Optimal Power Control for Discrete-Rate Link Adaptation Schemes with Capacity-Approaching Coding

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***Abstract*— In wireless communications, bandwidth is a scarce resource. By employing link adaptation we achieve bandwidth-efficient wireless transmission schemes. We propose a variable-power transmission scheme for slowly varying flat-fading channels using a fixed number of codes. Assuming that capacity-achieving codes for AWGN channels are available, the proposed power adaptation scheme maximizes the average spectral efficiency (ASE) for any finite number N of available rates. We show that the power adapted transmission scheme, using just four different rates, achieves a spectral efficiency within 0.15 bits/s/Hz of the Shannon capacity for continuous rate and power adaptation. Further, when restricted to N optimally chosen rates, introducing power adaptation has significant ASE and outage probability gains over a constant power scheme.**

I. Introduction

Link adaptation, in particular adaptive coded modulation (ACM), is a promising technique to increase throughput in wireless communication systems affected by fading. Today, adaptive schemes are already proposed for implementation in wireless systems such as Digital Video Broadcasting - Satellite Version 2 (DVB-S2) [1]. The underlying premise of ACM is its ability to adapt to a time-varying channel through variation of channel codes, modulation constellations and transmitted power [2]–[7]. Consider a wireless channel with additive white gaussian noise and fading. Under the assumption of slowly varying, frequency-flat fading, the channel can be approximated by a block fading channel [8], [9], so within the length of a codeword the transmitter sees a constant AWGN channel. Hence, an adaptive system such as shown in Fig. 1 can be designed to use codes that guarantee a certain bit error rate (BER) within a range of channel-signal-to-noise-ratios (CSNRs) on an AWGN channel. Based on a prediction of the channel, the highest spectral efficiency (SE) code satisfying the BER constraint is chosen. Adapting to the channel in such a way makes it possible to achieve a significant gain in *average spectral efficiency* (ASE), measured in information bits/s/Hz.

In [3], [4], [10] adaptive systems are designed subject to N *given* codes. The switching levels $\gamma_1, \gamma_2, \cdots, \gamma_N$ between the N codes are obtained by analyzing the codes in order to find at which CSNR level they will fulfill a certain bit error rate requirement BER $\leq$ BER$_0$ on an AWGN channel.

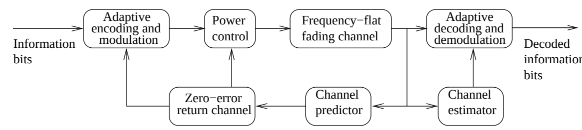


Fig. 1. System model.

Under the assumption of perfect channel knowledge at the transmitter, this approach will always provide an instantaneous BER $\leq$ BER$_0$. The average bit error rate will then typically be strictly smaller than BER$_0$. Since the lower average BER can be increased until it reaches BER$_0$, BER can be traded for a larger ASE, and thus the approach is not optimal from an ASE point of view.

In [11] a different approach is proposed. Given the number of codes, N, and assuming that capacity approaching codes for AWGN channels are available for any rate, the switching levels and corresponding rates are chosen such that they are optimal with respect to maximal ASE. An upper bound on the ASE of a practical ACM scheme with a finite set of discrete rates to choose between, is then denoted by the *maximum ASE for ACM* (MASA) [11].

Without power adaptation, the adaptive coded modulation scheme derived in [11] is restricted to N degrees of freedom corresponding to the number of permissible rates. From previous work by Chung and Goldsmith [10] we know that the spectral efficiency of such a restricted adaptive system increases if more degrees of freedom are allowed. In this paper we optimize a discrete-rate continuous-power ACM system to maximize the average spectral efficiency, while satisfying an average power constraint. We show that introducing power adaptation provides substantial ASE and outage probability gains when the number of rates is finite.

The remainder of the present paper is organized as follows. We introduce the wireless system model under investigation in Section II. In Section III we show results for the MASA with constant transmit power and then derive the optimal power adaptation scheme for a discrete-rate continuous-power MASA system. Section IV shows numerical results and plots of the maximum average spectral efficiencies for both MASA schemes, comparing them to the theoretical upper bounds given by the corresponding Shannon capacities. Finally, conclusions are listed in Section V.

II. System Model

We consider the single-link wireless system depicted in Fig. 1. The discrete-time channel is a wide-sense stationary (WSS) fading channel with time-varying gain. The fading is assumed to be slow and frequency-flat. Transmitting with signal power $\bar{S}$, we denote the instantaneous *pre-adaptation* received signal-to-noise ratio (SNR) by $\gamma[i]$ and the average pre-adaptation received SNR by $\bar{\gamma}$. Assuming that the transmitter receives perfect channel predictions, sent over a zero-error and zero-delay feedback channel, we can adapt the transmit power instantaneously at time i according to a power adaptation scheme $S(\gamma[i])$. The received *post-adaptation* SNR at time i is then given by $\gamma[i]S(\gamma[i])/\bar{S}$. By virtue of the WSS assumption, the distribution of $\gamma[i]$ is independent of the time index i and is denoted by $f_\gamma(\gamma)$. To simplify the notation we omit the time reference i from now on.

The transmission scheme under consideration is based on a set of N codes. Following [3], [11], we partition the range of γ into $N+1$ pre-adaptation SNR regions, which are defined by the switching thresholds $\{\gamma_n\}_{n=1}^N$ as illustrated in Fig. 2. Code n, with spectral efficiency R_n, is selected whenever γ is in the interval $[\gamma_n, \gamma_{n+1})$, implying a constant transmission rate within each region. For convenience, we let $\gamma_0 = 0$ and $\gamma_{N+1} = \infty$.

III. MASA Analysis

Using N distinct codes we first examine the MASA for a constant transmission power scheme. We then derive the optimal power adaptation scheme for discrete rates. We shall assume that the fading is so slow that capacity-achieving codes for AWGN channels can be employed, giving relatively tight upper bounds on the MASA [12], [13]. Now, recall that pre-adaptation SNR region n in an adaptive system is lower bounded by γ_n. Thus, we let $R_n = C_n$, where $C_n = \log_2\big(1 + \frac{S(\gamma_n)}{\bar{S}}\gamma_n\big)$ is shown below to be the highest spectral efficiency that can be supported within the range $[\gamma_n, \gamma_{n+1})$ for $1 \le n \le N$, after transmit power adaptation. Note that the fading is nonergodic within each codeword, and the results of [14, Section IV] do not apply.

Following [11], the basic principle is to create an expression for the MASA using a parameterized power adaptation scheme. The optimal switching thresholds and power adaptation parameters are then found by optimization techniques. In general the MASA, under the restriction of utilizing capacity-achieving codes designed for AWGN channels, is given by

$$\text{MASA} = \sum_{n=1}^{N} C_n P_n, \tag{1}$$

where $P_n = \int_{\gamma_n}^{\gamma_{n+1}} f_\gamma(\gamma)\,\mathrm{d}\gamma$ is the probability that code n be employed at any given time.

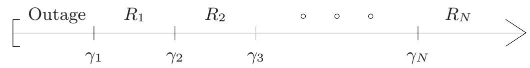


Fig. 2. The range of γ is partitioned into pre-adaptation SNR regions where $\{\gamma_n\}_{n=1}^N$ are the switching thresholds.

For a fading channel with AWGN, the MASA is thus given by (in bits/s/Hz)

$$\text{MASA} = \sum_{n=1}^{N} \log_2\Big(1 + \frac{S(\gamma_n)}{\bar{S}}\gamma_n\Big) \int_{\gamma_n}^{\gamma_{n+1}} f_\gamma(\gamma)\,\mathrm{d}\gamma, \tag{2}$$

subject to the average power constraint,

$$\sum_{n=0}^{N} \int_{\gamma_n}^{\gamma_{n+1}} S(\gamma) f_\gamma(\gamma)\,\mathrm{d}\gamma \le \bar{S}, \tag{3}$$

where $\bar{S}$ denotes the average transmit power. Eq. (2) is seen to be a discrete-sum approximation to the Shannon capacity given in [2, Eq. (4)].

A. Constant Transmission Power Scheme

When a single transmission power is used for all codes, we adopt the term *constant transmission power scheme* [15]. The optimal constant power policy is easily seen to be

$$\frac{S(\gamma)}{\bar{S}} = \begin{cases} \frac{1}{1-F_\gamma(\gamma_1)}, & \text{if } \gamma_n \le \gamma < \gamma_{n+1}, \\ & 1 \le n \le N, \\ 0, & \text{if } \gamma < \gamma_1, \end{cases} \tag{4}$$

where $F_\gamma(\cdot)$ denotes the cumulative density distribution function (CDF) of γ. From (4) we see that the received post-adaptation SNR monotonically increases within $[\gamma_n, \gamma_{n+1})$ for $1 \le n \le N$. Hence, $\log_2\big(1 + \frac{S(\gamma_n)}{\bar{S}}\gamma_n\big)$ is the highest possible spectral efficiency that can be supported over the whole of region n.

Introducing (4) in (2) we obtain a new expression for the MASA, denoted by MASA_N:

$$\text{MASA}_N = \sum_{n=1}^{N} \log_2\Big(1 + \frac{\gamma_n}{1 - F_\gamma(\gamma_1)}\Big) \int_{\gamma_n}^{\gamma_{n+1}} f_\gamma(\gamma)\,\mathrm{d}\gamma. \tag{5}$$

The optimal switching thresholds $\{\gamma_n\}_{n=1}^N$ are found by numerical optimization.

B. Optimal Power Adaptation Scheme

For each pre-adaptation SNR region, $[\gamma_n, \gamma_{n+1})$, we again use a capacity-achieving code which ensures an arbitrarily low probability of error for any AWGN channel with received SNR greater than or equal to $\frac{S(\gamma_n)}{\bar{S}}\gamma_n$. To obtain the optimal power adaptation scheme we propose, for the N regions where we transmit, *piecewise channel inversion* to keep the received SNR constant within each region, much like the bit error rate is kept constant in optimal adaptation for constellation restrictions in [3]. Since the rate is restricted to be constant in each region, it intuitively makes sense from a capacity perspective to also keep the received SNR constant. The optimality of this strategy is formally proven below.

Lemma 1: For the $N+1$ SNR regions the optimal power adaptation scheme is of the form

$$\frac{S(\gamma)}{\bar{S}} = \begin{cases} \frac{\beta_n \gamma_n}{\gamma}, & \text{if } \gamma_n \leq \gamma < \gamma_{n+1}, \\ & 1 \leq n \leq N, \\ 0, & \text{if } \gamma < \gamma_1, \end{cases} \tag{6}$$

where $\{\beta_n, \gamma_n\}_{n=1}^{N}$ are parameters to be optimized.

Proof: Assume for the purpose of contradiction that the power scheme given in (6) is not optimal, i.e., it uses too much power for a given rate. Then, by assumption, there exists at least one point in the set

$$\bigcup_{n=1}^{N} \{\gamma : \gamma_n \leq \gamma < \gamma_{n+1}\} \tag{7}$$

where it is possible to use less power; denote this point by γ'. Fix any $\epsilon > 0$ and let $\frac{S(\gamma')}{\bar{S}} = \frac{\beta_n \gamma_n}{\gamma'} - \epsilon$. This yields a received SNR of $\beta_n\gamma_n - \epsilon\gamma' < \beta_n\gamma_n$, but is less than the required SNR for a rate of $\log_2(1+\beta_n\gamma_n)$. Hence, there does not exist any point where the proposed power scheme can be improved, and the assumption is contradicted. ■

From (6) it is seen that β_n is the transmitted power (normalized by $\bar{S}$) when $\gamma = \gamma_n$. Using (6) the received SNR, after power adaptation, is then for $n = 1, 2, \cdots, N$ given as:

$$\frac{S(\gamma)}{\bar{S}}\gamma = \begin{cases} \beta_n \gamma_n, & \text{if } \gamma_n \leq \gamma < \gamma_{n+1}, \\ 0, & \text{if } \gamma < \gamma_1, \end{cases} \tag{8}$$

i.e., we have constant received SNR within each region, supporting a maximum spectral efficiency of $\log_2(1 + \frac{S(\gamma_n)}{\bar{S}}\gamma_n)$.

Introducing the power adaptation scheme (6) in (2) we get a new expression for the MASA, denoted by $\text{MASA}_{\text{Power}}$:

$$\text{MASA}_{\text{Power}} = \sum_{n=1}^{N} \log_2(1+\beta_n\gamma_n) \int_{\gamma_n}^{\gamma_{n+1}} f_\gamma(\gamma)\, \mathrm{d}\gamma. \tag{9}$$

We now seek to maximize (9) under the power constraint (3). For this purpose we change the inequality in (3) to an equality, and by inserting (6) in the resulting average power constraint we find

$$\sum_{n=1}^{N} \beta_n \gamma_n \int_{\gamma_n}^{\gamma_{n+1}} \frac{1}{\gamma} f_\gamma(\gamma)\, \mathrm{d}\gamma = 1. \tag{10}$$

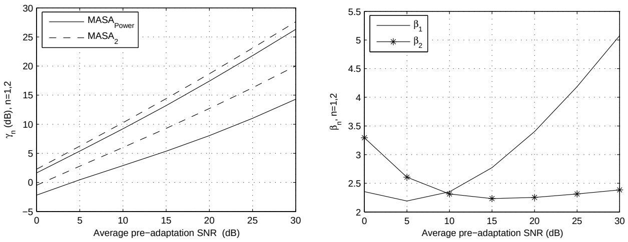
If we make a Rayleigh fading assumption the above constraint can be written in closed form as

$$\sum_{n=1}^{N} \beta_n \gamma_n \frac{1}{\bar{\gamma}} \left(E_1\left(\frac{\gamma_n}{\bar{\gamma}}\right) - E_1\left(\frac{\gamma_{n+1}}{\bar{\gamma}}\right)\right) = 1, \tag{11}$$

where $E_1(x)$ is the first order exponential integral defined by [16, p. xxxv]:

$$E_1(x) = \int_1^\infty \frac{1}{t} e^{-xt}\, \mathrm{d}t. \tag{12}$$

The optimal values of $\{\gamma_n, \beta_n\}_{n=1}^{N}$ are found through constrained numerical optimization. Details of the numerical optimization process are given in the Appendix. Numerical results for the resulting adaptive power policy and the corresponding spectral efficiencies are presented in Section IV.



(a) (b)

Fig. 3. (a) Switching levels as a function of average pre-adaptation SNR for $N = 2$. Solid lines: γ_1 (lowermost curve) and γ_2 (uppermost curve) for $\text{MASA}_{\text{Power}}$. Dashed lines: γ_1 (lowermost curve) and γ_2 (uppermost curve) for MASA_2. (b) Power parameters β_1 and β_2 for $\text{MASA}_{\text{Power}}$ versus average pre-adaptation SNR.

IV. Numerical Results

For the following numerical results, a Rayleigh fading distribution has been assumed.

A. Switching Thresholds and Power Adaptation

Figs. 3(a) and 3(b) respectively show the optimal switching levels $\{\gamma_n\}_{n=1}^{N}$ and power parameters $\{\beta_n\}_{n=1}^{N}$ for $N = 2$ and for $\bar{\gamma} \in [0, 30]$ dB. Increasing N yields similar results. We can interpret Figs. 3(a) and 3(b) as follows: given a number of codes N we find the switching thresholds for a given $\bar{\gamma}$. Then find the corresponding spectral efficiencies,

$$\text{SE}_n = \begin{cases} \log_2(1 + \frac{\gamma_n}{1-F(\gamma_1)}) & \text{for } \text{MASA}_N, \\ \log_2(1+\beta_n\gamma_n) & \text{for } \text{MASA}_{\text{Power}}. \end{cases} \tag{13}$$

For each $\bar{\gamma}$ of interest we then design optimal codes for these SE's, and use the adaptation schemes as given in (4) and (6) for MASA_N and $\text{MASA}_{\text{Power}}$, respectively. Table I shows numerical values for designing optimal systems with $N = 2$ for $\bar{\gamma} = 15$ dB. Fig. 4 illustrates the corresponding piecewise channel inversion power adaptation scheme $\frac{S(\gamma)}{\bar{S}}$ from (6). We see that the optimal transmit power $S(\gamma)$ ranges from 0 to $2.8\bar{S}$. In the analysis of Section III no stringent peak power constraint has been imposed, and as such it is interesting to note that $S(\gamma)$ does not take very high values.

B. Comparison of MASA Schemes

Under an average power constraint the average spectral efficiencies corresponding to MASA_N and $\text{MASA}_{\text{Power}}$, are plotted in Fig. 5 versus average pre-adaptation SNR. The plot shows that the power adapted system clearly outperforms the constant transmission power system. Specifically, we see that a constant power system needs four codes to reach the MASA of a power adapted system using just one code. This indicates that if the number of available codes is limited, there is much to gain by using power adaptation.

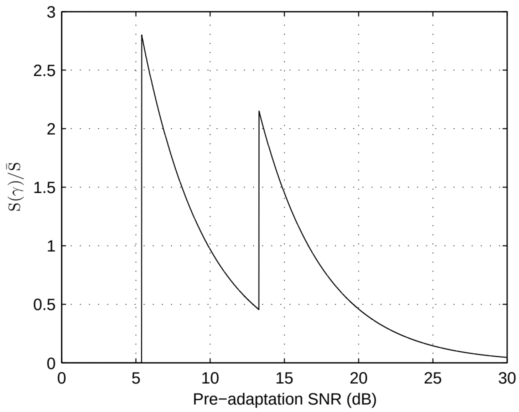


Fig. 4. Power adaptation scheme (6) as a function of pre-adaptation SNR at $\bar{\gamma} = 15$ dB.

TABLE I
RATE AND POWER ADAPTATION FOR TWO REGIONS, $\bar{\gamma} = 15\ \mathrm{dB}$

	MASA_2	$\mathrm{MASA}_{\mathrm{Power}}$
γ_1, γ_2 (dB)	9.3, 14.4	5.4, 13.2
β_1, β_2	-	2.8, 2.2
SE_1, SE_2 (bits/s/Hz)	3.2, 4.8	3.4, 5.6

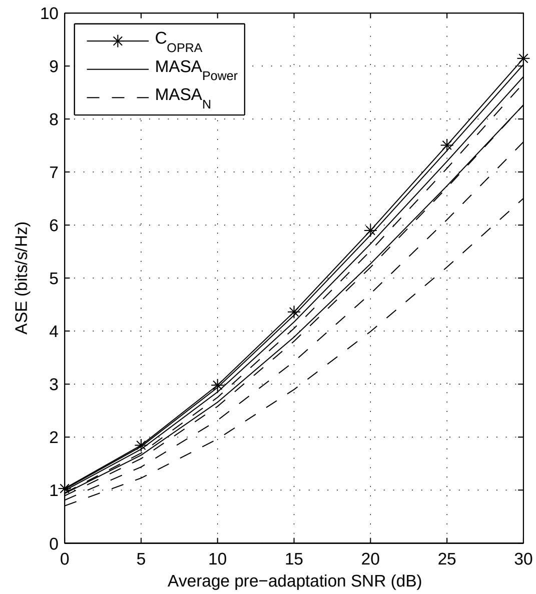


Fig. 5. Average spectral efficiency as a function of average pre-adaptation SNR. Solid lines: ASE of $\mathrm{MASA}_{\mathrm{Power}}$ with $N = 1$ (lowermost curve), $2, 4$ (uppermost curve). Dashed lines: ASE of MASA_N with $N = 1$ (lowermost curve), $2, 4, 8$ (uppermost curve). Solid-star line: ASE of C_{OPRA} as reference.

C. MASA versus Shannon Capacities

Assume that the channel state information γ is known to the transmitter and the receiver. Then, given an average transmit power constraint $\bar{S}$ the channel capacity of a Rayleigh fading channel with optimal *continuous* rate adaptation and constant transmit power, C_{ORA}, is given in [2], [17] as

$$C_{\mathrm{ORA}} = \log_2(e) e^{\frac{1}{\bar{\gamma}}} E_1\Big(\frac{1}{\bar{\gamma}}\Big). \tag{14}$$

Furthermore, if we include *continuous* power adaptation, the channel capacity, C_{OPRA}, becomes [2], [17]

$$C_{\mathrm{OPRA}} = \log_2(e)\Big(\frac{e^{\frac{-\gamma_c}{\bar{\gamma}}}}{\frac{\gamma_c}{\bar{\gamma}}} - \bar{\gamma}\Big), \tag{15}$$

where the "cutoff" value γ_c can be found by solving

$$\int_{\gamma_c}^{\infty} \Big(\frac{1}{\gamma_c} - \frac{1}{\gamma}\Big) f_\gamma(\gamma)\, \mathrm{d}\gamma = 1. \tag{16}$$

In principle MASA_N should be compared to C_{ORA}, while $\mathrm{MASA}_{\mathrm{Power}}$ should be measured against C_{OPRA}. But, as shown in [2], the difference between C_{ORA} and C_{OPRA} is negligible, so both MASA schemes will here be compared to C_{OPRA}.

The capacity in (15) can be achieved in the case that a continuum of capacity-achieving codes for AWGN channels, and corresponding optimal power levels, are available. That is, for each SNR there exists an optimal code and power level. Alternatively, we can attain C_{OPRA} by a fixed rate coding system as long as the single Gaussian code is long enough to reveal the ergodic properties of the channel [14], [18]. As the number of codes (switching thresholds) goes to infinity, MASA without power adaptation will reach the C_{ORA} capacity, while $\mathrm{MASA}_{\mathrm{Power}}$ will reach the C_{OPRA} capacity.

As shown in Fig. 5, both MASA schemes perform close to the theoretical upper bound (C_{OPRA}) for a small number of codes. Interestingly, we see that the power adapted MASA scheme, however, approaches the upper bound much faster, hence the power adaptation scheme has a significant effect. This is in contrast to the case of continuous rate adaptation, where introducing power adaptation gives negligible gain [2].

As a final remark we note that $\mathrm{MASA}_{\mathrm{Power}}$ for $N = 1$ gives, as expected, identical spectral efficiency to the Shannon capacity for truncated channel inversion given in [2, Eq. 12].

D. Probability of no transmission

The probability that the SNR be so low that the lowest code cannot guarantee a BER $\leq \mathrm{BER}_0$ is equivalent to the probability that the pre-adaptation SNR falls below γ_1, thus the outage probability can be calculated as

$$P_{\text{out}} = \int_0^{\gamma_1} f_\gamma(\gamma)\, \mathrm{d}\gamma. \tag{17}$$

Fig. 6 illustrates the outage probability for both MASA schemes as a function of the average pre-adaptation SNR. First, when the number of codes is increased, the lowest switching threshold γ_1 decreases, implying that the outage probability becomes smaller with increasing N. For a given N, $\mathrm{MASA}_{\mathrm{Power}}$ has a lower γ_1 than MASA_N, as illustrated in Fig. 3(a) for $N = 2$. Thus, introducing power adaptation significantly reduces the probability of no transmission, as shown in Fig 6.

It is not necessarily a disadvantage that the outage probability be high, unless the service under consideration has strict

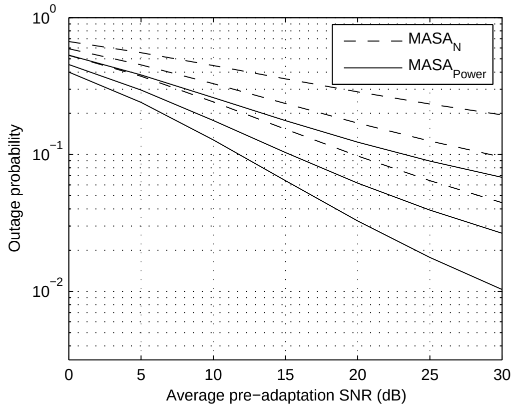


Fig. 6. Probability of outage as a function of average pre-adaptation SNR. Dashed lines: P_{out} for MASA_N with $N = 1$ (uppermost curve), $2, 4$ (lowermost curve). Solid lines: P_{out} for $\text{MASA}_{\text{Power}}$ with $N = 1$ (uppermost curve), $2, 4$ (lowermost curve).

real-time or low-delay requirements. For data-centric services, such as file or email transfer, the most important quality-of-service factor is the total time of data transmission. For large data sets, this time will be minimized independently of the value P_{out}, as long as the average spectral efficiency is maximized.

V. Conclusion

We have analyzed a capacity-achieving variable-rate and variable-power ACM scheme adapting to a time-varying communication channel. As long as capacity-achieving codes for AWGN channels are available, the proposed power adaptation scheme maximizes the average spectral efficiency for any finite number of available rates. The adaptive scheme presented in this paper is compared to the theoretical continuous-rate and continuous-power bound on spectral efficiency. Our results show that the power adapted MASA scheme using just four different rates achieves a spectral efficiency within 0.15 bits/s/Hz of the Shannon capacity for continuous rate and power adaptation. Further, introducing power adaptation for MASA has a large average spectral efficiency and outage probability gain over the constant power MASA scheme. As a result, we see that if the possible number of rates in a system is limited the gains which are achievable by introducing power adaptation are significant. This is of practical importance since it may be easier to implement the proposed power adaptation scheme than to design capacity-achieving codes for a large number of arbitrary rates.

The work in this paper can easily be extended to account for constraints on outage and block lengths as in [11]. Discrete power adaptation schemes (corresponding to quantized feedback) are treated in [19]. Extension to imperfect channel knowledge is a topic for further research.

Appendix

In Section III-B, to maximize (9) for $\gamma_n, \beta_n \geq 0$ ($n = 1, \cdots, N$) while satisfying the average power constraint (11), we use *MATLAB*. More specifically, we use the function `fmincon` from the Optimization Toolbox, allowing for a search for a constrained minimum of a function of several variables. Depending on the number of rates, N, for high values of $\bar{\gamma}$ the objective function can have very small variations for large variations of the γ_n's and β_n's. To remedy this we multiply the objective function by a positive constant and strengthen the termination tolerances used by `fmincon`, `TolX` and `TolFun`.

References

[1] Digital Video Broadcasting - Satellite Version 2. [Online]. Available: http://www.dvb.org.

[2] A. J. Goldsmith and P. P. Varaiya, "Capacity of fading channels with channel side information," *IEEE Transactions on Information Theory*, vol. 43, no. 6, pp. 1986–1992, Nov. 1997.

[3] A. J. Goldsmith and S.-G. Chua, "Variable-rate variable-power M-QAM for fading channels," *IEEE Transactions on Communications*, vol. 45, no. 10, pp. 1218–1230, Oct. 1997.

[4] K. J. Hole, H. Holm, and G. E. Øien, "Adaptive multidimensional coded modulation over flat fading channels," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 7, pp. 1153–1158, July 2000.

[5] H. Holm, "Adaptive coded modulation performance and channel estimation tools for flat fading channels," Ph.D. dissertation, Norwegian University of Science and Technology, 2002. [Online]. Available: http://www.tele.ntnu.no/projects/beats/Documents/HenrikHolmThesis.pdf

[6] B. Holter, "Adaptive coded modulation in spatial and multiuser diversity systems," Ph.D. dissertation, Norwegian University of Science and Technology, 2005. [Online]. Available: http://www.tele.ntnu.no/projects/beats/Documents/holter-thesis.pdf

[7] L. Hanzo, C. H. Wong, and M.-S. Yee, *Adaptive Wireless Transceivers: Turbo-Coded, Turbo-Equalized and Space-Time Coded TDMA, CDMA and OFDM Systems*. John Wiley & Sons, Inc., 2002.

[8] R. J. McEliece and W. E. Stark, "Channels with block interference," *IEEE Transactions on Information Theory*, vol. IT-30, no. 1, pp. 44–53, Jan. 1984.

[9] L. H. Ozarow, S. Shamai (Shitz), and A. D. Wyner, "Information theoretic considerations for cellular mobile radio," *IEEE Transactions on Vehicular Technology*, vol. 43, no. 2, pp. 359–378, May 1994.

[10] S. T. Chung and A. J. Goldsmith, "Degrees of freedom in adaptive modulation: A unified view," *IEEE Transactions on Communications*, vol. 49, no. 9, pp. 1561–1571, Sep 2001.

[11] H. Holm, G. Øien, M.-S. Alouini, D. Gesbert, and K. J. Hole, "Optimal design of adaptive coded modulation schemes for maximum average spectral efficiency," in *Proc. IEEE Workshop on Signal Processing Advances in Wireless Communications*, Rome, Italy, June 2003.

[12] S. Dolinar, D. Divsalar, and F. Pollara, "Code performance as a function of code block size," in *JPL TDA Progress Report 42-133*, 1998. [Online]. Available: http://tmo.jpl.nasa.gov/tmo/progress_report/42-133/133K.pdf

[13] ——, "Turbo code performance as a function of code block size," in *Proc. IEEE International Symposium on Information Theory*, Cambridge, MA, Aug. 1998, p. 32.

[14] G. Caire and S. Shamai (Shitz), "On the capacity of some channels with channel state information," *IEEE Transactions on Information Theory*, vol. 45, no. 6, pp. 2007–2019, Sept. 1999.

[15] C. Köse and D. L. Goeckel, "On power adaptation in adaptive signalling systems," *IEEE Transactions on Communications*, vol. 48, no. 11, pp. 1769–1773, Nov. 2000.

[16] I. Gradshteyn and I. Ryzhik, *Table of Integrals, Series and Products*, 6th ed. San Diego: Academic Press, 2000.

[17] M.-S. Alouini and A. J. Goldsmith, "Capacity of Rayleigh fading channels under different adaptive transmission and diversity-combining techniques," *IEEE Transactions on Vehicular Technology*, vol. 48, no. 4, pp. 1165–1181, July 1999.

[18] E. Biglieri, J. Proakis, and S. Shamai (Shitz), "Fading channels: Information-theoretic and communications aspects," *IEEE Transactions on Information Theory*, vol. 44, no. 6, pp. 2619–2692, Oct. 1998.

[19] A. Gjendemsjø and G. E. Øien, "Optimal discrete-level power control for adaptive coded modulation schemes with capacity-approaching component codes," Submitted to IEEE International Conference on Communications 2006, Istanbul, Turkey.