Adaptive Unequal Channel Protection for JPEG2000 Images

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Abstract

An adaptive unequal channel protection technique is proposed for JPEG2000 images by exploiting the hierarchical structure of the bit-stream. The proposed technique takes into account the effect of channel errors in different packets of the bit-stream in order to optimally protect the coded data. For a given transmission bandwidth and multi-layered JPEG2000 bit-stream, the proposed technique adaptively selects the best protection scheme according to the channel conditions. The robustness of the proposed technique is evaluated over a Rayleigh fading channel with a concatenation of a cyclic redundancy check code and a rate-compatible convolutional code. Comparisons are made with the case of equal channel protection and unequal channel protection when the protection is designed for the worst channel conditions. Simulation results show a significant improvement of the PSNR of the received images.

1. Introduction

Wireless multimedia communications have gained considerable importance in the last few years. As wireless channels have low bandwidth constraints, compression techniques are used to reduce the amount of data to be transmitted. However, the compressed bit-streams are highly sensitive to transmission errors, making the multimedia communications over noisy channels more challenging.

Recently, the JPEG2000 still image compression standard [1] has been established to provide a superior compression performance. The standard incorporates a set of tools that make the compressed information more resilient to errors. However, the use of the error resilient tools does not guarantee an error free received image, since residual bit-errors can still affect the coded information. The effect of error prone channels is typically reduced using automatic repeat request (ARQ) and forward error correction (FEC) techniques [2]. However, ARQ introduces additional delay whereas FEC increases the overall bit-rate.

FEC techniques generally employ an equal channel protection (ECP) scheme, and are designed for the worst channel conditions. If the information (e.g., the JPEG2000 bit-stream) has a hierarchical structure, ECP protection techniques fail to optimally protect the coded data. Hence an unequal channel protection (UCP) technique for JPEG2000 images was proposed in [3]. The technique exploits the hierarchical organization of the JPEG2000 bit-stream and protects the main header and the initial packets. Although the UCP technique improves the error resiliency of the JPEG2000 bit-stream, it does not fully exploit the hierarchical structure of the coded data, specifically the importance of the position and inclusion of the most significant bit-planes in different packets of the final bit-stream. Moreover, the protection scheme does not adapt to the channel conditions.

In this paper, an adaptive unequal channel protection (AUCP) technique for JPEG2000 coded images is proposed. The proposed technique exploits the importance of the position and inclusion of the bit-planes in the final code stream. It assigns more channel protection to the packets that contain the most significant bit-planes. The proposed channel protection is achieved by means of a cyclic redundancy check (CRC) outer coder and an inner rate-compatible convolutional (RCPC) coder.

The paper is organized as follows. Section 2 provides a review of the JPEG2000 standard. The proposed AUCP technique is described in Section 3. The performance of the proposed technique is presented in Section 4, followed by the conclusions.

2. Review of JPEG2000 Standard

In this section, we present a brief review of the JPEG2000 standard and the default error-resilient tools.

2.1. JPEG2000 Encoder

The JPEG2000 standard employs the discrete wavelet transform, and incorporates functionalities such as lossless and lossy compression, spatial and quality scalability, and error-resilient coding [1]. Fig. 1 shows the block schematic of the JPEG2000 encoder.

In JPEG2000, an image is first divided into rectangular blocks called tiles. Note that this tiling process is optional and the entire image can be regarded as a tile. Each tile is then discrete-wavelet transformed, and the transform coefficients are quantized using a uniform dead zone scalar quantizer. The quantized coefficients are divided into non-overlapping rectangles called code-blocks. A bit-plane context based arithmetic entropy coder is used to compress the quantized coefficients code-block by code-block. The code-blocks are coded one bit-plane at a time starting with the most significant bit-plane with a nonzero element to the least significant bit-plane [1]. The individual bit-streams, one from each code-block, are organized into packets and distributed across a number of layers. A main header and a collection of layers comprise the final JPEG2000 bit-stream.

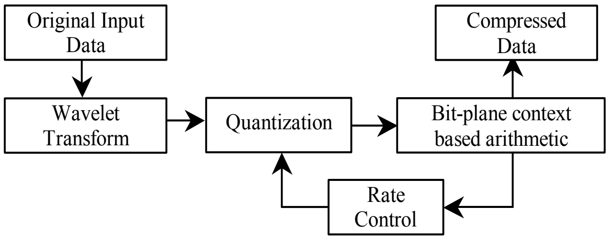

Figure 1. Block diagram of the JPEG2000 encoder.

2.2. Error-resilient tools in JPEG2000

The arithmetic entropy coder in JPEG2000 provides a good compression performance. However, the resulting coded data is highly prone to bit-errors [2, 4]. A set of error resilient tools has been included in the JPEG2000 standard to reduce the impact of transmission errors on compressed images. These tools work at the entropy coding and packet level, and have been shown to provide a better performance compared to the well-established JPEG standard [5].

Table I summarizes the tools for error-resilience in the JPEG2000 standard. These error resilient tools reduce the error propagation to which variable length coding is highly sensitive. This is achieved by independently coding the code-blocks, inserting markers in the code stream and terminating the arithmetic coder after each coding pass [1].

3. Proposed Technique

In this section, we present the proposed technique to achieve a superior performance compared to the ECP and UCP techniques. Here, the channel protection is optimally assigned to the coded-data according to the importance of every packet in the final bit-stream. To achieve a superior error resiliency, we consider the effect of the corrupted source bits due to channel errors on the quality of the reconstructed image. From the characteristics of every code-block in every subband in terms of the number of bit planes and the energy of the coefficients, we evaluate the contributions of bit-errors in a code-block to the overall mean-square error (MSE). In the following sections, we derive expressions for the effect of channel errors in code-blocks and packets in terms of the MSE.

Table I: Error resilient tools in JPEG2000.

Type of tool	Name
Entropy coding level	1. Independent coding of code-blocks 2. Termination and reset of the arithmetic coder for each pass 3. Selective arithmetic coding bypass (lazy coding mode) 4. Segmentation symbols
Packet level	5. Short packet format 6. Resynchronization marker

3.1. Effect of channel errors in a code-block

Because of the nature of the coding passes and the arithmetic entropy coding process, the magnitude of the distortion of the reconstructed image depends on the number and position of the bit-errors. A bit-error in the initial few bits of a code-block coded data generally results in a higher distortion compared to a bit-error in the later bits. Therefore, the worst case is the first bit-error occurring in the initial bits of the coded data of a code-block. Errors after this first bit-error gradually increase the value of the MSE for that code-block, until the maximum MSE value is reached (e.g. errors in the different bit-planes of a code-block).

The MSE, for a code block *b* in sub-band *s* (hereafter referred to as code-block (*b, s*)) can be expressed as:

$$\mathrm{M}_{b,s} = \frac{(\Delta_{b,s})^2}{N_{b,s}} \cdot \sum_{n=1}^{N_{b,s}} (C_n - \tilde{C}_n)^2 \qquad (1)$$

where C_n is the *n*th quantized coefficient in code-block *b* in sub-band *s*, $\tilde{C}_n$ is the corresponding corrupted coefficient, $N_{b,s}$ is the total number of samples in code-block (*b, s*) and $\Delta_{b,s}$ is the quantization step for code-block (*b, s*).

Some JPEG2000 decoders [6] are designed to provide error concealment. These decoders, after the occurrence of the first decoding error in a bit-plane of a code-block, assigns a value of zero to the subsequent bit-planes, and as a result errors after the first error do not increase the MSE of the code-block any further. In this paper, we assume such a decoder. The worst case is a bit-error occurring in the first bit-plane of a code-block. In this case, the coefficients of the entire code-block are set to zero. Hence, the maximum MSE (MMSE) for code-block (*b, s*) will be equal to the mean energy of the codeblock, which can be calculated as follows:

$$\mathrm{M}_{b,s} = \frac{(\Delta_{b,s})^2}{N_{b,s}} \cdot \sum_{n=1}^{N_{b,s}} C_n^{\,2} \tag{2}$$

The MMSE for code-block (b, s) on a per pixel basis (i.e. over the entire image) can be calculated as:

$$\overline{\mathrm{M}}_{b,s} = \frac{s_{b,s}}{B_s \cdot S} \cdot w_s \mathrm{M}_{b,s} = \frac{2^{-2r_{b,s}}}{B_s} \cdot w_s \mathrm{M}_{b,s} \tag{3}$$

where S is the total number of image pixels, $r_{b,s}$ is the resolution of sub-band s (r=1 corresponds to the first level of decomposition), $s_{b,s} = S/2^{2r_{b,s}}$ is the number of coefficients in sub-band s, B_s is the number of code-blocks in the sub-band (the code-blocks are of equal size) and w_s is the weighting factor of sub-band s. Note that w_s is used to compensate for the non-energy preserving characteristics of bi-orthogonal wavelets used in JPEG2000. The weighting factor is a function of the specific wavelet filters used and can be easily calculated from the filter coefficients [7].

The $\overline{\mathrm{M}}_{b,s}$ in Eq. (3) provides a measure of the effect of channel errors in code-block (b, s).

3.2. Effect of channel errors in a packet

When the coded data of a code-block is distributed across more than one layer, the packets that include the code-block for the first time are highly sensitive to errors. Bit-errors in these packets have a significant impact on the final MSE of the reconstructed image. The packets containing the rest of the coded data of a code-block will have an important effect on the MSE of the reconstructed image only if the packet that contains the code-block for the first time is free of errors. Hence, in the proposed technique no channel protection is provided for packets that do not contain any code-block for the first time.

Since each code-block is encoded independently from others, errors in one code-block will not propagate to other code-blocks. The MMSE in packet p with coded data from S sub-bands, each sub-band having B_s code-blocks, can be expressed as follows:

$$\overline{\mathrm{M}}_p \approx \sum_{s=1}^{S} \sum_{b=1}^{B_s} \left(\overline{\mathrm{M}}_{b,s} \cdot \psi(b) \right) \tag{4}$$

where $\psi(b)$ is 1 if the coded data for the *bth* code-block is included in packet p for the first time (otherwise it is zero), and $\overline{\mathrm{M}}_{b,s}$ is as given in Eq. (3). Note that the right side of Eq. (4) takes accounts of the MMSE of code-block (b, s) only if it is included for the first time in packet p.

3.3. Optimal Channel Code Rate Assignment

The overall distortion of an image, typically defined as the MSE between the original and the received image, can be calculated as follows [8]:

$$\begin{aligned} D = E\{(I_o - I_q)^2\} + E\{(I_o - I_c)^2\} \\ + E\{(I_o - I_q)(I_q - I_c)\} \end{aligned} \tag{5}$$

where I_o is the original image data, I_q is the noise-free reconstructed image, and I_c is the noisy reconstructed image. Under the assumption that the quantization noise is orthogonal to the channel noise, the third term in the right side of Eq. (5) becomes negligible. The overall distortion D can then be expressed as the summation of the individual distortions associated to each packet p multiplied by the probability of error $\mathrm{P_e}$ of every packet (e.g. unequal channel protection across the packets). For an image with K packets, the overall distortion can be computed as:

$$D = \sum_{p=1}^{K} \overline{\mathrm{M}}_p \cdot \mathrm{P}_e \tag{6}$$

where $\overline{\mathrm{M}}_p$ is as given in Eq. (4).

In order to find the optimal unequal channel protection, one must minimize D. Note that in order to accommodate the extra channel protection bits, some of the packets have to be discarded. Due to the embedded nature of the code stream, packets should be discarded in a sequential order starting with the last packet (if packet p is first discarded, the next packet to be discarded is always packet p-1). Each missing packet will increase the overall distortion (see Eq. (6)) of the image. Hence, Eq. (6) can be expressed as follows:

$$\begin{aligned} D &= \sum_{p=1}^{K} \mathrm{M}_p \cdot \mathrm{P}_e \cdot \phi(p) + \sum_{p=1}^{K} m_P \cdot \left[1 - \phi(p)\right] \\ &= \sum_{p=1}^{K} \phi(p) \cdot \left[\mathrm{M}_p \cdot \mathrm{P}_e - m_p\right] + \sum_{p=1}^{K} m_p \\ &= \sum_{P=1}^{K} \phi(P) \cdot \left[\mathrm{M}_P \cdot \mathrm{P}_e - m_P\right] + \bar{\varepsilon}_C \end{aligned} \tag{7}$$

where m_P is the amount of MSE that will be added to the overall distortion if packet p is discarded, and $\phi(p)$ is 1 if the *pth* packet is included in the code stream (otherwise it is zero). Note that $\sum_{p=1}^{K} m_p$ is the mean energy of the compressed image, denoted by $\bar{\varepsilon}_C$.

In the proposed AUCP technique, the distortion as given in Eq. (7) is minimized subject to the following rate constraint:

$$\frac{S_M}{R_M} + \sum_{p=1}^{K} \frac{S_p}{R_p} \le R_T \qquad (8)$$

where R_M is the channel code rate for the main header, R_p is the channel code rate for packet p, S_M is the number of bits in the main header and S_p is the number of source bits in packet p. Note that the left side of Eq. (8) is the actual bit-rate whereas R_T is the specified overall bit rate. When a packet receives no channel protection, the channel code rate is equal to one.

3.4. Transmission over a Rayleigh-fading Channel

The JPEG2000 bit-stream is expected to be transmitted over a variety of mobile noisy channels. In this paper, we consider a Rayleigh-fading channel as the transmission channel [9].

The error-rate of a Rayleigh-fading channel generally varies with time. In order to optimize the overall distortion in Eq. (7), one must express the probability of error as a function of the probability density function of the bit-error. For example, with FSK modulation, the probability density function can be derived as a function of the average signal-to-noise ratio ($\overline{SNR}$) and the channel attenuation α [10]. When using a family of RCPC codes, the bit error probability of the protected information can be computed from the error probability of a Rayleigh-fading channel and the characteristics of the transfer function of the mother code [11]. For different coding rates of a family of RCPC codes it is possible to obtain different bit error probabilities [12]. These different error probabilities are the probabilities of error P_e of the protected packets in the JPEG2000 code stream.

The minimum overall distortion in Eq. (7) is realized assuming a continuous code allocation for channel protection. However, the use of a family of RCPC codes results in discrete channel-coding rates. Furthermore, the amount of additional bandwidth obtained by discarding packets is also constrained by the discrete lengths of the JPEG2000 packets. These two constraints result in a sub-optimal solution.

In this paper, the optimization problem as represented by Eqs. (7) and (8) is solved by finding the points that lie on the lower convex hull of the rate-distortion plane corresponding to all possible channel-coding protection assignments. The points on the lower convex hull are found using an algorithm similar to the bit-allocation algorithm proposed in [13].

4. Simulation Results

In this section, we present the performance evaluation of the proposed AUCP technique over a Rayleigh-fading channel. The 512×512 gray-level Lena image is used as the test image. Both lossless and lossy compressions (at three bitrates: 0.5, 0.25, and 0.125 bpp) are considered. The overall transmission rate has been set to the transmission rate of the image with no channel protection.

The image is compressed using the Kakadu JPEG2000 codec software [6]. For lossless and lossy compression, the default reversible and irreversible wavelet transforms are used. The image is decomposed for five levels; the size of the code block is set to 64×64, and the size of the precinct is set to 512×512. The arithmetic coder is terminated after each coding pass, and segmentation symbols are added to the encoded bit-stream.

In order to achieve a superior performance, short JPEG2000 packets are used with several layers. Of compression. For losseless compression, the coded data is divided into 20 quality layers. For lossy compression, 15 quality layers are used for a rate of 0.5 bpp, while 10 quality layers are used for a rate of 0.25 and 0.125 bpp. To obtain different rates, the convolutional mother code of rate ¼ and generator matrix g = [23 35 27 33] (in octal notation), is punctured with a period of 8. The decoding process is performed using the Viterbi algorithm.

The main header and the data packets to be channel protected are divided into blocks of 384 bits. Each block is first protected by an outer 16-bit CRC code defined by the polynomial 210421 (in octal notation), followed by an inner RCPC code. No puncturing matrix is used to protect the blocks in the main header. Before transmission, a convolutional interleaver of depth 60 interleaves the protected information. The information regarding the channel coder rate and number of protected packets is assumed to be common knowledge to both the encoder and decoder and hence no side information needs to be transmitted.

The robustness of the proposed AUCP technique is evaluated over four different channel conditions with a carrier frequency of $900\,MHz$, a data rate of $15\,Kbits/s$ and a mobile speed of $3.6\,Km/h$. For comparison purpose, we have also evaluated the ECP and the UCP technique [3] designed for the worst channel conditions. The ECP technique protects all the packets and the main header with a concatenation of the 16-bit CRC code and a rate ¼ RCPC code. To provide a fair comparison, an outer CRC coder has been added to the UCP technique in [8]. The UCP technique protects the main header and first layer with a concatenation of the 16-bit CRC code and a rate ¼ RCPC code.

Each channel condition has been tested with 100 independent trials. Table II shows the average PSNR of the received images after FSK transmission over a Rayleigh fading channel with ECP, UCP and AUCP. When the header contains a large number of bit-errors, the JPEG2000 decoder may not be able to decode the

Table II: Average PSNR (in dB) and decoding probability for the JPEG2000 512×512 graylevel Lena image after transmission over a Rayleigh-fading channel with a carrier frequency of $900\,MHz$, a data rate of $15\,Kbits/s$ and a mobile speed of $3.6\,Km/h$. ECP is the equal channel protection technique. UCP is the unequal channel protection technique. AUCP is the proposed adaptive unequal channel protection technique.

Transmission Rate	Protection Technique	Average SNR (dB) of the channel							
		10 dB		15 dB		20 dB		25 dB	
		PSNR	Decoding Probability	PSNR	Decoding Prob.	PSNR	Decoding Prob.	PSNR	Decoding Prob.
Lossless 4.411 bpp 20 layers	ECP	21.21	0.85	27.46	0.97	31.98	1.00[1]	35.05	1.00[1]
	UCP	23.58	0.84	28.38	0.98	32.43	1.00[1]	37.46	1.00[1]
	AUCP	27.32	0.90	30.98	0.97	35.51	1.00[1]	39.01	1.00[1]
0.5 bpp 15 layers	ECP	24.42	0.88	27.47	0.99	28.74	1.00[1]	29.65	1.00[1]
	UCP	26.62	0.83	31.62	0.97	33.70	0.99	37.18	1.00[1]
	AUCP	29.13	0.89	34.02	0.98	36.10	0.99	38.06	0.99
0.25 bpp 10 layers	ECP	23.26	0.87	24.96	0.99	25.82	0.99	25.73	1.00[1]
	UCP	26.54	0.83	30.74	1.00[1]	31.42	0.99	33.11	1.00[1]
	AUCP	28.11	0.88	33.13	0.98	34.71	0.99	36.17	1.00[1]
0.125 bpp 10 layers	ECP	20.96	0.84	23.06	0.97	23.58	1.00[1]	23.60	1.00[1]
	UCP	23.89	0.86	28.15	0.97	29.50	0.99	29.26	1.00[1]
	AUCP	28.85	0.84	30.20	0.96	31.85	0.99	31.99	1.00[1]

[1] Approximately 1.00


(a) Original image (b) ECP 27.3468 dB (c) UCP 31.2549 dB (d) AUCP 33.9805 dB

Figure 2. Visual results at 0.5bpp over a Rayleigh fading channel with $\overline{SNR} = 15\,dB$, a carrier frequency of $900\,MHz$, a data rate of $15\,Kbits/s$ and a mobile speed of $3.6\,Km/h$. The images show the average quality for the three channel protection techniques. (a) Original image, (b) ECP, (c) UCP, and (d) AUCP.

received bit-stream. The decoding probability in Table II provides the probability of successful decoding the bit-stream.

Each channel condition has been tested with 100 independent trials. Table II shows the average PSNR of the received images after FSK transmission over a Rayleigh fading channel with ECP, UCP and AUCP. When the header contains too many bit-errors, the JPEG2000 decoder may not be able to decode the received bit-stream. The decoding probability in Table II provides the probability of successful decoding the bit-stream.

It is observed in Table II that the proposed technique provides an improvement of about 2 dB PSNR over the UCP technique and about 6 dB PSNR over the ECP technique. The proposed AUCP technique takes into account the effect of discarding packets on the overall distortion and the effect of channel errors of the protected packets. This results in a better protection scheme according to the channel conditions. Visual results over a channel with $\overline{SNR} = 15\,dB$ are shown in Fig. 2. Note the effect of discarding packets on the image protected using the ECP technique.

Table III shows the channel coding schemes obtained by minimizing the overall distortion in Eq. (7) for each channel condition and a transmission rate of 0.5bpp. These protection schemes show that depending on the image, it is sometimes preferable to assign less protection to the protected packets and transmit more packets rather than increase the protection and discard packets. Note how the channel protection assigned to the protected packets decreases as the channel conditions improve, while the number of transmitted packets increases.

TABLE III: Protection Scheme for the JPEG2000 512 × 512 graylevel Lena image at 0.5 bpp. Ninety packets comprise the final bit-stream. Packets No. 1,2,8,14,15,21,27,34,40,46,47,53, 59,65,71,72,77,78,84,90 received channel protection according to the proposed AUCP technique.

Channel conditions	Average SNR (dB) of the channel			
	10 dB	15 dB	20 dB	25 dB
No. of transmitted packets	87	87	88	88
RCPC coding rates of protected packets	[8/12 8/10 8/10 8/8 8/10 8/8 8/8 8/10 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8]	[8/10 8/10 8/10 8/10 8/10 8/8 8/8 8/10 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8]	[8/10 8/10 8/8 8/8 8/10 8/8 8/8 8/10 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8]	[8/10 8/10 8/8 8/8 8/10 8/8 8/8 8/10 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8 8/8]

5. Conclusions

We have presented an adaptive unequal channel protection technique for layered JPEG2000 bit-streams. The technique exploits the hierarchical organization of the JPEG2000 bit-stream and protects the main header and the packets that contain the most significant bit-planes of the code-blocks. The channel protection is achieved by means of a concatenation of an outer CRC code and an inner RCPC code. The robustness of the technique has been tested over a Rayleigh fading channel with different channel conditions. Simulation results show that the proposed protection technique outperforms the ECP and UCP over different channel conditions and transmission bit rates.

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