Layered unequal loss protection for progressive image transmission over packet loss channels

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ABSTRACT

In the past, many schemes have been proposed for progressive image transmission using unequal error protection (UEP) or unequal loss protection (ULP). However, most existing UEP/ULP schemes do not consider the minimum image quality requirement and usually have high computation complexity. In this paper, we propose a layered ULP (L-ULP) scheme for progressive image transmission over packet loss channels, which is able to solve the mentioned problems of existing ULP schemes by smartly choosing the layers. The numerical results show that the proposed L-ULP scheme is quite promising for fast image transmission over packet loss networks.

Keywords: Unequal loss protection, progressive image transmission, packet loss

1. INTRODUCTION

Wavelet-based image codes, such as SPIHT[1] and JPEG2000,[2] have shown to be superior to DCT-based image codecs in not only the coding efficiency but also the functionalities such as the progressive property, which allows the bitstream to be truncated in any position and thus provides rate scalability. Although the progressive image coding can provide excellent compression and scalability performance, it makes image bitstreams very sensitive to channel noise such as packet-loss in the Internet and bit errors in wireless links. An error in a bitstream may cause all the following bits become useless. Therefore, error control techniques such as forward error correction (FEC) and automatic repeat request (ARQ) are needed to combat with channel noise to ensure a reliable image transmission.

Recently, we have seen extensive studies in FEC-based joint source channel coding (JSCC) for progressive image transmission including Ref. 3, 4 for transmission over noisy channels and Ref. 5, 6 for transmission over packet loss channels. The common idea of these schemes is to combine progressive image source bitstreams with unequal error protection (UEP), i.e., the more important information is given more protection. The progressive image bitstreams can be well fit into UEP because the earlier portions of a progressive bitstream are always more important than the later parts. Although, comparing with equal error protection (EEP), UEP can obtain considerable performance gain and have the property of graceful performance degradation during channel mismatch cases, the complexity of UEP is much higher than EEP since it is not trivial to find the optimal UEP solution.

Many schemes[3–6] have been proposed to find the optimal UEP solutions. In Ref. 3, dynamic programming was employed to find the optimal UEP solution with fixed-length source data blocks. In Ref. 4, the authors also considered fixed-length source data blocks and developed an empirical model for optimal source channel rate allocation. In Ref. 5, Mohr et al. developed an unequal loss protection (ULP) framework with fixed-length channel coding blocks, and used a greedy and iterative search algorithm to find the optimal channel coding rates, which costs comparatively long execution time. Kim et al.[6] further reduced the complexity of the ULP by employing dynamic programming to find the optimal channel coding rates for each bitplane instead of each channel coding block. If we consider a data segment with independent choices for error or loss protection as a

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layer, for all the schemes above, the number of layers, n, is determined either by the length of channel packets or the number of bitplanes.

In this paper, we propose a layered ULP (L-ULP) scheme for progressive image transmission over packet loss channels. Comparing with the work in Ref. 5, 6, our propose L-ULP scheme has many advantages. First, L-ULP considers the minimal quality requirement and it can greatly reduce the probability of unsuccessful transmission. Second, L-ULP has the flexibility of choosing the number of layers n and thus by choosing a small value of n L-ULP can be executed much faster. In addition, we clearly analyze the L-ULP system and based on our analysis the problem of finding optimal ULP solutions can be converted as a problem of optimal bit allocation among independent units.

The paper is organized as follows. Section 2 states the problem of ULP in detail. Section 3 describes the proposed L-ULP system including the end-to-end rate-distortion (R-D) analysis and the L-ULP algorithm. Section 4 presents numerical results and finally concluding remarks are given in Section 5.

2. PROBLEM STATEMENT

In the benchmark ULP scheme,[5] a major problem is that it merely aims at maximizing the expected PSNR and does not have any control to prevent the occurence of low PSNR events. It is well known that the PSNR of a received image below a certain threshold is useless for any practical application. For example, the reconstructed standard 512x512 grayscale Lena image with the PSNR value of 22.17 dB shown in Fig. 1 is almost unreadable. Note that such a PSNR threshold can be determined according to human visual systems (HVS). In this research, we choose 25 dB as the lowest acceptable image quality. This is in line with the rising quality of service (QoS) requirements for multimedia communications. The ULP scheme does not consider such a minimum PSNR requirement and still allocates different amounts of FEC to the early portions of a bitstream whose corresponding PSNRs are less than the threshold. This results in unnecessary complexity increase and also increasing the probability of unsuccessful transmission if we consider any image transmission with a PSNR less than the threshold as a failure transmission. Fig. 2 shows a typical PSNR degradation performance of using ULP to transmit the Lena image coded at 0.2 bpp with 47 bytes per packet. It can be seen that a noticeable portion of the ULP results which is claimed superior to ELP (equal loss protection)[5] is actually below 25 dB and thus meaningless. Such an observation has also been pointed out in Ref. 7.

Figure 1. The reconstructed 512x512 Lena image with PSNR 22.17 dB.

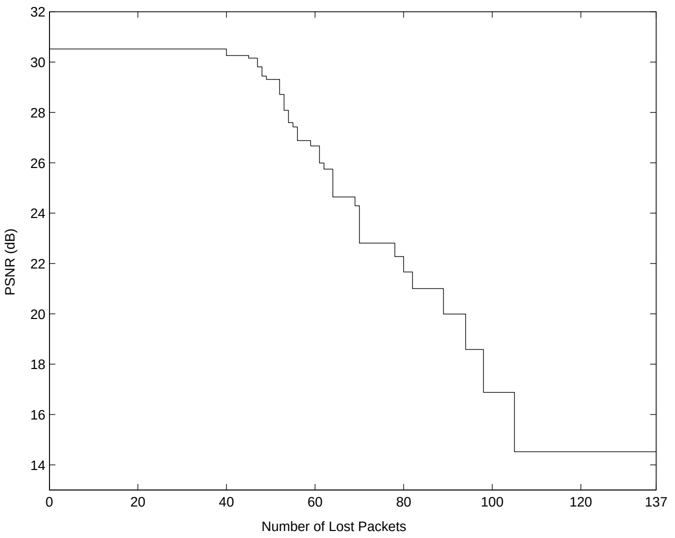

Figure 2. The PSNR performance of using ULP to transmit the Lena image coded at 0.2 bpp with 47 bytes per packet under different numbers of lost packets. The channel loss model is an exponential PMF (probability mass function) with a mean loss rate of 0.2.

Another major problem of ULP is its high complexity which has been mentioned in Section 1. As shown in Fig. 3, in ULP different amounts f_i of FEC codes are allocated to different streams. Each stream is basically a channel coding block. A greedy and iterative search algorithm is used in Ref. 5 to find the optimal ULP solutions $f_i, i = 1, 2, \ldots, L$. Although such a ULP scheme works fine for small packet size L such as the size of a ATM cell, it is not suitable for large values of L such as Internet packet sizes since with the increase of L the complexity and the execution time of ULP become intolerable. A straightforward idea to solve this problem is to give different protection for different layers, a bunch of streams, instead of different streams. Fig. 3 also shows the architecture of a general layered ULP scheme. However, from the figure, we can see that such a layered ULP is even more complicate because we need to find not only the optimal FEC allocation f_i but also the optimal layer division L_i. In Ref. 6, Kim et al. simplified this problem by mapping each bitplane into one layer. In this paper, we divide layers according to source coding R-D curves. The basic idea is to let each layer have equal distortion gain while the first layer must satisfy the minimum quality requirement. Details will be discussed in Section 3. After the layer division, the task left for L-ULP is to find the optimal solutions for $f_i, i = 1, 2, \ldots, n$.

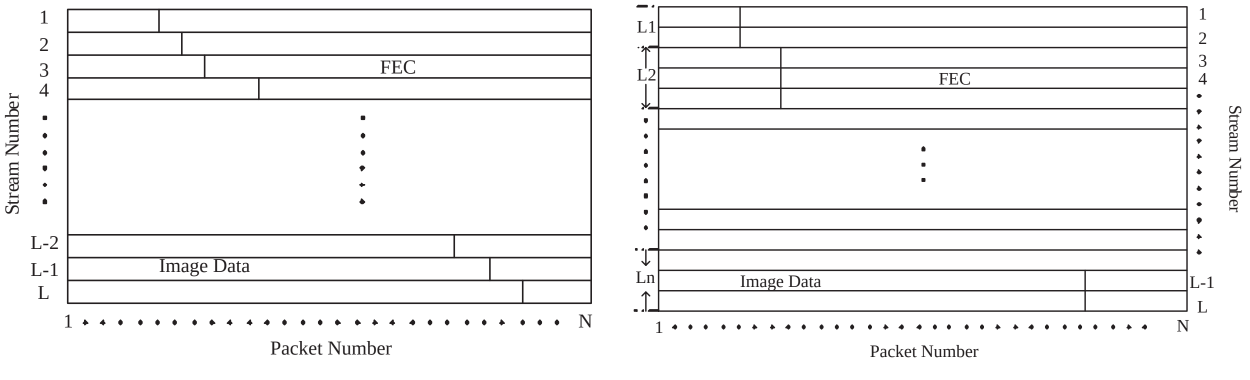

Figure 3. Left: The ULP structure. Right: A general layered ULP structure.

3. PROPOSED L-ULP SCHEME

3.1. Analysis of End-to-End Distortion

Similar to Ref. 5, the expected distortion at the receiver end can be formulated as

$$D(\overrightarrow{f}) = \sum_{i=0}^{n} P_i(\overrightarrow{f}) d_i, \tag{1}$$

where $P_i(\overrightarrow{f})$ is the probability of the first uncorrected loss happening at the $(i+1)$-th layer and d_i is the distortion of using the first i layers for reconstruction. Considering adopting the commonly used Reed-Solomon (RS) codes with 8 bits/symbol as FEC codes, $P_i(\overrightarrow{f})$ can be derived as

$$P_i(\overrightarrow{f}) = \sum_{k=1+f_{i+1}}^{f_i} P(N,k), \tag{2}$$

where $P(N,k)$ is the probability of having k lost packets out of the total N packets and we set $f_0 = N$ and $f_{n+1} = -1$. $P(N,k)$ can be calculated according to the given packet loss model. In this research, we use the packet loss model with the exponential probability mass function (PMF) the same as that in Ref. 5. Hence, $P(N,k)$ can be computed as

$$P(N,k) = \frac{\frac{1}{p_l} e^{-\frac{1}{p_l}\frac{k}{N}}}{\sum_{i=0}^{i=N} \frac{1}{p_l} e^{-\frac{1}{p_l}\frac{i}{N}}}, \tag{3}$$

where p_l is the mean packet loss rate. Other packet loss models such as the Gilbert-Elliott Channel (GEC) models[8] can also be adopted in our proposed system. Based on Eqns. (1) and (2), $D(\overrightarrow{f})$ can be further derived as

$$D(\overrightarrow{f}) = d_0 - \sum_{i=1}^{n} [\Delta d_i \sum_{k=0}^{f_i} P(N,k)], \tag{4}$$

where $\Delta d_i = d_{i-1} - d_i$.

The source R-D curve $D_s(R_s)$ of a progressive image coding scheme such as SPIHT can be obtained by extracting some R-D points such as the end points of each bitplane during the encoding process followed by linear interpolation between neighbor R-D points. Therefore, given the accumulated source data amount up to the i-th layer b_i, the corresponding distortion d_i is given by

$$d_i = D_s(b_i). \tag{5}$$

The proposed layer division can be described as

$$b_i = \begin{cases} 0 & \text{if } i = 0 \\ D_s^{-1}(D_s^H) & \text{if } i = 1 \\ \frac{R_t S}{8} - L\bar{f} & \text{if } i = n \\ D_s^{-1}(D_s^H - (i-1)\Delta d_s) & \text{if } i = 2, \ldots, n-1 \end{cases} \tag{6}$$

where $\bar{f}$ is the optimal ELP solution, $\Delta d_s = \frac{D_s^H - D_s^L}{n-1}$ and $D_s^L = D_s(b_n)$. The summary of the symbol definitions can be found in Table 1. In particular, the amount of the first layer source data b_1 is obtained according to the minimum quality requirement D_s^H. Then, we compute the largest amount of source data b_n according to the optimal ELP solution $\bar{f}$. This is because the maximum PSNR achieved by the optimal ELP is very close to that of the ULP scheme which has been demonstrated in Ref. 5. According to b_n, we can obtain the lowest distortion bound D_s^L. After this, the $n-1$ layers are divided based on the idea of having equal distortion gain Δd_s in the range of $[D_s^L, D_s^H]$ for each layer. Notice that the actual value of b_i may need to change a little during the implementation due to byte alignment and channel block alignment.

Table 1. The symbol definitions.

n	:	the actual number of layers
N	:	the number of packets
L	:	the length of a channel packet (in bytes)
R_t	:	the total bandwidth (bpp)
R_s	:	the number of bytes for source coding
$\overrightarrow{f}$	:	the FEC length in bytes for each layer
	:	$\overrightarrow{f} = \{f_1, f_2, \ldots, f_n\}$ where $f_1 \geq f_2 \geq \ldots \geq f_n$
$\bar{f}$	:	the FEC length of the optimal ELP
$P_i(\overrightarrow{f})$	:	the probability of the first uncorrected loss happening at the $(i+1)$-th layer
$P(n,k)$	:	the probability of having k lost packets out of the total n packets
p_l	:	the mean packet loss rate
$D_s(R_s)$	:	the source rate distortion function
D_s^H	:	the basic quality we need to maintain
D_s^L	:	the best quality which the L-ULP system can provide
d_i	:	the distortion of using the first i layers for reconstruction
Δd_i	:	the distortion gain of correctly decoding the the i-th layer
b_i	:	the number of bytes of the first i layers
l_i	:	the number of streams in the i-th layer
S	:	the total number of pixels in an image

Finally, based on Eqns. (4), (5) and (6), the overall R-D functions for the proposed L-ULP system can be summarized as

$$\begin{aligned} D(\overrightarrow{f}) &= d_0 - (d_0 - D_s^H)\sum_{k=0}^{f_1} P(N,k) - \Delta d_s \sum_{i=2}^{n}\sum_{k=0}^{f_i} P(N,k), \\ R &= N\sum_{i=1}^{n} l_i, \end{aligned} \tag{7}$$

where $l_i = \lceil \frac{b_i - \sum_{j=1}^{i-1} l_j(N-f_j)}{N-f_i} \rceil$ is the number of streams in the i-th layer. Correspondingly, the problem of finding the optimal ULP solutions can be formulated as

$$\min_{\overrightarrow{f}} D(\overrightarrow{f}), \quad \text{subject to} \quad \sum_{i=1}^{n} l_i \leq L \quad . \tag{8}$$

3.2. L-ULP Algorithm

Based on the analysis in Section 3.1, the proposed L-ULP algorithm, $L-ULP(R_t, L, n)$, is described as follows:

Step 1: Find the optimal ELP solution $\bar{f}$.

Step 2: Compute b_i according to Eqn. (6).

Step 3: Search to find the optimal ULP solution $\overrightarrow{f}$ based on Eqn. (8).

Notice that From Eqn. (7) we can see that the overall distortion can be separated into the n independent units if we neglect the alignment issue. Then, the problem of finding the optimal ULP solutions is the same as optimal bit allocation among different units, which can be solved by processing the falling convex hull of the R-D slopes. Details can be found in Ref. 9, 10. In this research, since the number of layers is typically very small, we still use iterative search to find the optimal ULP solution for simplicity.

4. NUMERICAL RESULTS

The standard 512x512 Lena image with 8 bits per pixel is used as the test image. We choose the packet size of 100 bytes and use the exponential PMF packet loss model. SPIHT is adopted as the codec for source coding and RS codes with 8 bits/symbol are used for channel coding.

4.1. PSNR Criteria Vs Distortion Criteria

The average PSNR based on the PSNR criteria is typically employed as the image quality measure in the literature such as in Ref. 5, 6. However, in this research, we use the average distortion for the quality measure as shown in Section 3 and only convert to PSNR at the last stage if needed, which is termed as the average PSNR based on the distortion criteria. This is because the maximal average PSNR based on the PSNR criteria does not correspond to the minimal average distortion due to the logarithm function. It is well-know that the logarithm function zooms in small values but zooms out large values, which makes the average PSNR based on PSNR criteria not appropriate to represent the expected quality of the received image. For example, if an image transmission system has 50% chance of obtaining the reconstructed image with PSNR 20 dB (Distortion: 25.5^2) and another 50% chance of obtaining the reconstructed image with PSNR 40 dB (Distortion: 2.55^2), the average PSNR based on the PSNR criteria is equal to $(20+40)/2 = 30$ dB while the average PSNR based on the distortion criteria is equal to $10log10(255^2 \times 2/(25.5^2 + 2.55^2)) = 22.97$ dB which is more reasonable in terms of mean square error. Fig. 4 shows the allocated FEC fractions of using the proposed L-ULP scheme with three layers (3L-ULP) to transmit the Lena image over the packet-loss channel model under different criteria. It can be observed that the system under the distortion criteria spends more bits for protecting the first layer than that under PSNR criteria in order to reduce the probability of obtaining large distortion.

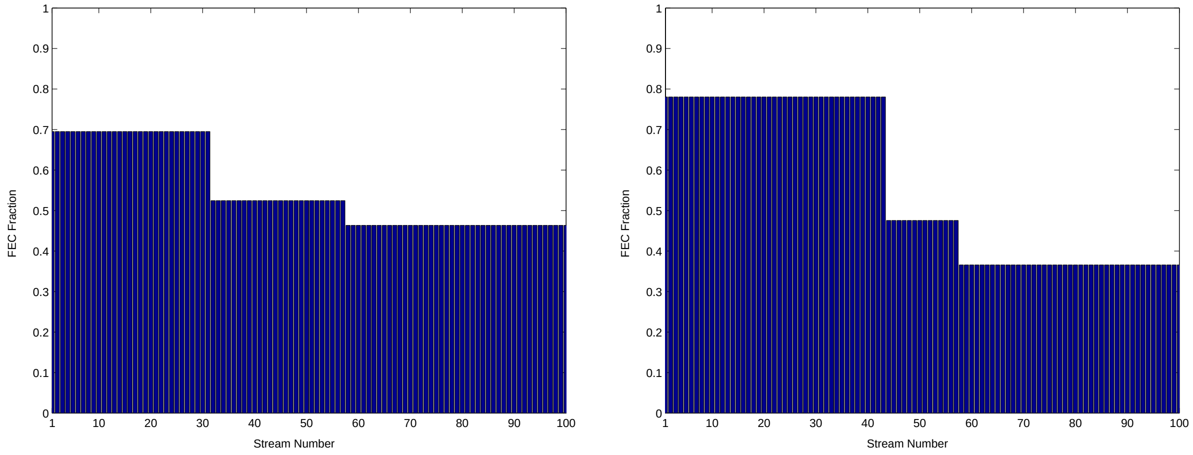

Figure 4. The allocated FEC fractions of using the 3L-ULP to transmit the Lena image over the packet-loss channel model with the exponential PMF and $p_l = 0.2$. The total bandwidth is 0.25 bpp. Left: Using the PSNR criteria. Right: Using the distortion criteria.

4.2. Experimental Results

Table 2 and 3 show the distortion distribution performance of transmitting the Lena image under different bit rates and different packet loss rates, respectively. The performance parameters include "P_f", "Average Distortion" and "Distortion STD". "P_f" denotes the probability of failure image transmission. "Average Distortion" is the average distortion shown in Eqn. (7) and "Distortion STD" denotes the corresponding standard deviation of the distortion. We compare the performance of three schemes: our proposed L-ULP with three layers (3L-ULP), the optimal EEP scheme (EEP) and the benchmark ULP scheme (ULP).

As shown in Table 2 and 3, the P_f of 3L-ULP is always the lowest under different bit rates and packet loss rates, which is about one magnitude lower than that of ULP. Since the P_f values are so small, we can say that

Table 2. The comparison of the distortion distribution performance of transmitting the Lena image under different bit rates over the packet-loss channel model with the exponential PMF and $p_l = 0.2$.

Bit Rate (bpp)	Scheme	$P_f(\%)$	Average Distortion (dB)	Distortion STD (dB)
0.125	EEP	2.71	22.72	24.81
	ULP	9.32	21.46	32.69
	3L-ULP	1.69	22.37	23.38
0.25	EEP	2.12	21.10	24.91
	ULP	3.85	19.31	32.92
	3L-ULP	0.69	20.31	23.86
0.5	EEP	1.20	19.40	23.48
	ULP	2.46	16.92	33.56
	3L-ULP	0.35	18.59	21.59

Table 3. The comparison of the distortion distribution performance of transmitting the Lena image over the packet-loss channel model with the exponential PMF and under different values of p_l. The total bandwidth is 0.25 bpp.

p_l	Scheme	$P_f(\%)$	Average Distortion (dB)	Distortion STD (dB)
0.05	EEP	0.22	16.36	20.04
	ULP	0.29	15.38	32.36
	3L-ULP	0.01	15.90	22.51
0.1	EEP	0.36	18.19	20.88
	ULP	1.24	17.05	33.23
	3L-ULP	0.05	17.81	21.98
0.2	EEP	2.12	21.10	24.91
	ULP	3.85	19.31	32.92
	3L-ULP	0.69	20.31	23.86

the proposed L-ULP can guarantee the minimum quality requirement. From the tables, we can also see that the distortion standard deviation of 3L-ULP is much lower than that of ULP, which means the distortion distribution of 3L-ULP is much denser around the mean value and thus the image qualities under different trials are more consistent. Note that the average distortion performance of 3L-ULP is about 1 dB higher than that of ULP. However, if we do not count the contributions of failure transmissions, the average distortion of 3L-ULP is very close to that of ULP. Moreover, the complexity of 3L-ULP is much lower than ULP which has 100 layers in this research.

5. SUMMARY

In this paper, we have presented the L-ULP scheme which considers the minimum quality requirement and solves the high complexity problem of ULP. We have also analyzed the R-D behavior of the proposed L-ULP scheme and have shown that the problem of finding optimal ULP solution for L-ULP is actually the same as the problem of optimal bit allocation. Numerical results have demonstrated that the proposed L-ULP scheme can satisfy the QoS requirement and can achieve comparable performance with very low complexity. Therefore, it is very suitable for practical fast image transmission over packet loss networks.

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