Effective Spectral Efficiency for Adaptive QAM with Diversity and Pilot Assisted Channel Estimation

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***Abstract*—This paper investigates the effects of non-ideal channel state information in adaptive M-ary quadrature amplitude modulation systems with subset diversity. The slow adaptive modulation (SAM) technique, which adapts the modulation parameters to slow channel variations, is considered. With respects to fixed scheme modulation systems, SAM achieves a good gain in terms of spectral efficiency (SE) and outage probability and, compared to fast adaptive modulation, reduces the system complexity by lowering the feedback rate. Resources dedicated to channel estimation affect both the system performance, in terms of error and outage probability, and the effective SE for which a proper definition is needed. Here, we evaluate the performance of SAM technique when pilot-assisted channel estimation errors are considered. Taking into account the number of pilot symbols transmitted, an effective SE is obtained to address the tradeoff between channel estimation quality and SE.**

I. Introduction

The diffusion of high speed digital wireless communications has increased the need of reliable high data rate transmission in variable channel conditions. Adaptive modulation techniques allow to maximize the transmitted spectral efficiency (SE) without compromising the performance in terms of bit error probability (BEP) and bit error outage (BEO) [1], [2]. By adapting system parameters to channel conditions, the optimal modulation level is selected maximizing the SE, still satisfying the requirements in terms of BEP and BEO [3]–[5]. It is worth noting that tracking the small scale fading as in fast adaptive modulation (FAM) with ideal channel state information (CSI) provides the best performance, at the cost of a frequent channel estimation and feedback. With respect to FAM, a gain in terms of feedback and complexity can be achieved by slow adaptive modulation (SAM) techniques, that adapt modulation parameters to the slow channel variations, that is large-scale fading. Although the SE achieved with FAM is slightly better than the one obtained with SAM, SAM achieves a significant improvement in terms of SE and outage probability when compared to a fixed modulation scheme, despite the lower complexity and the less frequent feedback [2].

In FAM and SAM, a critical role is played by the channel estimates. Non-ideal channel estimates poses a serious issue that has been addressed in several ways. The effects of outdated channel estimates are investigated for adaptive modulation systems with Rayleigh and Nakagami fading channel in [1] and [6], respectively. A general criterium is given to probe the effects of channel estimation errors in the instantaneous signal-to-noise ratio (SNR) in the feedback. More detailed analysis on adaptive modulation systems with non-ideal CSI are addressed in [7]–[9] for single- and multi-carrier systems. In [10] the relation between performance and pilot assisted channel estimation is addressed for MIMO-OFDM systems with FAM in Rayleigh fading channels.

To the best of our knowledge, the non-ideal CSI was addressed for FAM systems only and a metric suitable to take into account both estimation quality and SE was not defined. In this paper, in order to evaluate the effects of channel estimation errors in SAM systems, we investigate slow adaptive M-ary quadrature amplitude modulation (M-QAM) systems with subset diversity (SSD) and non-ideal channel state information [11]. Non-ideal CSI will affect diversity combining, bit reconstruction, and the choice of the optimal modulation size. Resources dedicated to channel estimates will affect both the system performance, in terms of BEP, BEO, and effective SE. Here, we analyze the resource allocation between data and channel estimation for a composite Rayleigh fading and log-normal shadowing channel in SAM systems. We then define a proper metric called effective SE which enables the design of the pilot scheme based on performance requirements and the effective number of data symbols transmitted within each coherence time.

II. System Model

We assume M-QAM modulated symbols transmitted over composite Rayleigh fading and log-normal shadowing channels employing SSD (independent identically distributed (i.i.d.) fading and same shadowing level over all branches, i.e., microdiversity). The receiver chooses the modulation format to be adopted and sent it back to the transmitter on an error-free channel. We denote by h_i the Rayleigh distributed fading gain on the i-th branch, by E_s the mean symbol energy, and by $N_0/2$ the additive white Gaussian noise two-sided power spectral density. The mean SNR per branch can be expressed as[1] $\overline{\gamma} = \mathbb{E}\left\{|h|^2\right\} E_\mathrm{s}/N_0$, where $\mathbb{E}\left\{|h|^2\right\} = 2\sigma_\mathrm{h}^2$. Due to log-

[1]Since we consider microdiversity, for sake of simplicity, in the following we omit the branch subscript in the mean SNR notation.

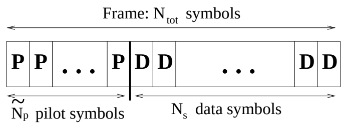

Figure 1. Transmitted pilot scheme.

normal shadowing, $\overline{\gamma}_{\text{dB}} = 10\log_{10}(\overline{\gamma})$ is Gaussian distributed with mean μ_{dB} and variance σ^2_{dB}.

We refer the reader to [2] for details on slow and fast adaptive modulation techniques in ideal CSI systems. In short, adaptive modulation allows to achieve the best SE accordingly with channel conditions, minimizing in the meanwhile the BEO. We consider a M-QAM system with a discrete set of J possible constellation sizes $\{M_0, M_1, \dots, M_J\}$. With SAM, the optimal constellation size is chosen depending on the mean SNR. When, even with the lowest constellation size M_0, $\overline{\gamma}$ is not able to guarantee the required target BEP $P_{\text{b}}^{\star}$, the system is in outage, otherwise the transmitted data rate corresponds to $\log_2 M_j,\ j = 0, 1, \dots, J$. The optimal data rate is chosen comparing the $\overline{\gamma}$ value with constellation size thresholds, that are set to guarantee the minimum BEP required when the M_j constellation size is adopted, that is $P_{\text{b}}(\overline{\gamma}_j^{\star}) = P_{\text{b}}^{\star}$. In particular, when the SNR value falls within the j-th region ($\overline{\gamma}_j^{\star} < \overline{\gamma} \leq \overline{\gamma}_{j+1}^{\star}$), the M_j constellation size is adopted for the transmission. If $\overline{\gamma}$ up-cross (down-cross) the SNR threshold, the constellation size is switched to a higher (lower) level, leading to an increasing (decreasing) of the SE.

In order to estimate the complex fading level, a pilot symbol assisted modulation (PSAM) is adopted [12]. In short, $\widetilde{N}_{\text{p}}$ symbols are inserted in each frame (typically with length equal to the coherence time of the channel), and transmitted with energy E_{p} per pilot symbol (Fig. 1). Note that, in a generic system with SSD, the number of transmitted pilot symbols, $\widetilde{N}_{\text{p}}$, might be different from the number of received pilot symbols[2], N_{p}. We assume a maximum-likelihood estimator and fading levels $\mathbf{h} = [h_1 h_2 \dots h_N]$ constant over a frame; the estimated channel coefficient is [11] $\widehat{h}_k = h_k + e_k$ where e_k is a zero-mean Gaussian process with variance per dimension $\sigma_{\text{e}}^2 = N_0/(2N_{\text{p}}E_{\text{p}})$.

III. Performance Metrics with Non-Ideal Channel Estimates at the Receiver

In this section, the BEP, BEO, and effective SE are obtained for systems employing SSD with non-ideal CSI.

A. Bit Error Probability

The performance of N-branches SSD in the presence of non-ideal CSI was studied in [11] where the symbol error probability (SEP) was obtained for arbitrary two-dimensional signaling constellations in i.i.d. Rayleigh fading channels. When M-QAM modulation is considered, the SEP as a function of the SNR averaged over the small scale fading and the alphabet $\{s_i\}$ is given by

$$P_{\text{e}}(\overline{\gamma}, N_{\text{p}}\varepsilon) = \frac{1}{M}\sum_i \omega_i^{(a)} I_N\left(\zeta^{(i)}, \Phi_2, \frac{\pi}{4}\right) + \frac{1}{M}\sum_i \omega_i^{(b)} I_N\left(\zeta^{(i)}, \Phi_4, 0\right), \tag{1}$$

$$I_N(\zeta, \phi, \psi) = \frac{1}{2\pi}\int_0^{\phi}\prod_{n=1}^{N}\left(\frac{\sin^2(\theta+\psi)}{\sin^2(\theta+\psi)+b_n\zeta}\right), \tag{2}$$

where $\Phi_M = \pi(M-1)/M$, N_{p} is the number of received pilot symbols, and the b_n depend on the diversity technique. The set of $\{\zeta^{(i)}\}$ is a function of the mean SNR:

$$\zeta^{(i)}(\overline{\gamma}, N_{\text{p}}\varepsilon) \triangleq \frac{E_{\text{s}}\rho^2}{\sigma_{\text{h}}^2\left(\frac{N_0}{2} + |s_i|^2\sigma_{\text{e}}^2\rho^2\right)} = \frac{\overline{\gamma}N_{\text{p}}\varepsilon\ c_{\text{MQAM}}}{\frac{1}{\overline{\gamma}} + N_{\text{p}}\varepsilon + \xi_i}, \tag{3}$$

where $c_{\text{MQAM}} = 3/(2(M-1))$, $\rho = \sigma_{\text{h}}^2/(\sigma_{\text{h}}^2 + \sigma_{\text{e}}^2)$. In particular, $\varepsilon \triangleq E_{\text{p}}/E_{\text{s}}$ is the ratio between pilot and data symbol energy. The parameters $\omega_i^{(a)}$, $\omega_i^{(b)}$ and $\xi_i \triangleq E_i/E_{\text{s}}$ depend on the modulation format, and are given in [11]. Note that the summation in (1) is performed over the non zero values $\omega_i^{(a)}$, $\omega_i^{(b)}$ and ξ. In the case of ideal channel estimates, (3) results given by $\zeta^{(i)} = \overline{\gamma}c_{\text{MQAM}}$. The set $\{b_n\}$ depends on the SSD technique. When a hybrid-selection maximal ratio combiner (H-S/MRC) [13] is adopted at the receiver, among N branches the strongest L are selected for being processed by the MRC. For such systems, the b_n are expressed as $b_n = 1$ for $n \leq L$ and L/n otherwise. When a MRC is considered at the receiver, $L = N$ and, thus, $b_n = 1, \forall n$.

In both ideal and non-ideal CSI systems, the modulation is selected based on SNR thresholds evaluated from the target BEP. Starting from the SEP, and assuming Gray coding between bits and symbols, the BEP can be lower bounded as:

$$P_{\text{b}}(\overline{\gamma}, N_{\text{p}}\varepsilon) \geq P_{\text{e}}(\overline{\gamma}, N_{\text{p}}\varepsilon)/\log_2(M). \tag{4}$$

By numerical root evaluations, the pilot assisted estimated mean SNR thresholds are obtained from (4) as the values that satisfy the target BEP, that is $P_{\text{b}}(\widehat{\gamma}^{\star}, N_{\text{p}}\varepsilon) = P_{\text{b}}^{\star}$. Note that, in a non-ideal CSI system, the thresholds are a function of the modulation level as well as the channel estimation quality.

B. Constraints and Energy Allocation for Pilot and Data Symbols

In adaptive modulation systems with non-ideal CSI, the performance strictly depends on the adopted pilot scheme. For systems with SSD, the portion of the frame dedicated to pilot insertion is defined as $n_{\text{p}} = \widetilde{N}_{\text{p}}/N_{\text{tot}}$, and the following constraints are imposed

$$\begin{cases} \widetilde{N}_{\text{p}} + N_{\text{s}} = N_{\text{tot}} \\ \widetilde{N}_{\text{p}}E_{\text{p}} + N_{\text{s}}E_{\text{s}} = E_{\text{tot}}. \end{cases} \tag{5}$$

From (5), it follows that the energy dedicated to the information symbols depends on the adopted pilot scheme, and the

[2]Although in our system model $\widetilde{N}_{\text{p}} = N_{\text{p}}$, in order to make the study suitable for any SSD system, we denote the number of received or transmitted pilot symbols with two different notations.

following expression can be derived

$$E_{\mathrm{s}}=\frac{E}{\frac{\widetilde{N}_{\mathrm{p}}}{N_{\mathrm{tot}}}(\varepsilon-1)+1}, \quad (6)$$

where $E \triangleq E_{\mathrm{tot}}/N_{\mathrm{tot}}$. Note that the increasing of $\widetilde{N}_{\mathrm{p}}\varepsilon$ leads to a better channel estimation and to a lowering of E_{s}, the two have opposite effects on the system performance. Thus, even the exact mean SNR in (1) is a function of the pilot scheme, that is $\overline{\gamma}=\overline{\gamma}(\widetilde{N}_{\mathrm{p}}\varepsilon)$, as

$$\overline{\gamma}=\mathbb{E}\{|h|^2\}\frac{E_{\mathrm{s}}}{N_0}=\frac{\mathbb{E}\{|h|^2\}}{N_0}\frac{E}{\frac{\widetilde{N}_{\mathrm{p}}}{N_{\mathrm{tot}}}(\varepsilon-1)+1}=\frac{\Upsilon}{\frac{\widetilde{N}_{\mathrm{p}}}{N_{\mathrm{tot}}}(\varepsilon-1)+1}, \quad (7)$$

where $\Upsilon=\mathbb{E}\{|h|^2\}E/N_0$. Substituting (7) in (1), the BEP can be expressed as a function of two parameters: $N_{\mathrm{p}}\varepsilon$ characterizing the pilot scheme design, and Υ representing the mean SNR per generic (pilot or data) symbol

$$P_{\mathrm{b}}=P_{\mathrm{b}}\left(\overline{\gamma}(\widetilde{N}_{\mathrm{p}},\varepsilon),N_{\mathrm{p}}\varepsilon\right)=P_{\mathrm{b}}\left(\Upsilon\frac{1}{\frac{\widetilde{N}_{\mathrm{p}}}{N_{\mathrm{tot}}}(\varepsilon-1)+1},N_{\mathrm{p}}\varepsilon\right).$$

Note that, unlikely the mean SNR $\overline{\gamma}$, Υ does not depend on the pilot scheme, but only on the mean energy over the frame, N_0, and $\mathbb{E}\{|h|^2\}$. This independent variable might be employed to compare systems with different pilot schemes. Thus, from here onwards, Υ will be the SNR variable in the BEP expression based on which the constellation size is chosen, and thus the SNR thresholds will be denoted by $\Upsilon^{\star}$.

C. Bit Error Outage

In adaptive modulation systems, an important figure of merit is the *bit error outage* (BEO), that is the probability that, when the lowest constellation size is considered, the BEP is greater than the target bit error probability [3]–[5]:

$$P_{\mathrm{o}}(P_{\mathrm{b}}^{\star})=\mathbb{P}\{P_{\mathrm{b}}(\Upsilon)>P_{\mathrm{b}}^{\star}\}=F_{\Upsilon}(\Upsilon_0^{\star})=F_{\Upsilon_{\mathrm{dB}}}\left(\Upsilon_{\mathrm{dB},0}^{\star}\right), \quad (8)$$

where $F_{\Upsilon_{\mathrm{dB}}}(\xi)$ is the cumulative density function (CDF) of Υ_{dB}. Since we assume that the mean SNR is log-normal distributed, that is Υ_{dB} is Gaussian with mean μ_{dB}' and variance σ_{dB}^2, the CDF of Υ_{dB} is given by

$$F_{\Upsilon_{\mathrm{dB}}}(\xi)=Q\left(\frac{\mu_{\mathrm{dB}}'-\xi}{\sigma_{\mathrm{dB}}}\right), \quad (9)$$

where (9) follows from the Gaussian behavior of the log-normal shadowing and $Q(x)\triangleq\int_x^{\infty}e^{-t^2/2}dt$ is the Gaussian-Q function. When an ideal system is considered (ideal CSI without constraints), $\Upsilon=\overline{\gamma}$, and $\mu_{\mathrm{dB}}'=\mu_{\mathrm{dB}}$, therefore the BEO can be evaluated as $P_{\mathrm{o}}(P_{\mathrm{b}}^{\star})=Q\left((\mu_{\mathrm{dB}}-\overline{\gamma}_{0,\mathrm{dB}}^{\star})/\sigma_{\mathrm{dB}}\right)$. Note that, the lower is the channel estimation quality (lower $N_{\mathrm{p}}\varepsilon$ values), the higher are the evaluated SNR thresholds overestimating the BEO. In the following, we compare the non-ideal CSI system to the ideal one by evaluating the median SNR BEO penalty, defined as

$$\Delta\mu_{\mathrm{dB}}\triangleq\mu_{\mathrm{dB},0}'-\mu_{\mathrm{dB},0}, \quad (10)$$

where $\mu_{\mathrm{dB},0}'$ and $\mu_{\mathrm{dB},0}$ are the median values that reach the target BEO when the lowest constellation size is considered for the non-ideal and the ideal CSI, respectively.

D. Effective Spectral Efficiency

Another important performance measure is the *mean spectral efficiency* defined as

$$\begin{aligned}\eta&=\sum_{j=0}^{J-1}\tilde{M}_j\ \mathbb{P}\left\{\Upsilon_j^{\star}<\Upsilon\leq\Upsilon_{j+1}\right\}+\tilde{M}_J\ \mathbb{P}\{\Upsilon_J^{\star}<\Upsilon\}\\&=\sum_{j=0}^{J-1}\tilde{M}_j\ \mathbb{P}\left\{\Upsilon_{\mathrm{dB},j}^{\star}<\Upsilon_{\mathrm{dB}}\leq\Upsilon_{\mathrm{dB},j+1}\right\}+\tilde{M}_J\ \mathbb{P}\left\{\Upsilon_{\mathrm{dB},J}^{\star}<\Upsilon_{\mathrm{dB}}\right\}\\&=\sum_{j=0}^{J-1}\tilde{M}_j\ \left[F_{\Upsilon_{\mathrm{dB}}}(\Upsilon_{\mathrm{dB},j+1}^{\star})-F_{\Upsilon_{\mathrm{dB}}}(\Upsilon_{\mathrm{dB},j})\right]+\\&+\tilde{M}_J\ \left[1-F_{\Upsilon_{\mathrm{dB}}}(\Upsilon_{\mathrm{dB},J}^{\star})\right], \quad (11)\end{aligned}$$

where $\tilde{M}_j=\log_2 M_j$. Note that η is the mean SE for each generic symbol within the frame. Considering that only N_{s} symbols are dedicated to data transmission, we define the effective mean SE per symbol per frame as

$$\eta^{(\mathrm{eff})}\triangleq\eta\ n_{\mathrm{s}}=\eta\ (N_{\mathrm{tot}}-\widetilde{N}_{\mathrm{p}})/N_{\mathrm{tot}}. \quad (12)$$

From (12), the tradeoff between estimation quality and transmitted data can be observed. The more pilot symbols are transmitted, the better is the channel quality at the cost of a lower effective spectral efficiency. In ideal systems, the SE can be evaluated from (11), with $\Upsilon=\overline{\gamma}$. Since no constraint is considered in the ideal case, $\eta^{(\mathrm{eff})}=\eta$. We define the mean spectral efficiency penalty as the ratio of the SE evaluated in the ideal and that in the non-ideal CSI case:

$$\Delta\eta\triangleq\eta^{(\mathrm{ideal})}/\eta^{(\mathrm{eff})}. \quad (13)$$

IV. Numerical Results

We now present numerical results in terms of the effective SE $\eta^{(\mathrm{eff})}$ and BEO for SAM systems. Coherent detection of M-QAM with H-S/MRC and Gray code mapping in composite Rayleigh fading and log-normal shadowing channels with either ideal and non-ideal CSI are considered, and $\widetilde{N}_{\mathrm{p}}=N_{\mathrm{p}}$. The effective SE is evaluated by (11) and (12), where the thresholds for both ideal and non-ideal CSI are evaluated as the SNR values that achieve a target BEP of 10^{-2} (typical values for uncoded systems) and a maximum BEO of 5% for different modulation sizes. For the non-ideal CSI case, the BEP is obtained from (4) and (1), where the Υ variable is introduced by means of (7). The SEP for ideal CSI systems is easily deducible from (1) with $\zeta^{(i)}=\Upsilon c_{\mathrm{MQAM}}=\overline{\gamma}c_{\mathrm{MQAM}}$.

In Fig. 2, the BEO as a function of the median value μ_{dB} for non adaptive 4-QAM and 64-QAM systems with eight-branches MRC is shown for both ideal and non-ideal CSI ($N_{\mathrm{p}}\varepsilon=1,2,6$). As expected, by increasing $N_{\mathrm{p}}\varepsilon$, the estimation quality improves, leading to a reduction of the BEO. In Fig. 3, we compare the fixed modulation scheme with SAM in terms of effective SE for various $N_{\mathrm{p}}\varepsilon$ and constellation size in the set $\{4,16,64,256\}$ with 4-branches MRC.

It can be observed the gain achieved by adopting the SAM technique rather than the non-adaptive one. For a target BEO, the minimum μ_{dB} value to transmit with SAM modulation depends on the channel estimation quality, as a consequence of the fact that the BEO is affected by estimation errors. The channel estimation errors affect not only the minimum μ_{dB}, but clearly also the effective SE. By increasing the channel estimation quality, and thus N_{p}, the number of transmitted data $(N_{\text{tot}} - N_{\text{p}})$ decreases, leading to a reduction of the effective SE. It follows that the number of pilot symbols is a tradeoff between the effective SE penalty and the gain achieved by having an improved channel estimates. By increasing μ_{dB}, the system with low $N_{\text{p}}\varepsilon$ may outperform system with better channel estimation quality. This crossing behavior can be better observed in Fig. 4. Here, the effective SE is shown as a function of μ_{dB} for both H-S/MRC ($L/N = 1/8$) and MRC ($L/N = 8/8$). The more complex MRC system achieves higher diversity than the H-S/MRC, leading to a higher effective SE and a lower BEO. More important, the more pilot symbols are inserted, the better is the estimation quality but the lower is the number of transmitted data. It follows that, only for low performance system, it is worthy having a high number of pilot symbols.

The case of $\varepsilon \neq 1$ is considered in Fig. 5, where the constraint (5) and the (6) are taken into account. In the figure, the median SNR BEO penalty and the SE penalty as a function of ε are reported for SAM systems with $M_{\text{max}} = 256$, 8-branch MRC receivers, and several N_{p} values. Considering the $\Delta\mu_{\text{dB}}$ in Fig. 5 (a), it can be noted that, by keeping the $N_{\text{p}}\varepsilon$ product constant but varying both the values N_{p} and ε values, different results can be achieved. For example, considering $N_{\text{p}}\varepsilon = 6$, the systems with $N_{\text{p}} = 6$ and $\varepsilon = 1$ achieves a $\Delta\mu_{\text{dB}}$ lower than the one with $N_{\text{p}} = 1$ and $\varepsilon = 6$. Note that a lower penalty means that the system achieves performance closer to the ideal case, thus $\Delta\mu_{\text{dB}}$ has to be minimized. This is due to the fact that, for a constant frame size N_{tot}, the latter has a lower number of data symbols. Note also that E_{s} decreases as N_{p} increases for a given total amount of energy. Thus, for high N_{p} values, the case of a low value of ε might outperform that with a high value of ε. In particular, among the considered systems, $N_{\text{p}} = 6$ and $\varepsilon \simeq 1$ is the one achieving the minimum median SNR BEO penalty. Analogously, considering the mean SE penalty (Fig. 5 (b)), $N_{\text{p}} = 6$ does not provide the minimum penalty, that is reached by $N_{\text{p}} = 1$ and $\varepsilon \simeq 9$. This means that, in order to reduce the mean SE penalty, low N_{p} values are preferred, due to the fact that the higher the pilot symbol number, the lower the data symbol number within each frame.

The two penalties already presented can be observed also in Fig. 6, where the $\eta^{(\text{eff})}$ as a function of $\mu\prime_{\text{dB}}$ is reported for several N_{p} values, when $N_{\text{p}}\varepsilon$ is constant and equal to 25. As already observed, constant $N_{\text{p}}\varepsilon$ values achieves different performance for different combination of N_{p} and ε: a small number of pilot symbols within a frame leads to a high effective SE, while high N_{p} values provide a decreasing of the BEO. From Fig. 5 and Fig. 6, it can be concluded that, based on the user requirements (minimization of the BEO or of the effective SE) the optimal pilot scheme can be designed.

V. Conclusions

In this paper, we analyzed a SAM technique with pilot assisted (non-ideal) channel estimates and subset diversity in composite small and large scale fading. We defined a proper measure of effective SE, to take into account the symbols devoted to channel estimation instead of data, and we compared SAM with fixed-modulation schemes in terms of BEO and effective SE. Even for non-ideal channel estimates, SAM technique achieves substantial improvement over non adaptive schemes. The tradeoff between channel estimation quality and SE has been addressed. Based on the user requirements, the optimal number of pilot symbols and energy allocation to be employed in the transmission can be evaluated.

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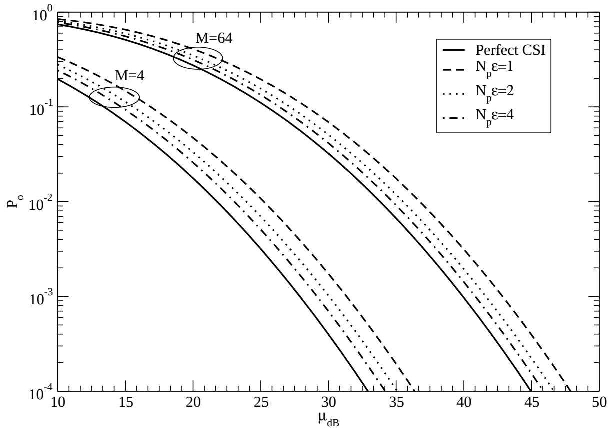


Figure 2. BEO vs. μ_{dB} for a non adaptive scheme with $P_{\mathrm{b}}^{\star} = 10^{-2}$, $\sigma_{\mathrm{dB}} = 8$, $N = 4$ (MRC), $M = 4$ and 64, and both ideal and non-ideal CSI systems with various $N_{\mathrm{p}}\varepsilon$.

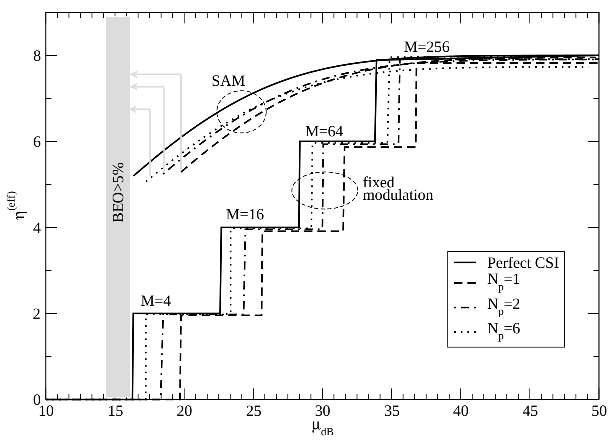


Figure 3. Effective SE vs. μ_{dB} for adaptive and non-adaptive schemes with $P_{\mathrm{b}}^{\star} = 10^{-2}$, $\sigma_{\mathrm{dB}} = 8$, $N = 4$ (MRC), $\varepsilon = 1$ ($\mu'_{\mathrm{dB}} = \mu_{\mathrm{dB}}$), $M_{\max} = 256$, and $N_{\mathrm{tot}} = 180$.

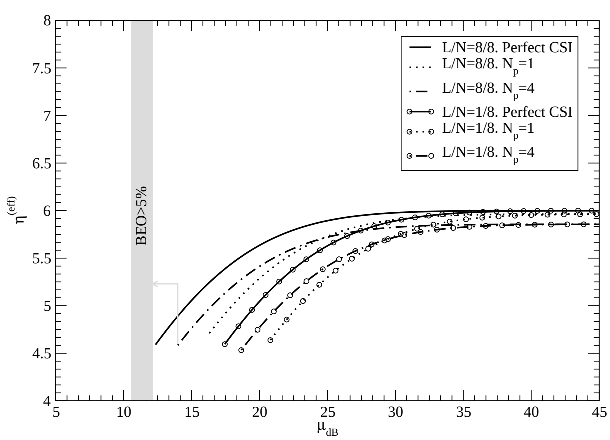
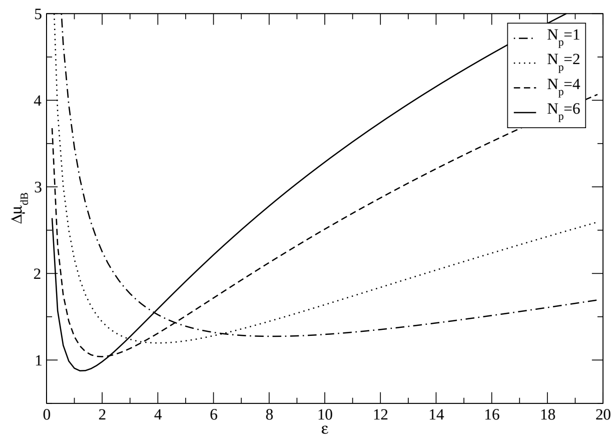
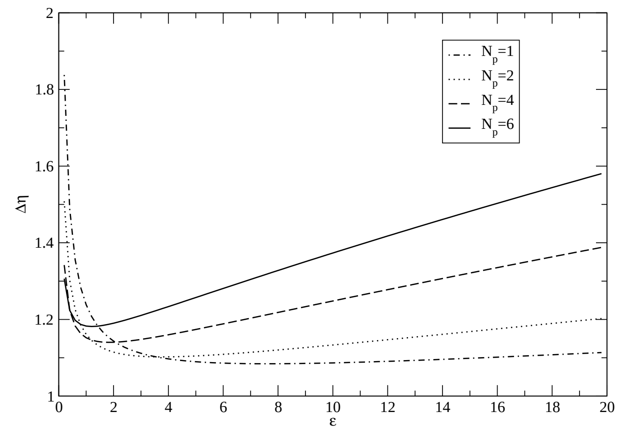


Figure 4. Effective SE vs. μ_{dB} for SAM systems with $P_{\mathrm{b}}^{\star} = 10^{-2}$, $\sigma_{\mathrm{dB}} = 8$, H-S/MRC ($L/N = 1/8$) and MRC ($L/N = 8/8$), $\varepsilon = 1$ ($\mu'_{\mathrm{dB}} = \mu_{\mathrm{dB}}$), $M_{\max} = 64$, and $N_{\mathrm{tot}} = 180$.



(a) Median SNR BEO penalty.



(b) Mean SE penalty.

Figure 5. Median SNR BEO penalty and mean SE penalty vs. ϵ for SAM systems with $P_b^{\star} = 10^{-2}$, $\sigma_{\mathrm{dB}} = 8$, MRC (N=4), and several values of pilot symbols ($N_{\mathrm{p}} = 1, 2, 4$,and 6). In the mean SE penalty plot (b), $\mu'_{\mathrm{dB}} = 15$.

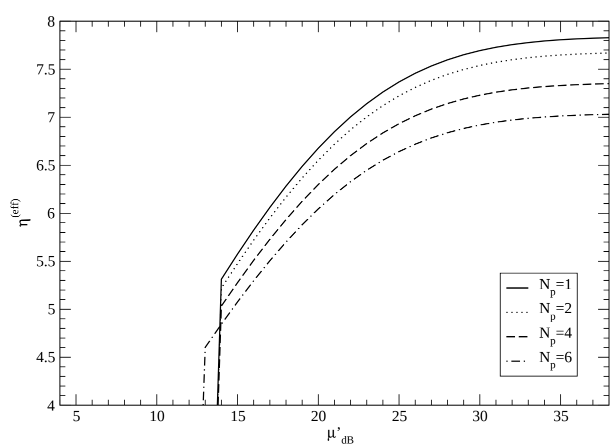


Figure 6. Effective SE vs. μ'_{dB} for SAM systems with $P_{\mathrm{b}}^{\star} = 10^{-2}$, $\sigma_{\mathrm{dB}} = 8$, MRC (N=8), maximum modulation $M_{\max} = 256$, $N_{\mathrm{tot}} = 180$, $N_{\mathrm{p}}\varepsilon = 25$ and various N_{p} values.