Throughput Improvement of an AMQAM Scheme by using New Switching Thresholds over Nakagami-m Fading Channels

Youngkou Lee, Sungsoo Choi, Insoo Koo, Seung-Geun Kim and Kiseon Kim

Dept. of Information and Communications, KJIST
1, Oryong-dong, Puk-ku, Gwangju, 500-712, Rep. of Korea
Tel: +82-62-970-2252, Fax: +82-62-970-2204, E-mail: yklee@kjist.ac.kr

Abstract: In this paper, we investigate the throughput improvement of an adaptive M-ary quadrature modulation (AMQAM) scheme by using new switching thresholds over slow frequency nonselective Nakagami-m fading channels. The new switching thresholds are obtained by using the approximated BER expressions with complimentary error functions for each modulation scheme given in AWGN channels. By using the new switching thresholds, we can improve the maximum system throughput. For example, we get the maximum throughput improvement about 0.32 when the target BER is 10^{-3} and the fading figure $m = 3$.

Keywords—Adaptive M-ary quadrature modulation (AMQAM), Nakagami-m distribution, Switching threshold, System throughput, Average bit error rate

1. Introduction

The signals transmitted through wireless mobile radio channel environments undergo harsh multipath fading which leads to severe degradation in the received signal-to-noise ratio (SNR). The conventional techniques, used for compensating the harsh fading effects, are generally designed to the worst-case channel conditions taking low utilization of the whole channel capacity. Therefore, it is required to adapt channel parameters of the transmitted signal according to the fading fluctuations to utilize the channel capacity more than the conventional methods.

The basic motivation of adaptive schemes are to satisfy the required system performance such as bit/symbol error rate (BER/SER) and system throughput. Adaptive modulation schemes can efficiently utilize the channel capacity than the fixed modulation schemes through adaptive variation of the transmitted symbol constellation size or power level [1]. Furthermore, by employing high constellation size under favorable channel conditions and low constellation size under deep fading channel conditions, the adaptive modulation schemes provide a higher average spectral efficiency without sacrificing signal power or BER.

Various adaptive modulation systems employing MQAM were characterized in the text book written by Hanzo et al. [2]. The application for a wideband video system was expressed in [3] with many helpful references. The numerical upper bound of AMQAM performance over slow Rayleigh flat-fading channels was evaluated by Torrance et al. [4]. Goldsmith et al. extended the result of [4] into more generalized fading environment, namely Nakagami-m fading channels [5]. In [5], they evaluated throughput and BER performance of the AMQAM schemes with the switching thresholds obtained by using the exponentially approximated equations of BERs given in the AWGN channels.

In this paper, we investigate the throughput (in the means of bits per symbol) improvement by using the proposed switching thresholds compared to the results given in [5] under Nakagami-m fading channels. The remainder of this paper is organized as follows. In Section 2, the adaptive system configuration, the fading channel model and the theoretical evaluation of BER performance calculation of the AMQAM scheme are described. The method of determining switching thresholds of the AMQAM is given in Section 3. In Section 4, we illustrate the results of the throughput improvement obtained by changing the switching thresholds against the results given in [5]. Finally, we conclude this paper with remarks in Section 5.

2. System Configuration and Channel Model

Table 1 lists the modulation schemes employed in the considering adaptive modulation system. As seen in Table 1, we use five modulation schemes to the adaptive system and four switching thresholds. When the channel fading is too harsh to achieve the target BER even for the BPSK signals, i.e. in the case of the received SNR γ is lower than γ_1, the system does not transmit data. In the case of $\gamma_1 < \gamma \leq \gamma_2$, when the channel fading is very deep but we can achieve the target BER by using BPSK modulation, the system employs BPSK signals. If the channel environment is somewhat favorable to employ higher level constellation than BPSK, that is in the case of $\gamma_2 < \gamma \leq \gamma_3$, the system employs QPSK modulation scheme to transmit the data. If the channel state is in light-fading to use higher level constellation than QPSK, that is in the case of $\gamma_3 < \gamma \leq \gamma_4$, the system transmits 16QAM signals. Finally, the system transmits 64QAM signals when the channel fading is negligible, namely in the case of $\gamma_4 < \gamma$. In other words, corresponding to the fading depth, the adaptive modulation can have various constellation size with different spectral efficiency. For example, the system achieve 1 bit/symbol (BPS) by using BPSK modulation, 2 BPS by quadrature modulation (quadrature phase shift keying (QPSK) or quadrature amplitude modulation (QAM)), and $log_2 M$ BPS by MPSK or MQAM scheme.

Figure 1 shows a conceptional block diagram of the considering adaptive modulation system equipped with a perfect channel estimator and reliable feed-back path.

1

1440

Table 1. Criteria of the adaptive modulation scheme.

Modulation Scheme	Decision Criteria	Bit per Symbol (BPS)
No Transmission	$\gamma \leq \gamma_1$	0
BPSK	$\gamma_1 < \gamma \leq \gamma_2$	1
QPSK	$\gamma_2 < \gamma \leq \gamma_3$	2
16QAM	$\gamma_3 < \gamma \leq \gamma_4$	4
64QAM	$\gamma_4 < \gamma$	6

Figure 1. Block diagram of a system employing an adaptive modulation scheme.

The decision device selects the rate and power to be transmitted based on the channel gain estimate $\hat{\alpha}$ and informs to the transmitter about that decision via the feed-back path. The pilot sequence is used for providing the channel state through channel estimator which estimates the channel induced envelope fluctuation α and phase shift ϕ induced by the fading channel. In this paper, we presume that the receiver performs perfect or ideal coherent detection (perfectly known phase shift ϕ) and no feed-back delay. The reader, who is interested in the effect of feed-back delay, can refer [5].

For a slow frequency nonselective fading channel, the received signal can be represented by an equivalent low-pass signal sampled at time i as follows:

$$r_i = \alpha_i s_i + n_i, \tag{1}$$

where s_i is the transmitted MQAM signal, n_i is a zero-mean complex Gaussian noise process with variance $\sigma_i^2 = N_0/2$ and α_i is the amplitude of the channel gain. A convenient probability density function (PDF) in evaluating the BER performance and the system throughput can be represented by using the received signal-to-noise ratio (SNR), $\gamma = \alpha^2 E_s/N_0$. The gamma distributed PDF of γ, $f_\Gamma(\gamma)$, is expressed as follows:

$$f_\Gamma(\gamma) = \left(\frac{m}{\bar{\gamma}}\right)^m \frac{\gamma^{m-1}}{\Gamma(m)} \exp(-\frac{m\gamma}{\bar{\gamma}}), \quad \gamma \geq 0, \tag{2}$$

where $m = \Omega^2/Var[\alpha^2]$, $m \geq 0.5$ is so-called the fading figure and $\Gamma(m) = \int_0^\infty e^{-t}t^{m-1}\,d\gamma$ and $\bar{\gamma}$ is the average received SNR.

The BER performance of the adaptive MQAM (AMQAM) system, using the switching thresholds and modulation criteria given in Table 1, can be expressed as follows [6]:

$$P_{adp} = [P_B(\gamma_1, \gamma_2) + 2P_Q(\gamma_2, \gamma_3) + 4P_{16}(\gamma_3, \gamma_4) + 6P_{64}(\gamma_4, \infty)]/T_{avg}, \tag{3}$$

where T_{avg} is the average system throughput. If m is an integer, the BER term $P_B(a,b)$ in Eq. (3) can be
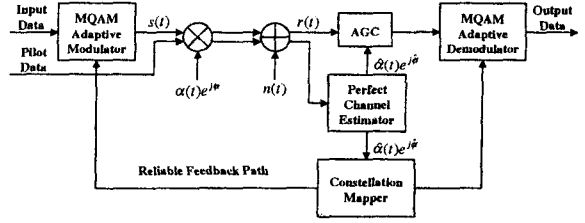
obtained in a closed form as following equation [9]:

$$
\begin{aligned}
P_B(a, b) = &\sum_{k=0}^{m-1} \frac{1}{\gamma_s^k k!} \{erfc(\sqrt{a})e^{-b/\gamma_s}a^k \\
&- erfc(\sqrt{b})e^{-b/\gamma_s}b^k \\
&- \frac{1}{\sqrt{\pi}}\sum_{j=1}^{k} \frac{\Gamma(k+\frac{1}{2})}{\Gamma(j+\frac{1}{2})} \frac{e^{-ua}a^{k-\frac{1}{2}} - e^{-ub}b^{k-\frac{1}{2}}}{u^{k-j+1}} \\
&- \frac{\Gamma(k+\frac{1}{2})}{\sqrt{\pi}u^{k+\frac{1}{2}}}[erfc(\sqrt{ua}) - erfc(\sqrt{ub})]\},
\end{aligned}
\tag{4}
$$

where $\gamma_s = \bar{\gamma}/m$, $u = 1 + 1/\gamma_s$ and $erfc(\cdot)$ is the complementary error function. By substituting Eq. (3) into the exact BER given in [4] and then by changing the parameters for the cases of MQAM schemes, we can get the error probability of the AMQAM scheme.

The average throughput T_{avg} of the AMQAM is given [6]:

$$
\begin{aligned}
T_{avg} = &B(\gamma_1, \gamma_2) + 2B(\gamma_2, \gamma_3) \\
&+ 4B(\gamma_3, \gamma_4) + 6B(\gamma_4, \infty),
\end{aligned}
\tag{5}
$$

where $B(a, b) = \int_a^b f_\Gamma(\gamma)d\gamma$ is the partial throughput of partial interval. The probability $B(a, b)$ can be expressed in a closed form as follows;

$$B(a, b) = \frac{\Gamma(m, \frac{ma}{\bar{\gamma}}) - \Gamma(m, \frac{mb}{\bar{\gamma}})}{\Gamma(m)}, \tag{6}$$

where $\Gamma(a, b)$ is so-called the complementary incomplete gamma function.

3. Determination of switching thresholds

The switching thresholds are related to the BER performance and the system throughput. Thus, it is worthy to determine the threshold values to enhance the system throughput while satisfying the required BERs (target BERs). In this section, we discuss the determination method of switching thresholds in detail.

After choosing the target BER, BER_{tg}, the switching thresholds, $\gamma_l, l = 1, 2, 3$ and 4, are then determined to satisfy the target BER using MQAM schemes over an AWGN channel. In [5], the switching thresholds are set

2

Table 2. Switching thresholds of the AQAM scheme when the target BER $BER_{tg} = 10^{-2}, 10^{-3}, 10^{-4}$ and 10^{-5}.

Target BER \ Switching Level	Switching Level 1			Switching Level 2			Switching Level 3			Switching Level 4		
	γ_{GS1}	γ_{AP1}	Diff.	γ_{GS2}	γ_{AP2}	Diff.	γ_{GS3}	γ_{AP3}	Diff.	γ_{GS4}	γ_{AP4}	Diff.
10^{-2}	4.32	4.32	0	7.77	7.33	0.44	14.76	13.90	0.86	20.99	19.73	1.26
10^{-3}	6.78	6.78	0	10.23	9.80	0.43	17.24	16.54	0.70	23.47	22.55	0.92
10^{-4}	8.39	8.39	0	11.81	11.40	0.41	18.80	18.22	0.58	25.04	24.30	0.74
10^{-5}	9.58	9.58	0	12.96	12.59	0.37	19.95	19.45	0.50	26.19	25.57	0.62

as follows:

$$\gamma_1 = [erfc^{-1}(2BER_{tg})]^2,$$

$$\gamma_l = \frac{2}{3}K_0(2^l - 1); \quad l = 2,3,4, \tag{7}$$

where $K_0 = -ln(BER_{tg})$. The switching thresholds are selected from the fact that the BER performance of MQAM scheme approximated by exponential function is very closely match to the exact BER performance in AWGN channels when the modulation degree $M > 4$ [5]. However, it is well known that the BER performance can more closely match to the exact BER expression if we use the complimentary error function [5]. The exact expressions for the BER of square MQAM, when the number of bits per symbol M is even, are expressed in [4]. Therefore, we choose new switching thresholds by using the inverse complimentary error function of the approximated BER function under AWGN channels as following equations:

$$\gamma_1 = [erfc^{-1}(2BER_{tg})]^2,$$

$$\gamma_2 = 2 * [erfc^{-1}(2BER_{tg})]^2,$$

$$\gamma_3 = 10 * [erfc^{-1}(\frac{8}{3}BER_{tg})]^2, \tag{8}$$

$$\gamma_4 = 42 * [erfc^{-1}(\frac{24}{7}BER_{tg})]^2.$$

Table 2 shows the switching thresholds of the AMQAM scheme when the target BER, BER_{tg} is $10^{-2}, 10^{-3}, 10^{-4}$ and 10^{-5}. In the table, γ_{GSi} and γ_{Api} represent the switching thresholds obtained by using Eq. (7) and Eq. (8), respectively. From the table, the followings are noted. First, for the same target BER, as the constellation size increases (or the threshold level increases), the difference of the switching thresholds between the two schemes increases. Second, for the same switching thresholds, as the target BER gets high, the difference between two schemes increases. In other words, as the target BER becomes high and the constellation size gets large, the required SNR becomes low by using the proposed switching thresholds while satisfying the target BER. Figure 2 shows the BER performance of the AMQAM scheme, when the target BER $BER_{tg} = 10^{-3}$, obtained by using the proposed switching thresholds given in Table 2. As we can see in the figure, the new switching thresholds satisfy the perfor-
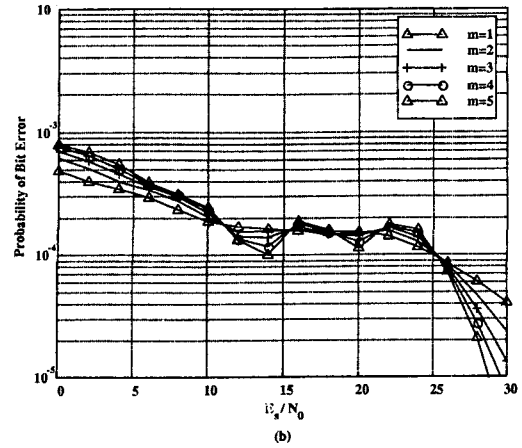

Figure 2. BER performance of the AMQAM scheme when the fading figure, $m = 1$, 2, 3, 4 and 5 with $BER_{tg} = 10^{-3}$.

mance restriction (lower BER than the target BER) over all the system operation range.

4. Numerical results of the adaptive MQAM modulation scheme

With the switching thresholds given in Table 2, we can obtain the throughput by substituting the values into Eq. (5). In order to show the throughput improvement obtained by using new switching thresholds, Figure 3 shows the improved throughput versus the received average SNR $\bar{\gamma} = E_s/N_0$ and the target BER $BER_{tg} = 10^{-2}, 10^{-3}, 10^{-4}$ and 10^{-5} when the fading figure m is (a) 1 and (b) 3, respectively. From the figure, the followings are observed. First, the trend of throughput improvement with different target BER is very similar to each other, the only distinct point is the improved amount. Second, the improved throughout amount increases as the target BER becomes high and the value of fading figure increases. Third, the throughput improvement gives the local peaks at each switching threshold except the first switching threshold because of the same value of the two schemes, and a global peak at the last (here, fourth) switching threshold.

In other aspect, it is noteworthy to observe the largest throughput improvement because the value can give a meaningful inspection of designing the system under fading channel environments. Figure 4 shows the largest throughput improvements corresponding to the target BERs and the fading figures. From the figure, we can observe the following things. First, the largest throughput improvement is dependent on both the target BER and the fading figure, that is, the value increases as the target BER becomes high and the fading figure increases. For example, when the target BER is 10^{-3}, the value is about 0.38, 0.32 and 0.23 for $m = 5$, $m = 3$ and $m = 1$, respectively. Second, the value increases almost linearly as m increases when the target BER is lower than 10^{-4}. In other words, if we want to design a system to achieve the maximum throughput in a partial
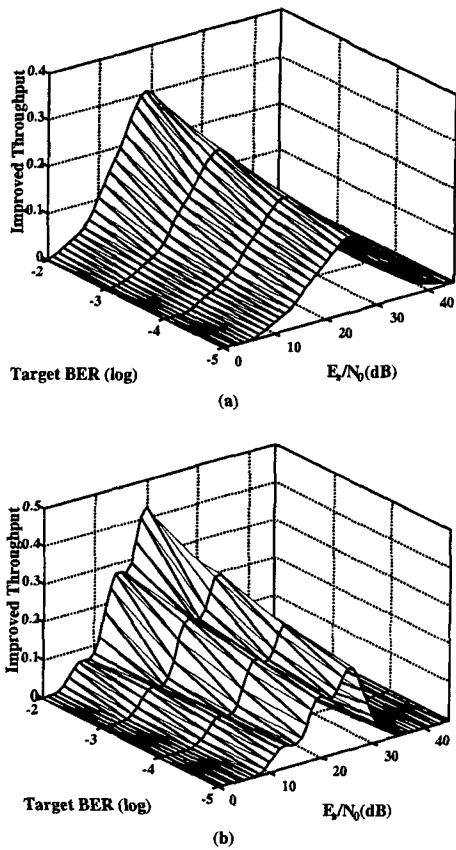
3

(a)

(b)

Figure 3.   Improved throughput of the AMQAM scheme versus E_s/N_0 and versus the target BER, $BER_{tg} = 10^{-2}$, 10^{-3}, 10^{-4} and 10^{-5} when (a) $m = 1$ and (b) $m = 3$.
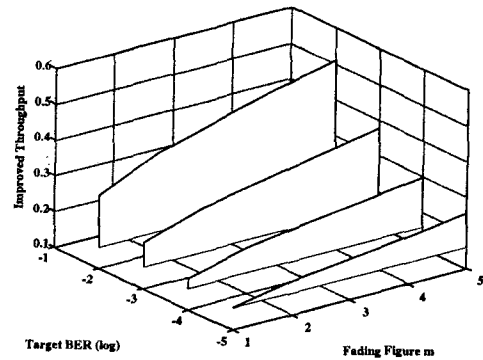

Figure 4.   The largest throughput improvements of the AMQAM scheme vs. the fading figure $m = 1, 2, 3, 4$ and 5 when the target BER, $BER_{tg} = 10^{-2}$, 10^{-3}, 10^{-4} and 10^{-5}.

From the results, the following observations were noted. First, the difference of switching thresholds between the two schemes increases as the target BER becomes high and the fading becomes light (the fading figure increases). Second, the trend of throughput improvement with different target BER is very similar to each other. Third, the largest throughput improvement by using the proposed switching thresholds increases as the target BER gets high and m increases, and the value increases almost linearly as m increases when the target BER is lower than 10^{-4}. From the observations, we can say that if we want to design an AMQAM system to get throughput improvement in the point of maximum throughput, then we should reflect the effect of both the target BER and the fading depth.

scope of the received average SNR, then we should take into account the effect caused by both the target BER of the system and the fading depth of the channel.

5. Conclusions

In this paper, we investigated the throughput improvement of an adaptive M-ary quadrature amplitude modulation (AMQAM) scheme employing the proposed alternative switching thresholds under slow frequency nonselective Nakagami-m fading channels. The new switching thresholds were obtained by using the complimentary error function for the BER functions given in AWGN channels. To give numerical results, we compared the throughput to that of the switching thresholds obtained by the exponentially approximated function to the BER expressions of each modulation scheme in AWGN channels. By using the proposed switching thresholds, we can improve the maximum system throughput. For example, in the fading figure $m = 3$, the case of lighter fading than Rayleigh, we got the throughput improvement about 0.43, 0.32, 0.25 and 0.21 when the target BER is 10^{-2}, 10^{-3}, 10^{-4} and 10^{-5}, respectively.

References

[1] W. Webb and R. Steele, "Variable Rate QAM for Mobile radio," *IEEE Trans. Commun.*, vol. COM-43, pp. 2223-2230, July 1995.

[2] L. Hanzo, W. Webb and T. Keller, Single-and multicarrier Quadrature Amplitude Modulation: *Principles and Applications for Personal Communications, WATM and Broadcasting*. Piscataway, NJ, New York: IEEE, Wiley, 2000.

[3] L. Hanzo, C. Wong and P. Cherriman, "Channel Adaptive Wideband Wireless Video Telephony," *IEEE Signal Processing Magazine*, pp. 10-30, July 2000.

[4] J. Torrance and L. Hanzo, "Upper bound performance of adaptive modulation in a slow Rayleigh fading channel," *Electron. Lett.*, vol. 32, pp. 718-719, Apr. 1996.

[5] M. Alouni and A. Goldsmith, "Adaptive M-QAM modulation over Nakagami fading channels," *IEEE Globecom Conf.*, Nov. 1997.

[6] B. Choi, M. Munster, L. Yang and L. Hanzo, "Performance of Rake reciver assisted adaptive-modulation based CDMA over frequency selective slow Rayleigh fading channels," *Electron. Lett.*, vol. 37, pp. 247-249, Feb. 2001.

[7] I. S. Gradshteyn and M. Rhyzik, *Tables of Integrals, Series and Products*, Academic Press, New York, 1980.

[8] M. Alouni, X. Tang and A. Goldsmith, "An Adaptive Modulation Scheme for Simulaneous Voice and Data Transmission over fading channels," *IEEE JSAC*, vol. 17, pp. 837-850, May 1999.

[9] Y. Lee, S. Choi, S. Kim, and K. Kim, "Transition Probabilities of Coded BPSK Signals for hard-Decision Decoding with k-Bit CSI in Nakagami-m fading Channels," *IEEE Commun. Lett.*, vol. 6, pp. 28-30, Jan. 2002.

4