Adaptive modulation for DFE equalized systems

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Abstract: In this paper, an adaptive quadrature amplitude modulation (AQAM) scheme for an equalized system over a selective channel is investigated. To reduce intersymbol interference (ISI), a minimum-mean-squared-error decision feedback equalizer (MMSE-DFE) with an unbiased decision rule is used. In order to select the appropriate modulation mode, the receiver estimates the MSE at the equalizer output. This estimated MSE is then sent back to the transmitter which adjusts the modulation level. The influence of channel variations on the AQAM-DFE performances was also investigated. Simulation results illustrate that the MSE is accurately estimated and represents a viable switching metric. It is also shown that switching between different modulation modes does not affect the equalizer coefficients adaptation. Linear region of practical transmitter amplifiers is limited. Thus when switching from one modulation scheme to an other, it is important to control the peak power.

Key–Words: Adaptive modulation, MMSE-DFE, unbiased receiver

1 Introduction

The basic idea of the adaptive modulation is to switch between different modulation constellation when the channel state changes. For deep fades, a modulation with a small size constellation is chosen to reduce the error probability and to maintain the target bit error rate (BER) [1, 2]. However, if the channel conditions are favorable, the throughput is increased by the use of a high order modulation scheme.

Adaptive modulation has been investigated by several researchers [1–4]. An exhaustive analysis of adaptive modulation for Rayleigh flat fading channels has been examined in [2]. The effect of the imperfect channel estimates and the impact of the time delay on the performance of the adaptive modulation have been discussed in the literature [2, 4]. Adaptive modulation assisted by channel prediction for flat fading channels has been examined in [4, 5]. For this case, a linear channel predictor is used to estimate the current channel status and to choose the appropriate modulation level. Adaptive modulation scheme for free space optical (FSO) systems using subcarrier phase shift keying (S-PSK) intensity modulation is studied in [6] Some adaptive modulation architecture for multi-input multi-output (MIMO) systems are discussed in [7–9]

Recently, AQAM technique for frequency selective channels has been investigated in [10–12]. For these wide-band channels, received signals are affected by ISI. A channel equalizer is thus needed at the receiver to counteract the frequency selectivity. Analysis of systems combining AQAM scheme and channel equalization have been proposed in [10, 11]. To switch the modulation modes, a pseudo-SNR estimation at the DFE equalizer output was introduced in [10]. The evaluation of the pseudo-SNR parameter as defined in [10] requires accurate knowledge of the channel coefficients. Hence, in addition to the DFE equalizer, the receiver proposed in [10] uses a channel estimator. For this AQAM method, channel estimation mismatch may adversely influence the modulation selection criterion.

In this paper, we propose an AQAM scheme for transmission over frequency selective channels. To reduce channel ISI, an unbiased MMSE-DFE equalizer is used. The suggested modulation switching protocol is based on the MSE as estimated at the MMSE-DFE equalizer output. Since the true transmitted symbols are not available at the receiver, the MSE is approximated using the estimates of the transmitted symbols and by replacing the expectation by the time average. Thus, the modulation switching metric that we propose is obtained with a low implementation complexity and does not require channel estimation.

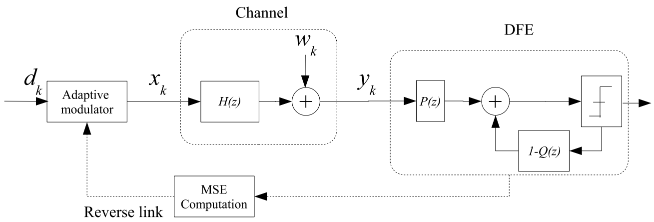

Figure 1: Transmission scheme.

2 System Overview

The discrete baseband system model considered is shown in Fig. 1. Based on channel the state feedback from the receiver, the transmitter chooses the appropriate modulation mode from a set of M-QAM modulations with different constellation sizes, a fixed symbol rate $1/T_s$ and a constant variance σ_x^2. For any transmitted frame, known symbols are added to information symbols to train DFE filters taps. The setting of the modulation switching levels will be discussed in next sections. The symbol rate, transmit filter and the carrier frequency remain constant. Let us denote x_k the transmitted signal, the observed channel noisy output y_n is then

$$y_n = \sum_{k=0}^{L-1} h_k x_{n-k} + w_n \tag{1}$$

where L is the channel memory length, w_n is an AWGN with variance σ_w^2 and $\{h_k\}$ is the channel impulse response.

3 The MMSE-DFE receiver

3.1 Spectral factorization

The transmission system model given by equation (1) can be characterized by its autocorrelation function [13]

$$R_{yy}(z) = R_{hh}(z)R_{xx}(z) + R_{ww}(z) \tag{2}$$

or its power spectrum [13]

$$S_{yy}(z) = S_{hh}(z)\sigma_x^2 + \sigma_w^2 \tag{3}$$

For noisy system ($\sigma_w^2 > 0$), the power spectrum function is strictly positive and $S_{yy}(z)$ is factorizable

$$S_{yy}(z) = S_0 G_\lambda(z) G_\lambda^*(1/z^*) \tag{4}$$

The positive real scalar S_0 represents the system average energy given by [13]

$$S_0 = \frac{\sigma_x^2 \|h\|^2 + \sigma_w^2}{\|g\|^2} \tag{5}$$

where $\{g_k\}$ is the impulse response of $G(z)$.

3.2 MMSE-DFE equalizer

The DFE is a nonlinear equalizer that uses previous detector decisions to eliminate the ISI. The DFE equalizer is made up of two parts, the feedforward $P(z)$ and the feedback $1 - Q(z)$ filters. The $P(z)$ and $Q(z)$ filter taps are obtained by minimizing the mean squared error given by

$$J = |x_n - r_n|^2 \tag{6}$$

where r_n is the equalized signal. The optimum feedforward filter is given by [13]

$$P(z) = \frac{\sigma_x^2 Q(z) H^*(1/z^*)}{S_0 G_\lambda(z) G_\lambda^*(1/z^*)} \tag{7}$$

The optimum feedback filter is given by

$$Q(z) = G_\lambda(z) \tag{8}$$

Furthermore, the error sequence $e(z)$ is white and its average energy is [13]

$$\mathrm{M}SE_{DFE} = \frac{\sigma_x^2 \sigma_w^2}{S_0} \tag{9}$$

3.3 SNR and unbiased MMSE-DFE receiver

The MMSE-DFE makes decisions on $\{x_n\}$ based on $\{r_n\}$. The SNR at the decision signal can be then defined as [13]

$$\begin{aligned} \mathrm{S}NR_{DFE} &= \frac{E\left[|x_n|^2\right]}{E\left[|x_n - r_n|^2\right]} \\ &= \frac{\sigma_x^2}{\mathrm{M}SE_{DFE}} = \frac{S_0}{\sigma_w^2} \end{aligned} \tag{10}$$

The MMSE-DFE presented in 3.2 is biased and therefore suboptimum on the error probability [13]. It was shown in [13] that the bias can be easily removed by scaling the equalized signal. The unbiased receiver increases the MSE and the SNR but reduces the error probability [13]. The SNR at the unbiased MMSE-DFE receiver is given by [13]

$$\mathrm{S}NR_{DFE,U} = \mathrm{S}NR_{DFE} - 1 = \frac{S_0}{\sigma_w^2} - 1 \tag{11}$$

It is noted that, for M-QAM modulation with constellation size ($M > 4$), unbiasedness is important to improve the BER performances [13].

4 Adaptive modulation with constant power and MMSE-DFE equalizer

In this section, we propose and investigate a modulation switching protocol based on the SNR at the equalizer output with an unbiased decision rule. In fact, it was shown in [14] that the channel capacity, for any ISI channel, depends on the optimized SNR at the unbiased MMSE-DFE equalizer output. Authors in [14] affirm that the best limit on the achievable data rate is determined by the $\mathrm{S}NR_{DFE,U}$ and is independent of any other parameter. The relationship between channel capacity and the $\mathrm{S}NR_{DFE,U}$ is given by [14]

$$C = B\log_2\left(1 + \mathrm{S}NR_{DFE,U}\right) \qquad (12)$$

where B is is the channel bandwidth.

4.1 Modulation switching protocol

Let us consider a family of M-QAM modulation schemes with N different modulation modes $(M_1, M_2, \cdots, M_N)$ varying from lower constellation size to higher constellation size with increasing order. The spectral efficiency of any modulation is $\eta_i = \log_2(M_i)$ bits/symbol. For AQAM system, this spectral efficiency is parameterized by the desired BER. So, it is important to find the relationship between the spectral efficiency and the BER.

For a Gaussian system, the maximum-likelihood symbol-by symbol detector selects the signal which is closest to the decision variable (r_n). In this case, the error probability can be easily obtained using the distortion variance, the average mean transmitted power and the complementary Gaussian distribution function. Nevertheless, the distortion factor at the unbiased MMSE-DFE equalizer is a combination of a Gaussian noise and a not Gaussian residual ISI. However, as it was shown in [13], the residual ISI can be assumed Gaussian and this assumption yields a good BER estimation. So, the BER of the unbiased MMSE-DFE receiver for a square $\mathrm{M_i}$-QAM with Gray bit mapping is

$$P_b = \frac{4\left(\sqrt{M_i}-1\right)}{\sqrt{M_i}\log_2\sqrt{M_i}} Q\left(\sqrt{\frac{3}{M_i-1}\mathrm{S}NR_{DFE,U}}\right) \qquad (13)$$

This BER expression can be approximated by [2]

$$\begin{aligned} P_b &\approx 0.2\exp\left[\frac{-1.6}{M_i-1}\mathrm{S}NR_{DFE,U}\right] \\ &\approx 0.2\exp\left[\frac{-1.6}{M_i-1}\frac{\sigma_x^2 - \mathrm{M}SE_{DFE}}{\mathrm{M}SE_{DFE}}\right] \\ &\approx 0.2\exp\left[\frac{-1.6}{M_i-1}\frac{S_0-\sigma_w^2}{\sigma_w^2}\right] \end{aligned} \qquad (14)$$

The AQAM-DFE system that we propose adjusts the modulation size M in order to maintain a desired BER subject to constant average transmitted energy σ_x^2. From equation (14) and for a given BER, the maximum constellation size is obtained with the following constraint

$$M_i \le 1 - \frac{1.6}{\ln(5P_b)}\left[\frac{\sigma_x^2}{\mathrm{M}SE_{DFE}} - 1\right] \qquad (15)$$

For an AQAM-DFE system, we define some switching levels $(l_0, \cdots, l_{N-1})$. If $\mathrm{M}SE_{DFE} < l_0$, there is no transmission and if $\mathrm{M}SE_{DFE} \ge l_{N-1}$, we choose the modulation of size M_N. For $l_{p-1} \le \mathrm{M}SE_{DFE} < l_p$, the constellation size M_p is chosen.

The $\mathrm{M}SE_{DFE}$ can be approximated using the estimates of the transmitted symbols and by replacing the expectation by the time average. In this paper, it is assumed that the channel is slowly varying and the delay in the feedback link is neglectible. The transmitter can thus use the current $\mathrm{M}SE_{DFE}$ estimate to adjust the next frame modulation size. The maximum constellation size can also be expressed as a function of S_0

$$M_i \le 1 - \frac{1.6}{\ln(5P_b)}\left[\frac{S_0}{\sigma_w^2} - 1\right] \qquad (16)$$

From this equation (16), we can see that the system average energy S_0 is an important parameter in the switching protocol. For time-varying channels, S_0 changes from one frame to the next. In section 5, we investigate the influence of S_0 variation on the AQAM-DFE system.

We note that the DFE equalizer filters and its MSE do not depend on the modulation mode but depend on the average transmitted power σ_x^2. The constellation shape does not influence the equalizer behavior. Thus, for the AQAM-DFE system, it is important to keep σ_x^2 constant. Otherwise, when we switch the modulation mode, optimum MMSE-DFE filters change significantly. This reduces the convergence speed of the DFE equalizer. It is also important to control the transmitted peak power of the AQAM in order to avoid transmitter amplifier saturation. In addition, high peak to average power ratio introduces a nonlinear distortion in the transmitter and reduces the BER performance and the spectral efficiency. In section 7, we discuss an AQAM-DFE scheme with a peak power constraint.

4.2 AQAM-DFE Performances in Rummler channel

To confirm the analysis of the AQAM-DFE system performances, a series of computer Monte Carlo simulations have been carried out. The simulated channel is based on Rummler's simplified three-path model given by the following transfer function

$$H(f) = a\left[1 - be^{-j2\pi(f-f_o)\tau}\right] \tag{17}$$

In equation (17), parameters f_0 and τ ($\sim$ 6.3 ns) represent the notch frequency and the delay between the direct and the multipath component. In the past, Rummler channel parameters were considered static. This propriety was based on assumption that the channel is slowly time-varying in comparison to the symbol rate and that there is no hysteresis in the transmission system behavior [15]. This classical assumption has been questioned in [16] and can not always be applied. Thus, we have simulated a dynamic Rummler channel. The channel dynamic characteristics considered in our simulations are obtained from [16]. These researches state that in more than 99% of cases, the variation of the notch depth is less than 100 dB/s and the variation of the notch frequency is less than 600 MHz/s.

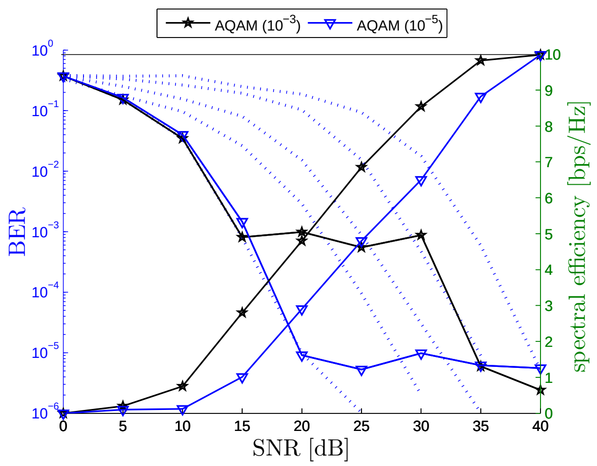

Figure 2: The BER and spectral efficiency (bits/Symbol) of the AQAM-DFE over Rummler channel with notch depth variation of 100 dB/s.

Figure 2 illustrates the BER and the spectral efficiency of the AQAM-DFE system over Rummler channel with notch depth variation of 100 dB/s. The simulated system switches between five M-QAM sizes ($M \in \{4, 16, 64, 256, 1024\}$). Two target BERs of 10^{-3} and 10^{-5} have been considered. The symbol data rate is fixed to $1/T_s = 10$ MSymbols/s and the frame size is $N_T = 10^5$ symbols. The BER performances (dotted curves) of individual fixed M-QAM modulations are also reported in Fig. 2. When that desired BER is equal to 10^{-3}, the AQAM-DFE system reaches this BER at an SNR of 15 dB. For an SNR less than 15 dB, the system is equivalent to an 4-QAM/DFE scheme. In the SNR range of 15 to 30 dB, the BER of the AQAM-DFE system is close to 10^{-3}. However, for this SNR range, the spectral efficiency is improved. For instance, when a fixed modulation scheme is used, to achieve a BER of 10^{-3} at an SNR of 30 dB, the spectral efficiency must be less than 6 bits/symbol. The system improves this spectral efficiency to 8.5 bits/symbol. At higher SNRs ($\geq$ 35 dB), the 256-QAM and 1024-QAM modulations dominate. For an SNR of 35 dB, the BER and the spectral efficiency of the system are better than that of the 256-QAM scheme. As expected, at an SNR of 40 dB, the AQAM-DFE system is equivalent to 1024-QAM scheme and practically and there is no switching to lower order modulations. Desired BER of 10^{-5}, is obtained at an SNR of 25 dB. Over the SNR range of 20-30 dB, the BER of the system remains close to 10^{-5}. However, the spectral efficiency increases as the SNR increases.

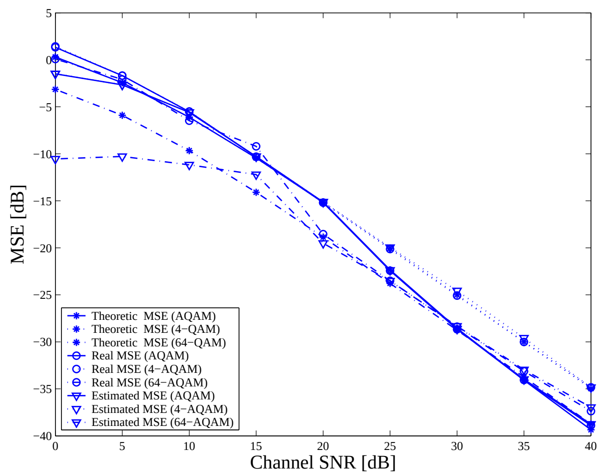

Figure 3: MSE at the MMSE-DFE equalizer.

The MSE at the DFE equalizer output has a crucial impact on the AQAM-DFE system performances. As it is mentioned above, the MSE is approximated using the estimates of transmitted symbols. Figure 3 compares the approximated MSE and the MSE obtained using the real transmitted symbols. The solid curves correspond to the AQAM-DFE system with target BER of 10^{-5}. The dotted and dash-dotted curves are respectively relative to fixed 4-QAM and 64-QAM systems. Theoretic MSEs calculated as in equation (9) are also plotted in Fig. 3. For the AQAM-DFE and the 4-QAM systems, results of Fig. 3 show a close correspondence between the approximated MSE, the real MSE and the theoretic MSE. However, for the 64-QAM system and a lower SNR (less than 15 dB), an important discrepancy between the approximated MSE and the real MSE is observed. For an SNR less than 15 dB, the BER of the 64-QAM system is higher than 10^{-2}. In this situation, replacing the transmitted sequence by the estimated one is not viable. This explains why the approximated MSE is smaller than the real one. Nevertheless, over the SNR range of 0-15 dB, the system is equivalent to 4-QAM/DFE scheme and the observed discrepancy does not influence the system performances. Thus, we can conclude that for SNRs of interest the MSE approximation is accurate.

Figure 4 gives the normalized capacity of the simulated channel. The normalized capacity (C/B) was evaluated according to equation (12). Since the simulated channel is time-varying, the parameter $SNR_{DFE,U}$ was obtained by time-averaging instantaneous unbiased SNRs. In Fig. 4, we have also plotted the spectral efficiencies of fixed QAM-DFE and AQAM-DFE system with target BERs of 10^{-3} and 10^{-5}. Obviously, channel capacity is higher than achieved spectral efficiencies. The transmission rate for AQAM-DFE system is better than that of systems with a fixed modulation mode. However, for a higher SNR, the spectral efficiencies of the AQAM-DFE and the fixed QAM-DFE systems converge to the same value of 10 bits/symbol. In fact, for small noise variances, the 1024-QAM modulation becomes the dominant modulation mode.

5 Effect of channel variation

The switching protocol is based on the MSE_{DFE}. This metric is strongly related to the system average energy S_0 which depends on the channel impulse response and the noise variance σ_w^2. To investigate the influence of S_0 metric on the AQAM-DFE system performances, let us consider a simple channel transfer function $H(z) = 1 + bz^{-1}$, where the second path level is time-varying with a fade rate of 100 dB/s. Let us also assume that the frame length is T_f=1 ms. In this case, the maximum variation in the second path in one frame period of 1 ms is 0.1 dB.

For the given channel transfer function, we can easily evaluate the system average energy S_0 and

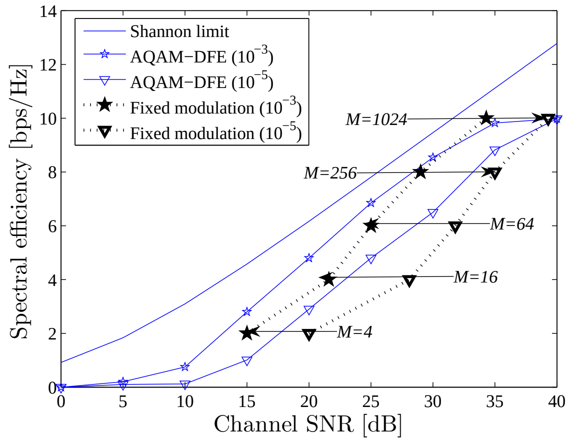

Figure 4: Shannon limit and spectral efficiency.

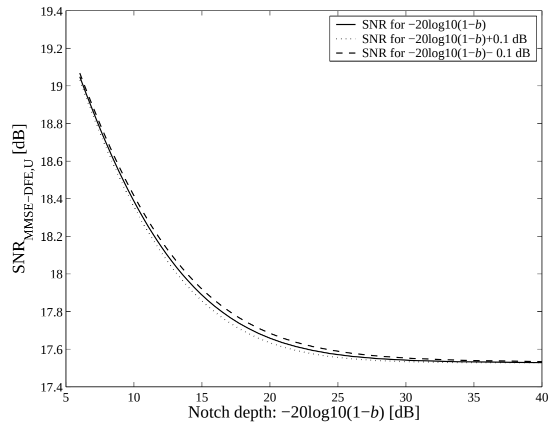

Figure 5: MSE_{DFE} versus notch depth (Channel SNR = 20 dB).

the parameter $SNR_{DFE,U}$. Figure 5 shows the $SNR_{DFE,U}$ versus the notch depth for a channel SNR of 20 dB. It is important to examine the influence of the channel variation on the $SNR_{DFE,U}$ ratio. Thus, in Fig. 5, we have also plotted the variation of the $SNR_{DFE,U}$ when the notch depth increases or decreases from one frame to the next. It is shown, in this figure, that when the notch depth varies by 0.1 dB, the $SNR_{DFE,U}$ variation is negligible. The maximum deviation of $SNR_{DFE,U}$ is about 0.03 dB.

6 Pseudo-SNR versus $SNR_{DFE,U}$

This section compares two AQAM-DFE systems. The first one, denoted by (A), uses the modulation protocol proposed in this paper. The second system, denoted by (B), uses the strategy given in [10].

Let $\mathbf{p} = [p_0, p_1, \cdots, p_{N_f-1}]$ the feedforward filter of length N_f and $\mathbf{q} = [q_0, q_1, \cdots, q_{N_b-1}]$ the feedback filter of length N_b. To switch the modulation mode, authors in [10] use the pseudo-SNR γ_{DFE} at the DFE equalizer defined by

$$\gamma_{DFE} = \frac{E\left[\left|x_k \sum_{m=0}^{N_f-1} p_m h_m\right|^2\right]}{\sum_{m=-(N_f-1)}^{-1} E\left[|f_m x_{k-m}|^2\right] + \sigma_w^2 \sum_{m=0}^{N_f-1} |p_m|^2} \quad (18)$$

where $f_m = \sum_{l=0}^{N_f-1} p_l h_{l+m}$.

The pseudo-SNR expression requires the knowledge of the channel impulse response. Thus, the sequence $\{h_k\}$ has to be estimated. Let us denote $\hat{h}_k$ the estimate of h_k and ε_k the channel estimation error, i.e.

$$\hat{h}_k = h_k + \varepsilon_k \quad (19)$$

Figures 6 and 7 give BER performances and spectral efficiencies of both (A) and (B) systems. For system (B), two situations have been simulated. In the first situation, perfect channel estimation was considered. The second situation assumes that the estimation error is $\sigma_\varepsilon^2 = 0.01$. It is shown that, for a perfect channel estimation, systems (A) and (B) have the same spectral efficiency. For $\sigma_\varepsilon^2 = 0.01$, the system spectral efficiency increases. For this case, the transmitter has an imperfect knowledge of the channel state. Thus, transmitter increases the transmission throughput even if channel conditions do not allow it. This spectral efficiency gain influences the BER performances. As it is shown in Fig. 7, when $\sigma_\varepsilon^2 = 0.01$, the BER of system (B) is higher than that when the channel estimation is perfect. It is noted that, for $\sigma_\varepsilon^2 = 0$, BER performances of systems (A) and (B) are practically similar.

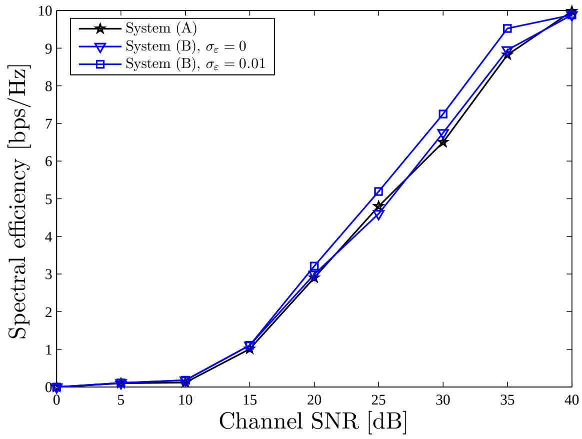

Figure 6: Spectral efficiencies of (A) and (B) systems (Target BER: 10^{-5}).

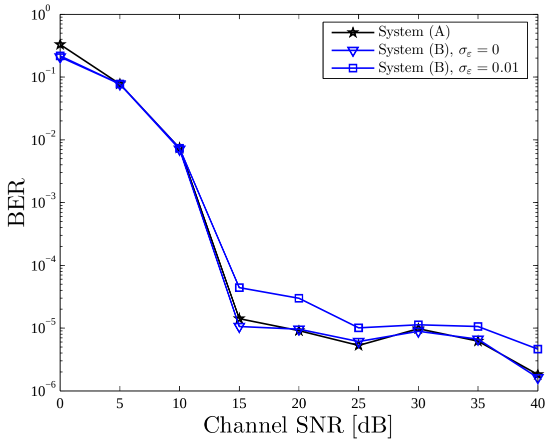

Figure 7: BER performances of (A) and (B) systems (Target BER: 10^{-5}).

7 AQAM-DFE scheme with peak power constraint

In previous sections, we have seen that it is important to keep the average power at equalizer input constant. For adaptive modulation scheme with constant average power, the peak power increases as the constellation size increases. Thus, adaptive modulation with constant average power may be susceptible to high peak-to-average power ratios. In fact, the peak power changes continuously and occupies a large bandwidth. In addition, high peak-to-average power ratio introduces nonlinear distortion in the transmitter and reduces the BER performance and the spectral efficiency. Thus, it is essential to control the peak power in order to avoid transmitter amplifier saturation.

A simple solution consists in fixing the average power so that the maximum peak power falls within the amplifier linear region. This approach reduces the peak power of smaller size modulations. It is however possible to keep the peak power E_p (instead of average power $E_s = \sigma_x^2$) constant when we switch between modulations and to control the mean power at the equalizer input. Naturally, $\mathrm{M_i}$-QAM modulations are chosen so that E_p is equal (or close) to the maximum peak power that the system can support. An automatic gain control can be placed before the MMSE-DFE to adjust the average power at the equalizer input. In fact, to maintain the convergence speed of the MMSE-DFE equalizer, it is important that the received power spectrum given by equation (3) remains constant.

The AGC module is used to change the varying mean power of the received signal and bring it to a predefined target power level E_T. The AGC is a one-tap real filter with output $z_n = a_n y_n$ which satisfies

$$E\left\{|z_n|^2\right\} = E_T \tag{20}$$

The AGC coefficient are controlled by an adaptive algorithm

$$A_n = A_{n-1} + \mu_A \left[E_T - |z_n|^2\right] \tag{21}$$

$$a_n = \sqrt{|A_n|} \tag{22}$$

where $A(0) = 1$ and μ_A is a small positive step-size.

The QAM demodulator has to take into account the power adjustment performed by the AGC. The scaling introduced by the AGC biases the decision variable. This scales the decision region at the demodulator which has to remove the bias at the decision point. Obviously, to determine and adjust the decision regions, the receiver must know perfectly the current transmitted constellation.

Figure 8 illustrates the spectral efficiency of two scenarios with peak power constraint. The dotted curve corresponds to the scenario with a constant average power. This later is chosen so that the maximum peak power remains equal to the fixed power level $E_{p,max}$. The solid curve is relative to the proposed scenario with constant peak power $E_p = E_{p,max}$ and variable average power. It is shown that the spectral efficiency of the proposed scheme is better than that of the scenario (A) specially for higher noise variance. In fact, the proposed technique allows to increase the average transmit power for lower order modulations. For $\sigma_w^2 = 20$ dB, the gain obtained by the proposed technique is about 1 [bps/Hz]. However, when the noise variance decreases, the gain is much smaller. This is explained by the fact that for small variance noise, there is no switching to lower order modulations.

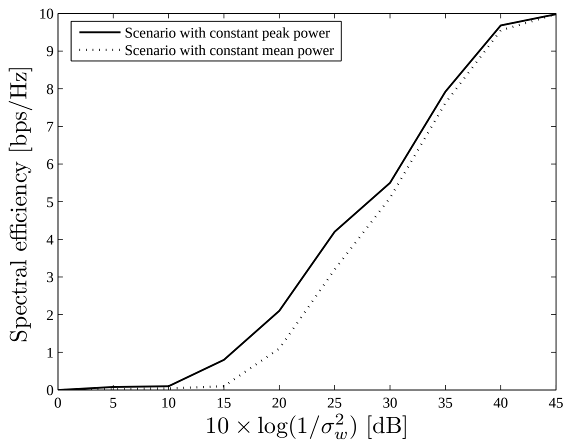

Figure 8: Spectral efficiency of AQAM-DFE system with peak power constraint (Target BER: 10^{-5}).

8 Conclusion

In this paper, we investigate an adaptive modulation technique for frequency selective channels. The analyzed system combines an AQAM scheme and a MMSE-DFE equalizer. To adjust the modulation mode, we have suggested to use an approximation of the $\mathrm{M}SE_{DFE}$ metric. The advantage of this switching protocol is that channel estimation is not required. Simulation results show that for SNRs of interest and small target BER, the $\mathrm{M}SE_{DFE}$ is accurately estimated. Furthermore, for a channel with two paths and a fade rate of 100 dB/s, channel variations have a negligible impact on the $SNR_{DFE,U}$ value. Simulation comparisons show that, for perfect channel estimation, the proposed AQAM-DFE method has the same performances as the technique of [10] which uses the pseudo-SNR criterion. However, the channel estimation mismatch influences the AQAM-DFE system based on the pseudo-SNR metric. Indeed, with an imperfect channel estimation, the transmitter increases the transmission throughput even if the channel conditions do not allow it. In this situation, the spectral efficiency is increased at the expense of the BER. In the final section, a peak power control technique have been proposed. We have suggested to keep the peak power constant when we switch from a modulation scheme to another. For this scenario, the average power is not constant. Thus, a AGC module can be used before the MMSE-DFE equalizer. The AGC brings the power of the received signal to a predefined constant level.

References:

[1] W. Webb and R. Steele, "Variable rate QAM for mobile radio," *IEEE Trans. Commun.*, vol. 43, no. 7, pp. 2223–2230, Jul. 1995.

[2] A. J. Goldsmith and S.-G. Chua, "Variable-rate variable-power MQAM for fading channels," *IEEE Trans. Commun.*, vol. 45, no. 10, pp. 1218–1230, Oct. 1997.

[3] A. J. Goldsmith and S. G. Chua, "Adaptive coded modulation for fading channels," *IEEE Trans. Commun.*, vol. 46, no. 5, pp. 595–602, May 1998.

[4] S. Falahati, A. Svensson, T. Ekman, and M. Sternad, "Adaptive Modulation Systems for Predicted Wireless Channels," *IEEE Trans. Commun.*, vol. 52, no. 2, pp. 307–316, Feb. 2004.

[5] V. K. N. Lau and M. D. MacLeod, "Variable-rate adaptive trellis-coded QAM for high-bandwidth efficiency applications in Rayleigh fading channels," in *Proc., IEEE Veh. Technol. Conf.*, 1998, pp. 348–352.

[6] N. D. Chatzidiamantis, A. S. Lioumpas, G. K. Karagiannidis, and S. Arnon, "Adaptive subcarrier psk intensity modulation in free space optical systems," *IEEE Trans. Commun.*, vol. 59, no. 5, pp. 1368–1377, 2011.

[7] J. Huang and S. Signell, "On Performance of Adaptive Modulation in MIMO Systems Using Orthogonal Space-Time Block Codes," *IEEE Trans. Veh. Technol.*, vol. 58, pp. 4238–4247, 2009.

[8] C.-C. Weng, C.-Y. Chen, and P. P. Vaidyanathan, "MIMO Transceivers With Decision Feedback and Bit Loading: Theory and Optimization," *IEEE Trans. Signal Processing*, vol. 58, no. 3, pp. 1334–1346, 2010.

[9] M. L. Ammari, K. Zaouali, and P. Fortier, "Adaptive modulation and decision feedback equalization for frequency-selective MIMO channels," *International Journal of Communication Systems*, vol. 2013, 2013.

[10] C. H. Wong and L. Hanzo, "Upper-bound performance of a wide-band adaptive modem," *IEEE Trans. Commun.*, vol. 48, no. 3, pp. 367–369, Mar. 2000.

[11] M. S. Yee and L. Hanzo, "A wide-band radial basis function decision feedback equalizer-assisted burst-by-burst adaptive modem," *IEEE Trans. Commun.*, vol. 50, no. 5, pp. 693–697, May 2002.

[12] M. L. Ammari, F. Gagnon, and J. Belzile, "Adaptive M-QAM scheme and unbiased MMSE-DFE receiver," in *Proc., IEEE Veh. Technol. Conf.*, Sep. 2005, pp. 1935–1939.

[13] J. M. Cioffi, G. P. Dudevoir, M. V. Eyuboglu, and G. D. J. Forney, "MMSE decision-feedback equalizers and coding. Part-I: Equalization results," *IEEE Trans. Commun.*, vol. 43, no. 10, pp. 2582–2594, Oct. 1995.

[14] ——, "MMSE decision-feedback equalizers and coding. Part-II: Coding results," *IEEE Trans. Commun.*, vol. 43, no. 10, pp. 2595–2604, Oct. 1995.

[15] W. D. Rummler, R. P. Coutts, and M. Liniger, "Multipath Fading Channel Models for Microwave Digital Radio," *IEEE Commun. Mag.*, vol. 24, no. 11, pp. 30–42, Sep. 1986.

[16] J. Hoffmeyer, "Measurement, modeling, and simulation of digital LOS microwave channels with applications to outage prediction," *IEEE Trans. Commun.*, vol. 39, no. 9, pp. 1295–1305, Sep. 1991.