

OPTIMAL DESIGN OF ADAPTIVE CODED MODULATION SCHEMES FOR MAXIMUM AVERAGE SPECTRAL EFFICIENCY

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Abstract— Adaptive coded modulation (ACM) is a promising tool for transmission in a fading environment. The main motivation for employing ACM schemes is to improve the spectral efficiency of wireless communications. In this paper, we present a method for optimizing the average spectral efficiency of an ACM system. One important result of this work is that only a small number of optimally designed codes is needed to yield throughput close to the Shannon limit.

Technical Area—Fundamental limits on capacity and performance analysis.

1. INTRODUCTION

An adaptive coded modulation (ACM) system [1]–[9] designed for a flat-fading wireless channel utilizes a set of channel codes and modulation constellations with different spectral efficiencies (SEs) and thus different error-protecting properties. Each code typically guarantees a certain bit error rate (BER) within a range of signal-to-noise ratios (SNRs) on an additive white Gaussian noise (AWGN) channel. At specific time instants, an estimate of the instantaneous SNR is utilized to decide the highest-SE code that can be used while still fulfilling the target BER requirement. The system thus compensates for periods with low SNR by transmitting at a low SE, while transmitting at a high SE when the SNR is favorable. This way, a significant overall gain in *average spectral efficiency* (ASE)—measured in information bits/s/Hz—can be achieved for a given BER level, compared to fixed-SE systems.

Previously, when analyzing ACM systems, a set of N codes has been given as a design criterion [1]–[3], [5] [6, Ch. 6]. The decision of which code to use has been made by assigning *switching levels* $s_1, s_2, \dots, s_N$ to the N codes. The switching levels are obtained by analyzing each of the codes in order to find at which SNR level the codes will fulfill a certain target BER requirement, $\text{BER} \leq \text{BER}_0$, on an AWGN channel. This way, the range of SNRs from 0 to ∞ is quantized into regions bordered by the switching levels. An illustration of a typical SNR range partitioning is shown in Fig. 1.

The above approach will—under the idealized assumption of perfect channel knowledge at the transmitter—always provide an instantaneous $\text{BER} \leq \text{BER}_0$. The *average* BER is therefore typically strictly smaller than BER_0 . Thus, a system

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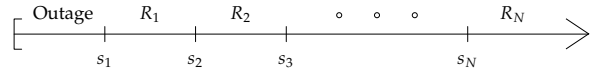


Fig. 1. The SNR range is partitioned into regions where s_n are the switching levels.

designed according to the above scheme will not be optimal from the ASE point of view, since the lower average BER could be increased until it reaches BER_0 , thus trading BER for a larger ASE. Several authors [5], [6, Ch. 6], [9] have suggested a method of re-designing the switching levels under such a constraint on the average BER_0 , rather than on the instantaneous BER. In this paper, we propose a different approach, deriving the switching levels that are optimal for a given fading distribution, from an information-theoretic point of view.

The paper is organized as follows: In Section 2, we introduce the wireless model under investigation and describe the problem under study. In Section 3 we then present the optimization method and show some numerical examples. Some practical modifications are outlined in Section 4, before the conclusions are given in Section 5.

2. SYSTEM MODEL AND PROBLEM FORMULATION

2.1. System Model

We consider a single-link wireless system perturbed by flat fading which is assumed to be wide-sense stationary (WSS). We assume that the fading is slow (symbol period much smaller than the channel's coherence time) and that the transmitter receives perfect channel state information (CSI) via a noiseless, zero-delay return channel. The transmission scheme is to be based on a set of N codes, so that the SNR range is partitioned into $N + 1$ regions. If the SNR γ falls in the lowest region, i.e., $\gamma < s_1$, it is assumed that none of the codes can guarantee a $\text{BER} \leq \text{BER}_0$. The transmitter must then buffer the information while it is waiting for better channel conditions. This will be referred to as an *outage*.

2.2. Problem Formulation

In [10], Goldsmith and Varaiya provide the expression for the Shannon capacity of a fading channel under certain idealized assumptions. Alouini and Goldsmith [11] use this general result to derive the capacity of a Nakagami- m fading channel.

The capacity of an AWGN channel is well known to be $C = \log_2(1 + \gamma)$ information bits/s/Hz, where γ is the SNR. This means that there exist codes that can transmit with arbitrarily

$$\nabla \text{MASA} = \begin{bmatrix} \frac{\partial \text{MASA}}{\partial s_1} \\ \frac{\partial \text{MASA}}{\partial s_2} \\ \vdots \\ \frac{\partial \text{MASA}}{\partial s_n} \\ \vdots \\ \frac{\partial \text{MASA}}{\partial s_N} \end{bmatrix} = \begin{bmatrix} \frac{1}{1+s_1} \int_{s_1}^{s_2} f_\gamma(\gamma) d\gamma - \ln(1+s_1)f_\gamma(s_1) \\ \ln(1+s_1)f_\gamma(s_2) + \frac{1}{1+s_2} \int_{s_2}^{s_3} f_\gamma(\gamma) d\gamma - \ln(1+s_2)f_\gamma(s_2) \\ \vdots \\ \ln(1+s_{n-1})f_\gamma(s_n) + \frac{1}{1+s_n} \int_{s_n}^{s_{n+1}} f_\gamma(\gamma) d\gamma - \ln(1+s_n)f_\gamma(s_n) \\ \vdots \\ \ln(1+s_{N-1})f_\gamma(s_N) + \frac{1}{1+s_N} \int_{s_N}^{s_\infty} f_\gamma(\gamma) d\gamma - \ln(1+s_N)f_\gamma(s_N) \end{bmatrix} = \mathbf{0} \quad (2)$$

small BER at all SEs up to C bits/s/Hz, provided that the SNR is (at least) γ .

Now, recall that SNR region n in an ACM system is lower-bounded by a switching level s_n . Thus, if error-free transmission is to be always guaranteed, this region can support codes with SEs up to $C_n = \log_2(1 + s_n)$. The region's contribution to the ASE of the scheme is the SE of the n th code, times the probability P_n that it is employed. An upper bound on the ASE of the ACM scheme—for a given set of codes/switching levels—is therefore the *maximum ASE* for ACM, defined as

$$\text{MASA} = \sum_{n=1}^N C_n P_n = \sum_{n=1}^N \log_2(1 + s_n) \int_{s_n}^{s_{n+1}} f_\gamma(\gamma) d\gamma, \quad (1)$$

where $f_\gamma(\gamma)$ is the probability density function (PDF) of the SNR. Eq. (1) is basically a discrete-sum approximation of the integral expressing the variable rate, constant power Shannon capacity in [10]. If arbitrarily long codewords can be used, the bound can be approached from below with arbitrary precision for an arbitrarily low BER. Note that the switching level s_{N+1} for convenience is defined to be $s_{N+1} = \infty$. Our goal is now to find an optimal set of levels in order to maximize the MASA for a given SNR distribution.

3. OPTIMAL DESIGN FOR MASA

3.1. Optimal Switching Levels

In order to find the optimal set of switching levels $\{s_n\}_{n=1}^N$, we first calculate the gradient of the MASA—as defined by Eq. (1)—with respect to the switching levels. The gradient is then set to zero, and we attempt to solve the resulting set of equations. The gradient of the MASA can be expressed as in Eq. (2). In this equation and in the optimization that follows, we assume for simplicity that the MASA is expressed in nats/s/Hz. The terms in the expression for the MASA are then $\ln(1 + s_n) \int_{s_n}^{s_{n+1}} f_\gamma(\gamma) d\gamma$, where the natural logarithm ($\ln$) is used instead of the binary one ($\log_2$). This is equivalent to multiplying the expression for the MASA with a constant, and it will therefore not affect the switching level values. In the numerical results that follow, however, the MASA will be presented in bits/s/Hz.

3.1.1. Optimal Switching Levels in Rayleigh Fading: For the case of Rayleigh fading, it is possible to express all other switching levels as recursive functions of s_1 . That means that the MASA can be expressed as a function of s_1 only, and this function can then be maximized with respect to s_1 .

The first step is to apply the—relatively simple—expression for the exponential PDF of the SNR when the channel is subject to Rayleigh fading:

$$f_\gamma(\gamma) = \frac{1}{\bar{\gamma}} e^{-\gamma/\bar{\gamma}}, \quad (3)$$

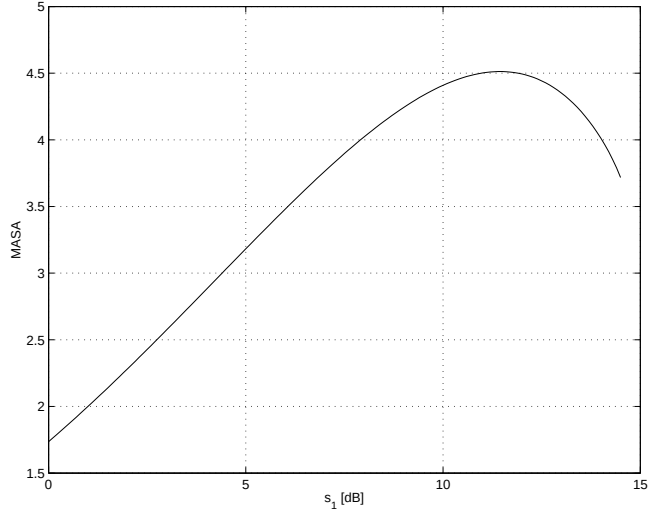


Fig. 2. MASA as a function of s_1 , for $\bar{\gamma} = 20$ dB and $N = 2$.

where $\bar{\gamma}$ is the expected value of the SNR. The integrals in Eq. (2) now become particularly simple:

$$\int_{s_n}^{s_{n+1}} f_\gamma(\gamma) d\gamma = e^{-\frac{s_n}{\bar{\gamma}}} - e^{-\frac{s_{n+1}}{\bar{\gamma}}}. \quad (4)$$

The first equation of the equation set in (2) then becomes

$$\frac{1}{1+s_1} (e^{-\frac{s_1}{\bar{\gamma}}} - e^{-\frac{s_2}{\bar{\gamma}}}) - \ln(1+s_1) \frac{1}{\bar{\gamma}} e^{-\frac{s_1}{\bar{\gamma}}} = 0, \quad (5)$$

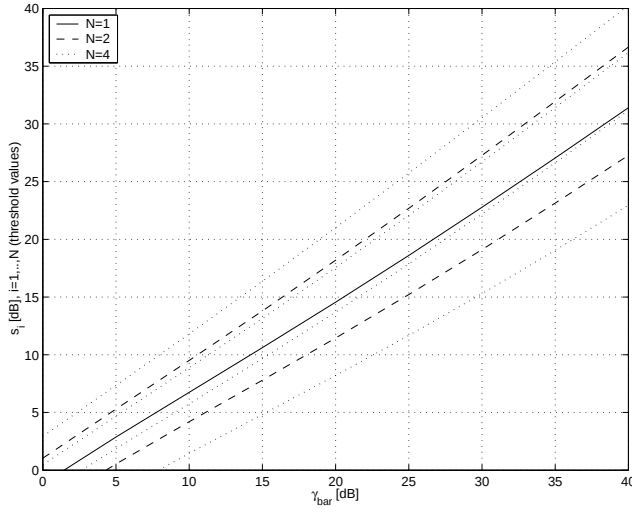
which can be solved with respect to s_2 as:

$$s_2 = s_1 - \bar{\gamma} \ln \left(1 - \frac{1}{\bar{\gamma}} (1 + s_1) \ln(1 + s_1) \right). \quad (6)$$

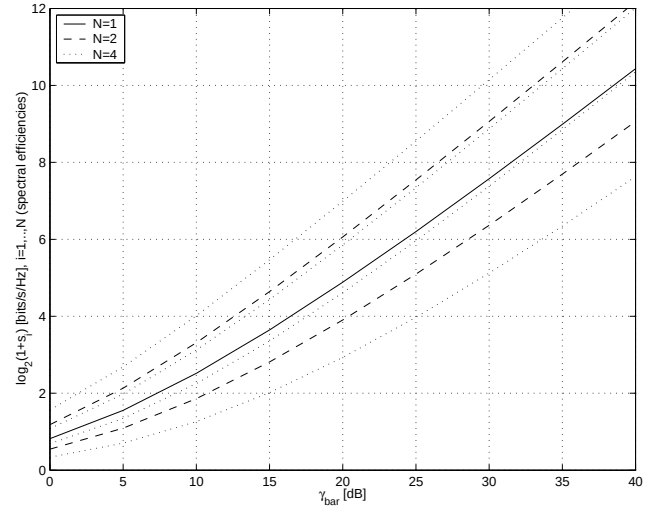
Thus we have s_2 expressed in terms of s_1 . The other equations may be solved recursively in a similar way, albeit the expressions become slightly different:

$$s_n = s_{n-1} - \bar{\gamma} \ln \left(1 - \frac{1}{\bar{\gamma}} (1 + s_{n-1}) \ln \left(\frac{1 + s_{n-1}}{1 + s_{n-2}} \right) \right), \quad (7)$$

for $n = 3, \dots, N$. This way, each switching level $s_n \in \{s_3, \dots, s_N\}$ can be expressed in terms of s_{n-1} and s_{n-2} . Eventually it can then be expressed recursively in terms of s_1 . We have now used the $N - 1$ first equations from the set in (2). The last equation could be used in order to reduce the problem to one equation of one unknown. However, because of the recursion, the resulting equation would become prohibitively involved. With equations (6) and (7) it is possible to instead express the MASA as a



(a) Switching levels as a function of $\bar{\gamma}$



(b) Spectral efficiency for each code

Fig. 3. Solid line: the switching level s_1 (a) and the corresponding SE requirement (b) when only one code is employed. Dashed lines: s_1 and s_2 (a) and SE requirements (b) when $N = 2$ codes are used. Dotted lines: s_1 , s_2 , s_3 , and s_4 (a) and SE requirements (b) when $N = 4$.

function of one single variable, s_1 . The expression for the MASA can then be optimized with respect to s_1 , and the rest of the switching levels can be found via the equations (6) and (7). As illustrated in Fig. 2, $\text{MASA}(s_1)$ has only one maximum.

3.1.2. Other Fading Distributions: For fading conditions other than the Rayleigh case, e.g. Nakagami- m fading, the PDF of the SNR is not on such a beneficial form. We have therefore not been able to solve the equations from (2) in the nested form as for Rayleigh fading. The optimization must be done entirely numerically, either by optimizing the MASA directly, or preferably by solving Eq. (2) numerically. This is however not considered in the present paper.

3.2. Numerical Examples and Discussion

One important outcome of the research presented here is the opportunity the results provide for assessing the relative significance of the number of SNR regions (and thus codes) used. It is in many ways desirable to use as few codes as possible in ACM schemes, as this may help overcome several problems relating to implementation complexity, adaptation with faulty CSI, adaptation in the presence of fast fading, *et cetera*. Thus, if we can come close to the maximum MASA (i.e., the channel capacity) with only a small N by choosing our SEs and codes optimally, this is potentially of great practical interest.

Two performance merits will be taken into account: The MASA, representing an approachable upper bound on the throughput when the scheme is under the restriction of a certain number of codes, and the outage probability P_{out} , the probability that the SNR falls into the lowest SNR region.

3.2.1. Dependence of Switching Levels and SEs on Average SNR: Fig. 3(a) shows the set of optimal switching levels $\{s_n\}_{n=1}^N$ for $N = 1, 2, 4$ and for $0 \text{ dB} < \bar{\gamma} < 40 \text{ dB}$. For design purposes, it also is interesting to consider the optimized

SE requirements to which these levels correspond. The SE bounds $\log_2(1 + s_i)$ corresponding to the switching levels are provided in Fig. 3(b). The two plots in Fig. 3 should be interpreted as follows: With the mean SNR $\bar{\gamma}$ and the number of codes N in mind, find the set of switching levels $\{s_n\}_{n=1}^N$ in Fig. 3(a). Then find the corresponding SE requirement in Fig. 3, and design optimal codes for these SEs, for each $\bar{\gamma}$ of interest. Example: With $N = 2$ and $\bar{\gamma} = 15 \text{ dB}$, switching levels $s_1 = 8$ and $s_2 = 14$ (both dB) can be read from where the dashed lines cross $\bar{\gamma} = 15$ in Fig. 3(a). The SE requirements 2.8 and 4.6, respectively (both bits/s/Hz), are then found where the dashed lines cross $\bar{\gamma} = 15$ in Fig. 3(b).

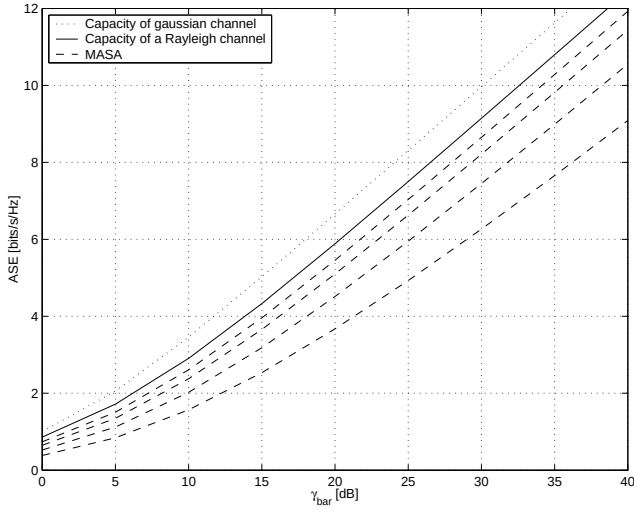
3.2.2. Comparison of MASA with Shannon Capacity: The capacity of transmission on a Rayleigh fading channel when optimal rate adaption (ora) and constant average transmit power is being used is given by [12, Eq. (34)]:

$$C_{\text{ora}} = \log_2(e) e^{1/\bar{\gamma}} E_1(1/\bar{\gamma}) \quad [\text{bits/s/Hz}], \quad (8)$$

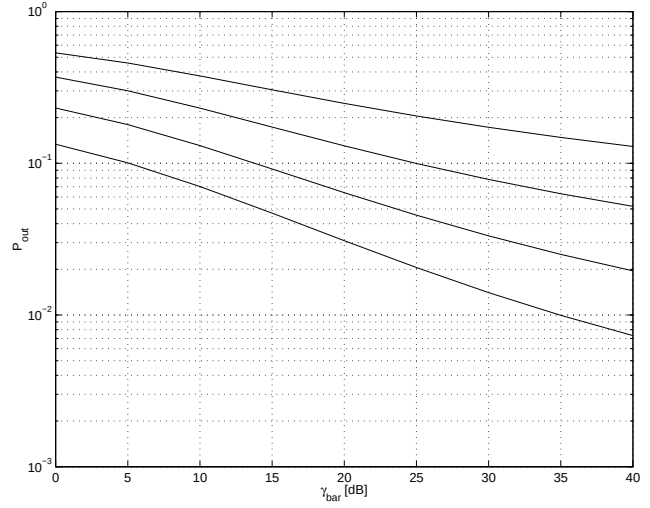
where $E_1(\cdot)$ is the exponential integral of first order [13, p. xxxv]. This capacity can be reached only if one assumes that a continuum of codes is available, i.e., for every SNR there exists an optimal code. The MASA found by doing the optimization as suggested in this paper will reach the C_{ora} capacity when the number of switching levels approach infinity. Of course, this is not a practically feasible approach; however, as shown in Fig. 4(a), a relatively small number of optimally designed codes will indeed yield performance that is very close to the capacity for any given $\bar{\gamma}$.

3.2.3. Probability of no transmission: The probability that the SNR is so low that the smallest code cannot guarantee a $\text{BER} < \text{BER}_0$ is equivalent to the probability that the SNR falls below s_1 , and for the Rayleigh fading case it can be calculated as follows:

$$P_{\text{out}} = \int_0^{s_1} f_{\bar{\gamma}}(\gamma) d\gamma = 1 - e^{-\frac{s_1}{\bar{\gamma}}}. \quad (9)$$



(a) Dotted line: capacity of an AWGN channel with SNR $\gamma = \bar{\gamma}$. Solid line: C_{ora} from Eq. (8). Dashed lines: optimal MASA as a function of mean SNR on the channel, with number of switching levels $N = 1$ (lowermost curve), 2, 4, 8 (uppermost curve).



(b) P_{out} as a function of mean SNR on the channel, with number of switching levels $N = 1$ (uppermost curve), 2, 4, 8 (lowermost curve).

Fig. 4. MASA and P_{out} as a function of mean SNR on the channel, $\bar{\gamma}$.

When the number of codes is increased, the SNR range will be partitioned into a larger number of regions. As shown in Fig. 3(a), the lowest switching level s_1 will become smaller. P_{out} will therefore decrease, as illustrated in Fig. 4(b).

It is not necessarily a disadvantage that the probability of no transmission is high, unless the service under consideration has strict real-time or low-delay requirements. For data-centric services, such as WWW browsing and file or email transfer, the most important thing from a quality-of-service point of view is probably the total time of data downloading experienced by a user. If the ASE is maximized, this time will be minimized no matter what the P_{out} is.

However, if it for some reason is desired that P_{out} should not exceed some prescribed maximal value, we may simply—using Eq. 9—compute s_1 to be the highest SNR value which ensures that this constraint is fulfilled. Then we may subsequently solve for $s_2, s_3, \dots, s_N$ recursively as before, to obtain the highest possible ASE under the given P_{out} constraint.

4. PRACTICAL MODIFICATIONS AND APPLICATIONS

4.1. Introducing an SNR Margin

The results so far give strict upper bounds on the MASA under the assumption that truly capacity-achieving codes for AWGN channels can be employed. This assumes that codeword lengths approaching infinity, and Gaussian code alphabets, can be used. In practice, however, discrete symbol constellations such as M -QAM will be employed. Even more importantly; on a mobile fading channel, where the SNR changes with time, the ACM transmitter must be allowed to do code adaptation periodically, so that it may truly track the temporal changes in channel quality. Thus, the faster

the temporal fading variations, the higher the necessary adaptation frequency, and the smaller the possible ACM codeword length.

We can take both discrete code alphabets and limited block lengths (as well as other practical implementation losses such as limitations on path memory in Viterbi decoders, or limitations on the number of iterations in turbo decoders) into account by inserting an *SNR margin* into our capacity formulas: For a given SNR γ , the achievable SE can then be written as $\log_2(1 + \lambda\gamma)$, where $0 < \lambda < 1$ is the SNR margin due to various implementation losses. I.e., at SNR γ the codes are only able to perform on the level of capacity-achieving codes operating at an SNR of $\lambda\gamma < \gamma$. The actual value of the margin λ will depend on (amongst other things) the block lengths we are allowed to use, and the computational complexity of the decoders.

The modification on the achievable SE suggested above will not affect the basic principles behind our method of MASA optimization. However, the actual formulas will have to be slightly modified to take the margin into account. This modification is straightforward; therefore, due to space restrictions, we choose not to go into further detail on this here.

4.2. How to Account for Imperfect CSI

Our results so far also assume that perfect CSI is available at the transmitter. In practice, the available CSI will be a noisy estimate or prediction of the true SNR value. This means that there is always a nonzero probability of choosing a code which is not optimized for the region where the true SNR actually lies. This will lead either to a too high instantaneous BER, or a too low instantaneous spectral efficiency. The first

of these two effects must usually be considered the most serious.

The probability P_h of choosing a code with too high SE, however, can be controlled by increasing the switching levels (while keeping the SEs constant at the optimized level) in an appropriate fashion. For a Rayleigh fading channel, an analytical method for securing a prescribed P_h is described in [14]. Again, this switching level shift does not influence the switching level optimization method suggested in this paper: The optimization and the subsequent shift of the levels are done independently of each other.

4.3. Applications and Extensions: Cellular Systems and Average Area Spectral Efficiency

It may be tempting to question the applicability of our results in real-world scenarios, where the channel statistics most often are not WSS. For example, consider a cellular communication system with the base stations placed in the middle of circular cells. In such a system, a user in a region close to the base station will experience different fading statistics from those experienced by a user near the cell border. Typically, due to path loss (and possibly shadowing), the expected SNR may be radically different in these two cases. This means that two such users should employ two entirely different sets of optimized codes.

Our belief is that one can actually take advantage of this "drawback", at least as long as the variation in the channel statistics can themselves be analytically modelled in either a deterministic or a stochastic fashion. Just as we have suggested making systems adaptive with respect to the instantaneous SNR for a WSS channel model, we might consider making systems adaptive with respect to the expected SNR. By quantizing the expected SNR range in a similar way to what we have done for the instantaneous SNR range, we may in principle switch between different sets of optimal codes, according to available estimates of the expected SNR. Of course, it is then of particular interest to keep the number of codes low for each expected SNR region.

Interestingly, the curve corresponding to $N = 1$ in Fig. 4(a) actually corresponds to *only* tracking the variations in the expected SNR. In this case there are only two regions for each $\bar{\gamma}$ —the outage region, and a fixed-SE transmission region. Such a simple ACM system would probably be of particular interest in a multiuser environment, as it would also mean a significant decrease of the amount of overhead information (CSI) travelling back and forth in the network, compared to more advanced ACM schemes.

Furthermore, adaptivity with respect to the channel model will necessarily be of a much slower nature than the adaptivity designed to handle the stochastic variations within each particular model; thus it is also easier to implement. This is particularly true for scenarios where the temporal correlation of the instantaneous fading is low (e.g. in systems with high user velocities). Also, as can be seen, there is already a significant ASE gain in doing only this "slow" adaptivity. Moreover, the additional returns associated with adjustments to the instantaneous fading becomes successively more diminishing the more codes we add.

Finally, our method may be extended to take other relevant measures of cellular system efficiency, such as *area spectral efficiency* [4], into account as optimization criteria. This is also among our subjects for further research.

5. CONCLUSIONS

We have devised a method for optimization of the switching levels and corresponding spectral efficiencies in an adaptive coded modulation system, in order to maximize a strict upper bound on the ASE for a given fading distribution. The technique basically corresponds to optimal discretization of the integral expressing the Shannon capacity of the channel.

For the Rayleigh fading case, we obtain analytical solutions which can be solved in a recursive manner for an arbitrary number of codes. The results show that performance close to the Shannon limit may be achieved with only a small number of optimally designed codes.

The method can be easily augmented to encompass more practical scenarios, by taking various fading distributions, imperfect CSI, and SNR margins due to various implementation losses into account. Moreover, in wireless communication systems where the channel model is nonstationary, the results may be used to introduce yet another degree of adaptivity, with respect to the 1st order moment of the fading distribution. This is of interest for example in cellular systems.

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