} = 16$ dB. First, note the strong increase of the spectral efficiency with the number of active users K, due to the properties of the pdf (22). This is called the multiuser diversity effect [15]. Second, the relatively large prediction error represented by an NMSE 0.1 results in only a small reduction of the average capacity. As could be suspected from Fig. 1 and Fig. 2, little capacity is lost by using the rate limits optimized without taking prediction errors into account. However, the lower dash-dotted line for $\bar{\sigma}^2 = 0.9$ and NMSE 0.495 illustrates the importance of having a reasonably small prediction error. In this case, which almost corresponds to just predicting the average power level, we can no longer "ride the peaks", and allocate the bin to the best user, since the peaks become unpredictable. The multiuser diversity effect is therefore lost.

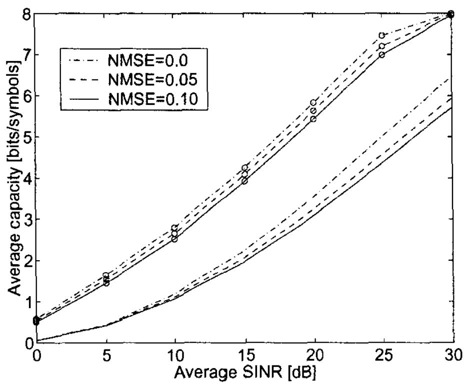

Fig. 3. Spectral efficiency (23) as a function of the average SINR which is equal for all users for $K = 1$ terminal (lower curves) and $K = 20$ (upper curves with markers). Results for perfect predictions (dash-dotted) NMSE 0.05 (dashed) and NMSE 0.10 (solid).

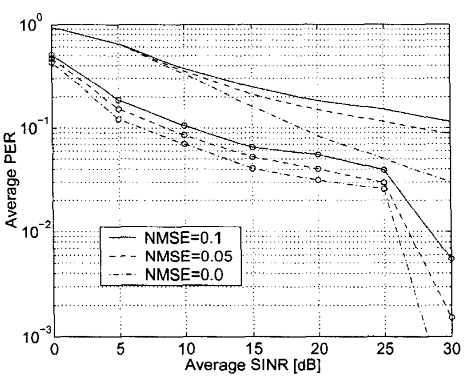

Fig. 4. Average frame error rate as a function of the average SINR, which is equal for all users, for $K = 1$ and $K = 20$ terminals (with markers). Results for 108 symbols per frame.

VII. Concluding Remarks

A method for adaptive modulation based on uncertain SINR predictions has been proposed, and it was evaluated analytically assuming all users having the same average SNR. The performance in more realistic cases with users having

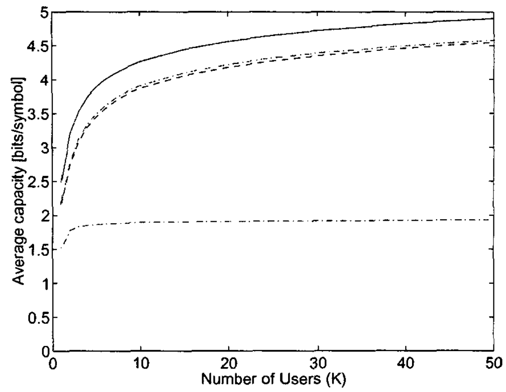

Fig. 5. Spectral efficiency (23) when all users have average SINR 16 dB, and the user with highest SINR among K terminals with Rayleigh fading channels is selected. Solid: perfect prediction. Dash-dotted: prediction NMSE $\sigma^2_{\Delta\gamma/\gamma} = 0.1$, with optimized rate limits. Dashed: prediction NMSE 0.1, rate limits as for perfect prediction. Lower dash-dotted: NMSE 0.495.

differing fading statistics is under investigation. The sensitivity to prediction errors when using coded M-QAM is also under investigation. We may expect the sensitivity of some such schemes to increase with a decreasing code rate.

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