EMBEDDED IMAGE TRANSMISSION BASED ON ADAPTIVE MODULATION AND CONSTRAINED RETRANSMISSION OVER BLOCK FADING CHANNELS

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ABSTRACT

In this paper, we consider the problem of embedded image transmission with feedback of channel state information (CSI) and retransmission request. Adaptive modulation is employed to improve the spectral efficiency. Constrained retransmission is employed to provide reliable packet transmission with limited delay. Performance analysis and numerical results over Nakagami block-fading channels are provided for the transmission system with statistical or instantaneous CSI at the transmitter. The results show that CSI at the transmitter is very important for adaptive modulation/coding over fading channels.

1. INTRODUCTION

The embedding property is one of the most important features of modern image compression. The image can be progressively transmitted and reconstructed at any target bit rate without extra cost [1, 2]. However, it is a challenge to transmit an embedded image over noisy channels, especially over time-varying fading channels. Our focus in this paper will be upon **embedded image transmission** over block fading channels. The objective is to improve the spectral efficiency while keeping the embedding property.

Communication Over Time-varying Noisy Channels If the channel is time-varying, the channel capacity is time-varying, consequently the optimal transmission system should also be time-varying, or adaptive, according to the channel state information (CSI) available at the transmitter. This involves power adaptation and rate adaptation (**adaptive modulation/coding**). As pointed out in [5], rate adaptation is the key for increasing the spectral efficiency.

Packet Transmission Over Fading Channels There are two kinds of packet transmission systems: with feedback or without feedback. Without feedback, it is difficult to guarantee the requirements of transmission delay, transmission reliability, and spectral efficiency simultaneously. For systems with feedback, adaptive modulation/coding can be used to improve spectral efficiency with the feedback of CSI, and packet retransmission can be used to improve the transmission reliability with the feedback of retransmission request [8, 10]. The penalty for feedback systems is the round-trip delay introduced.

Contribution of This Paper In reference [3], adaptive modulation and constrained retransmission have been employed for general packet transmission over block fading channels. In this paper we extend the application of adaptive modulation and constrained retransmission to embedded image compression over block fading channels. The concepts of “prediction loss” and “coding loss” are proposed to evaluate the adaptive modulation system.

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Paper Organization This paper is organized as follows. Section II explains the requirement of embedded image transmission. Section III describes the system model and transmission scheme. The goal is to maximize the spectral efficiency while keeping the embedding property. Performance analysis and numerical results are provided in Section IV. Section V gives the conclusions.

2. THE REQUIREMENTS OF EMBEDDED IMAGE TRANSMISSION

We will discuss the following four features of embedded image transmission: 1) spectral efficiency, 2) loss tolerance, 3) error intolerance, and 4) delay sensitivity [4].

Spectral Efficiency Similar to any other services over communication channels, embedded image transmission demands spectral efficiency close to theoretical limit, so that embedded images can be transmitted rapidly and reliably. We will use adaptive modulation to improve the spectral efficiency.

Loss Tolerance Embedded image compression is essentially lossy compression. Depending upon the user’s individual requirements, the transmitted image can be a thumbnail for quick browsing, of acceptable quality for viewing, or of satisfactory quality for storage. As a result, a feedback channel is needed.

Error Intolerance Although embedded image transmission is loss tolerant, errors cannot be tolerated since the coded bits depend on each other. The information transmitted first is very sensitive to channel errors. Therefore, we want high transmission reliability. Our solution involves error detection and the feedback of retransmission requests.

Delay Sensitivity The embedding property is weakened by packetization delay, across-packet interleaving delay, retransmission delay, and queuing delay. In quality-scalable embedded image coding, packetization delay implies that image quality can be improved only after the whole packet is received, decoded, and verified. To reduce the effect of packet delay, the packet length is not very large, the interleaving is kept within each packet, and **delay-constrained retransmission** is used.

To summarize, embedded image transmission requires high spectral efficiency, low transmission delay, and high transmission reliability. Adaptive modulation and constrained retransmission provide a good trade-off among these requirements.

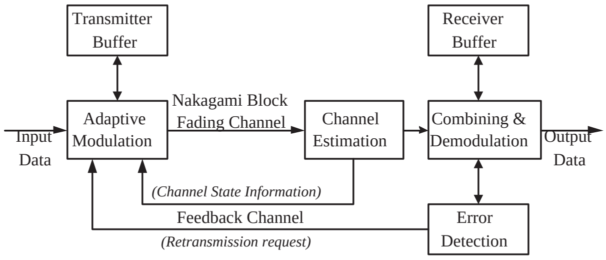

Fig. 1. Packet transmission system with adaptive modulation and constrained retransmission.

3. SYSTEM MODEL AND TRANSMISSION SCHEME

The simplified model for our end-to-end packet transmission system is shown in Figure 1. The forward communication channel is a Nakagami block fading channel. Perfect channel estimation and coherent demodulation are assumed at the receiver. The CSI through the feedback channel helps determine the modulation profile for each **original packet**. If there is an error detected in the received original packet, one retransmission request is sent through the feedback channel. The retransmission packets are combined with the original packet at the receiver to guarantee the reliability of packet transmission. We explain the system model and transmission scheme in detail.

1. **Nakagami Block-fading Channels**

The forward communication channel with multi-path fading is characterized by the signal-noise-ratio (SNR) at the receiver. For general Nakagami fading channels, the probability density function (PDF) of SNR γ is given by $\gamma \sim Gamma(\overline{\gamma}, m)$ [9]:

$$p_\gamma(\gamma) = \frac{m^m \gamma^{m-1}}{\overline{\gamma}^m \Gamma(m)} \exp(-\frac{m\gamma}{\overline{\gamma}}), \tag{1}$$

where $\overline{\gamma} = E(\gamma)$ is the average SNR at the receiver, $\Gamma(m) = \int_0^\infty t^{m-1} \exp(-t) dt$ is the gamma function, and m is the Nakagami fading parameter ($m \geq 1/2$). The SNR γ is assumed constant over the duration of each packet [7]. The resulting forward communication channel is a Nakagami block-fading channel.

2. **CSI at the Transmitter** At the receiver, the CSI is estimated based on the training symbols or the pilot tones inserted in each packet. Perfect channel estimation is assumed. The channel estimation results are used for coherent demodulation. At the same time, the statistical or instantaneous CSI is sent back to the transmitter. We will consider two extreme scenarios: I. For the i.i.d. fading channels, only statistical CSI is available at the transmitter. II. For highly correlated channels with long coherence time, instantaneous CSI is available at the transmitter.

3. **Adaptive Modulation** The available CSI at the transmitter helps determine the constellation size ($M = 2^n$) of multi-level quadrature amplitude modulation (QAM) for each original packet. This is called adaptive QAM. The objective is to maximize the spectral efficiency (η). There are two kinds of QAMs considered in this paper, the square QAM ($M = 4, 16, 64, 256$) and the rectangular QAM ($M = 2, 8, 32, 128$). Each QAM modulation consists of two independent PAM modulations, M_I-PAM for the I branch and M_Q-PAM for the Q branch [6]. For square QAM, $M_I = M_Q = \sqrt{M}$. For rectangular QAM, $M_I = \sqrt{2M}$, $M_Q = \sqrt{M/2}$.

4. **Constrained Retransmission and Maximal-Ratio Combining** If there is an error detected in the original packet received, only one retransmission request is sent back to the transmitter to retransmit N_r packets for each request, i.e., there are multiple retransmission responses per request. We also limit the maximum retransmission number by setting $N_r \leq 6$. This is called constrained retransmission. Constrained retransmission is employed to minimize the maximum delay while guaranteeing the reliability of packet transmission. The maximum delay with constrained retransmission is the sum of forward transmission delay, one round-trip delay, and queuing delay.

We assume that retransmitted packets are copies of the original packet. The retransmitted packets and the original packet are combined at the receiver using maximal-ratio-combining (MRC) to guarantee the transmission reliability in terms of packet error rate. This is equivalent to adaptive time-diversity. The SNR of the **combined packet** is [9]:

$$\pi_0 = \gamma_0 + \sum_{i=1}^{N_r} \gamma_i, \tag{2}$$

where γ_0 is the SNR of original packet, γ_i is the SNR of retransmitted packet i.

5. **Miscellaneous** The feedback channel is assumed to be error-free. Packet error detection is assumed to be perfect. Symbol time and bandwidth are constant. Symbol peak power is also constant, so that only rate adaptation is used. We assume the same packet length in our transmission schemes. Each packet has N_p symbols. The objective of embedded image transmission is to maximize spectral efficiency subject to transmission reliability. In our transmission scheme, the transmission reliability is defined as the expected packet error rate (PER_0) after retransmission and combining. The spectral efficiency (η) is defined as average transmission rate (R) over Shannon bandwidth (W):

$$\eta \text{ (Bits/Sec/Hz/Dim)} = \frac{R}{W} = RT_s \text{ (Bits/Sym)}, \tag{3}$$

where T_s is the symbol time. The actual calculation of spectral efficiency depends on the packet overhead and the resources for feedback. To simplify the analysis, packet overhead (for synchronization, estimation, signaling, sequence number, and error detection) is ignored, and resources for feedback are not considered.

4. PER APPROXIMATION AND PERFORMANCE ANALYSIS

We first obtain an approximation of packet error rates for M-QAM modulation, then compute the average spectral efficiency for both scenario I and II.

PER Approximation for M-QAM The packet error rate for M-QAM modulation, $PER(\gamma)$, can be expressed as:

$$\begin{aligned} PER(\gamma) &= 1 - (1 - SER(\gamma))^{N_p} \leq \min(1, N_p SER(\gamma)) \\ &\leq \min(1, a N_p \exp(-g\gamma)), \end{aligned} \tag{4}$$

where γ is the signal-noise-ratio, $SER(\gamma)$ is the symbol error rate of M-QAM, and constant a can be easily determined from $SER(\gamma)$ [6]. Instead of using the upperbound, we use the following approximation (γ_t is the turning point, $A_p = A * N_p$):

$$\begin{aligned} PER(\gamma) &\simeq A_p \exp(-g\gamma_t) = 1, \text{ for } \gamma < \gamma_t = \ln(A_p)/g, \\ PER(\gamma) &\simeq A_p \exp(-g\gamma), \qquad \text{for } \gamma \geq \gamma_t. \end{aligned} \tag{5}$$

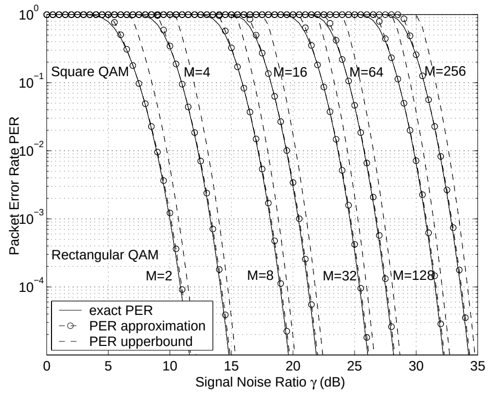

Fig. 2. Approximation and upperbound of packet error rate for M-QAM modulation, N_p=256 and $PER_a = 0.1$.

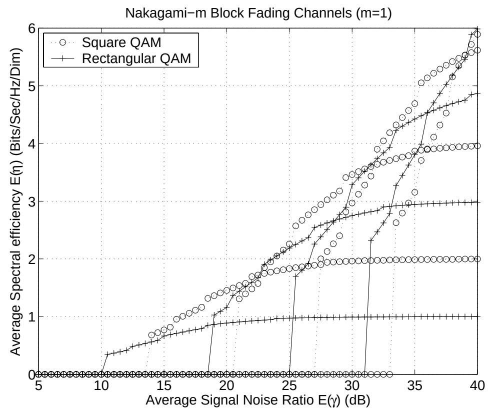

Fig. 3. Average spectral efficiency for M-QAM modulation with $PER_0 = 10^{-6}$ and $\max(N_r) = 6$.

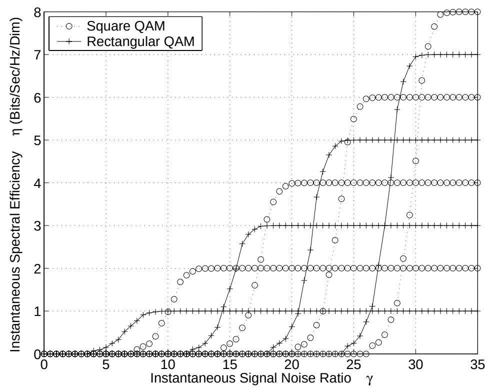

Fig. 4. Instantaneous spectral efficiency for M-QAM modulation with $PER_0 = 10^{-6}$ and $\max(N_r) = 6$.

The precision of the approximation depends on the parameter A, which is determined by the following equations:

$$PER(\gamma_a) = PER_a = AN_p \exp(-g\gamma_a). \tag{6}$$

Hence the approximation is exact at some point (γ_a, PER_a). Figure 2 shows the approximation for M-QAM modulation.

Adaptive QAM for Scenario I For scenario I, the fading of each packet is independent and identically distributed. Hence

$$\gamma_i \sim Gamma(\overline{\gamma}, m), \text{for } i = 0, 1, ..., N_r. \tag{7}$$

With maximal-ratio combining, the combined packet is also Gamma distributed:

$$\pi_0 \sim Gamma((N_r + 1)\overline{\gamma}, (N_r + 1)m). \tag{8}$$

The statistical CSI $\overline{\gamma}$ and m are available at the transmitter. The average packet error rate is:

$$\begin{aligned}\overline{PER}(\overline{\gamma}, m) &= \int_0^{\gamma_t} P_\gamma(\gamma)d\gamma + \int_{\gamma_t}^{\infty} A_p e^{-g\gamma} P_\gamma(\gamma)d\gamma \\ &= 1 - \frac{\Gamma(m, \gamma_t m/\overline{\gamma})}{\Gamma(m)} + A_p \frac{\Gamma(m, \gamma_t(g + m/\overline{\gamma}))}{(1 + g\overline{\gamma}/m)^m \Gamma(m)},\end{aligned} \tag{9}$$

where $\gamma \sim Gamma(\overline{\gamma}, m)$, and $\Gamma(\cdot, \cdot)$ is the complementary incomplete gamma function. The retransmission probability is the average packet error rate of the original packet, $\overline{PER}(\overline{\gamma}, m)$. The expected packet error rate after retransmission and combining is approximated by the average packet error rate of the combined packet, $\overline{PER}((N_r + 1)\overline{\gamma}, (N_r + 1)m)$. To guarantee transmission reliability, the following inequality is solved to obtain N_r:

$$\overline{PER}((N_r + 1)\overline{\gamma}, (N_r + 1)m) \leq PER_0. \tag{10}$$

We can calculate the statistical spectral efficiency $\overline{\eta}(\overline{\gamma}, m, M)$ of M-QAM as following:

$$\overline{\eta}(\overline{\gamma}, m, M) = \frac{\log_2^M}{1 + N_r \overline{PER}(\overline{\gamma}, m)}. \tag{11}$$

The results for Rayleigh fading channels are shown in Figure 3. The modulation type will be chosen to maximize the spectral efficiency according to the statistical CSI $\overline{\gamma}$ and m at the transmitter.

The average spectral efficiency with adaptive QAM for scenario I is:

$$\eta_{QAM-I} = \max_M \overline{\eta}(\overline{\gamma}, m, M), \tag{12}$$

Adaptive QAM for Scenario II For scenario II, the instantaneous CSI is available at the transmitter. For simplicity, we also assume that the retransmission packets and the original packet have the same SNR. Therefore, the transmission of each individual packet can be considered over an AWGN channel. We derive the packet error rate and spectral efficiency for each individual packet with instantaneous SNR γ_0:

$$\begin{aligned}&\pi_0 = (N_r + 1)\gamma_0, \\ &PER(\gamma_0) = A_p \exp(-g\gamma_0), \\ &PER(\pi_0) = A_p \exp(-g(N_r + 1)\gamma_0) \leq PER_0, \\ &\eta(\gamma_0, M) = \frac{\log_2^M}{1 + N_r PER(\gamma_0)}.\end{aligned} \tag{13}$$

The results for Rayleigh fading channels are shown in Figure 4. The modulation type will be chosen to maximize the spectral efficiency of each individual packet according to the instantaneous

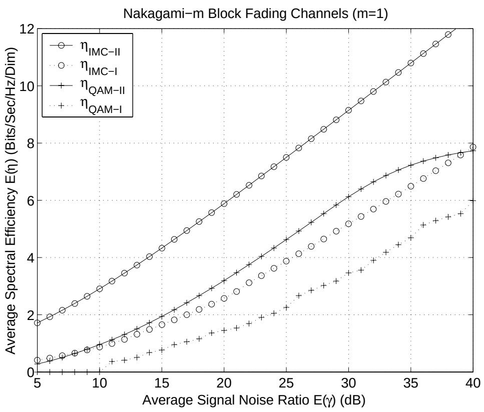

Fig. 5. Average spectral efficiency for adaptive QAM or adaptive IMC with $PER_0 = 10^{-6}$ and $\max(N_r) = 6$.

CSI (γ_0) at the transmitter. Assuming the turning points to switch the modulation types are $\{\lambda_i\}$, the average spectral efficiency with adaptive QAM for scenario II is:

$$\eta_{QAM-II} = \int_0^\infty \{\max_M \eta(\gamma, M)\} P_\gamma(\gamma) d\gamma$$
$$= \sum_{n=1}^{8} \int_{\lambda_n}^{\lambda_{n+1}} \eta(\gamma, 2^n) P_\gamma(\gamma) d\gamma. \quad (14)$$

If the SNR's of retransmission packets are not the same as that of the original packet ($\gamma_i \neq \gamma_0$), scenario II is slightly modified.

Adaptive Ideal Modulation/Coding To evaluate the efficiency of adaptive modulation system, we calculate the spectral efficiency upperbound based on ideal modulation/coding over AWGN channels. The AWGN channel capacity is:

$$C_{AWGN}(\gamma) = W \log_2(1 + \gamma). \quad (15)$$

We define "ideal modulation/coding (**IMC**)" as the modulation /coding which achieves the channel capacity. Assuming that IMC has transmission rate $R_c = C_{AWGN}(\gamma_c)$ over an AWGN channel, then

$$PER(\gamma) = 0, \text{ if } \gamma \leq \gamma_c, \qquad PER(\gamma) = 1, \text{ if } \gamma > \gamma_c.$$
$$R_c/W = C_{AWGN}(\gamma_c)/W = \log_2(1 + \gamma_c). \quad (16)$$

Adaptive IMC with statistical CSI provides the upperbound on spectral efficiency for scenario I. Adaptive IMC with instantaneous CSI provides the upperbound on spectral efficiency for scenario II, which is nothing but the channel capacity of Nakagami fading channels with constant transmit-power [5].

The results for Rayleigh fading channels are shown in Figure 5. We conclude that instantaneous CSI is very important for fading channels. Without instantaneous CSI, the channels in scenario I are least predictable compared to those in scenario II. The resulting SNR loss is called "maximum prediction loss", which is around 11dB in high SNR for both adaptive QAM and adaptive IMC. The spectral efficiency with adaptive QAM is less than that with adaptive IMC. The resulting SNR loss is called "coding loss", which is around 8dB and not sensitive to CSI. The coding loss is the potential coding gain from replacing M-QAM with more powerful modulation/coding.

5. CONCLUSIONS

We propose a new transmission scheme for embedded image transmission based on adaptive modulation and constrained retransmission over Nakagami multi-path block fading channels. The modulation is adaptive according to the statistical or instantaneous CSI available at the transmitter. The constrained retransmission includes one round-trip feedback of retransmission request and multiple retransmission response per request. As a result, the embedding property of embedded image compression is preserved, the transmission reliability is guaranteed, and the spectral efficiency is improved. Performance analysis and numerical results are given to demonstrate the efficiency of adaptive modulation and constrained retransmission.

The concepts of **prediction loss** and **coding loss** are also proposed to evaluate the adaptive modulation system. The results show that the prediction loss is more sensitive to CSI at the transmitter than the coding loss, hence CSI at the transmitter is very important for adaptive modulation over fading channels. Further work will consider the adaptive modulation/coding for correlated block fading channels with partial CSI.

6. REFERENCES

[1] D. Taubman, "High performance scalable image compression with EBCOT," *IEEE Transactions on Image Processing*, vol. 9(7):1158-1170, July 2000.

[2] K. Peng and J. Kieffer, "Embedded image compression based on pixel classification and sorting," submitted to *IEEE Transactions on Image Processing*, 2002.

[3] Q. Liu, S. Zhou, and G. Giannakis, "Joint adaptive modulation and adaptive packet retransmission over block fading channels," submitted to *Proc. of the 37th Conference on Information Sciences and Systems*, Baltimore Maryland, 2003.

[4] V. Chande and N. Farvardin, "Progressive transmission of images over memoryless noisy channels," *IEEE Journal on Selected Areas in Communications*, Special Issue on Error Resilient Coding, vol. 18(6):850-860, June 2000.

[5] M. Alouini and A. Goldsmith, "Adaptive modulation over Nakagami fading channels," *Kluwer Journal on Wireless Communications*, vol. 13(1-2):119-143, May 2000.

[6] S. Zhou and G. Giannakis, "Adaptive modulation for multi-antenna transmissions with channel mean feedback," submitted to *IEEE Transactions on Wireless Communications*, 2002.

[7] E. Biglieri, J. Proakis, and S. Shamai, "Fading channels: information-theoretic and communication aspects," *IEEE Transactions on Information Theory*, vol. 44(6):2619-2692, Oct. 1998.

[8] E. Malkamaki and H. Leib, "Performance of truncated type-II hybrid ARQ schemes with noisy feedback over block fading channels," *IEEE Transactions on Communications*, vol. 48(9):1477-1487, Sep. 2000.

[9] G. Stuber, "Principles of mobile communication (Second Edition)," Massachusetts: *Kluwer Academic Publishers*, 2001.

[10] 3GPP TSG RAN WG1, "UTRA high speed downlink packet access," in *Technical report of 3rd generation partnership project*, 2000.