Content-based Retransmission with Error Concealment for Astronomical Images

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Abstract

The James Webb Space Telescope (JWST) is expected to produce a vast amount of images that are valuable for astronomical research and education. To support research activities related to JWST mission, NASA has provided funds to establish the Structures Pointing and Control Engineering (SPACE) Laboratory at the California State University, Los Angeles (CSULA). One of the research activities in SPACE lab is to design an effective and efficient transmission system to disseminate JWST images across the Internet

This paper presents a prioritized transmission method to provide the best quality of the transferred image based on the joint-optimization of content-based retransmission and error concealment. First, the astronomical image is compressed using a scalable wavelet-based approach, then packetized into independently decodable packets. To facilitate the joint-optimization of two mutually dependent error control methods, a novel content index is declared to represent the significance of the packet content as well as its importance in error concealment. Based on the defined content index, the optimal retransmission schedule is determined to maximize the quality of the received image under a delay constraint with the given error concealment method. Experimental results demonstrate that the proposed approach is very effective to combat the packet loss during transmission to achieve a desirable quality of the received astronomical images.

Keywords: CARQ, Error concealment, Joint-optimization, Astronomical image, Concealment profit

1. Introduction

One of the major goals of the National Aeronautical and Space Administration (NASA) ORIGINS program is to determine the origins of life in our universe. To this end, the James Webb Space Telescope (JWST), which is scheduled for deployment in 2011 as the successor to the Hubble Space Telescope, has been designed to achieve greater optical range and sensitivity than the Hubble. En route to discovering the origins of life, vast amounts of high-quality astronomical image data must be analyzed, so the JWST is expected to produce large quantities of such images for ground-based observation. Astronomers, as well as scientists in related fields, from around the world must be able to simultaneously access these images quickly in order to conduct research productively. Additionally these images must be made available for education and public outreach purposes as well. As such the design of a system for the efficient and effective transmission of astronomical images across a global network is a topic of importance.

The Structures, Pointing, and Control Engineering (SPACE) Laboratory was established at the California State University, Los Angeles in 1994 under funding from NASA to study some of the new technologies that need to be developed as part of the James Webb Space Telescope project [1]. In particular, one of the SPACE Laboratory research activities involves the design of an efficient image transmission system that is optimized for astronomical images. Due to the great optical range, sensitivity, and volume of images that the JWST will generate, as well as the marked interest by the scientific community to study these images, such a system is essential in enabling productive ORIGINS-related investigations throughout the world. By balancing the constraints of network bandwidth, time delay, and image quality, and by capitalizing on the properties of astronomical images, a novel image transmission system would allow audiences, including scholars, educators, and the general public, to maximize their respective efforts in the study of the images.

This paper considers the optimization of image transmission using two different transmission technologies, namely content-based retransmission [2, 3] and error concealment [4], in the context of astronomical images. Given the limitations of bandwidth and time delay constraints, a practical image transmission system should not naively attempt to transmit all packets of an image. Instead, an optimal subset of packets should be selected for transmission to produce the highest quality image at the receiver under the constraints. This idea governs the transmission decisions made by the system.

The research presented in this paper is an extension of our previously proposed approach to optimize the video transmission quality over lossy channels [5]. Due to the special characteristics of astronomical images, the error control mechanism that works for general images and video cannot yield desirable results. Hence, to optimize the performance of astronomical image transmission, its special characteristics have to be considered. To quantify the significance of an astronomical image packet, a novel content index is defined by jointly considering the information content of each packet, the impact of error concealment, and the characteristics of the image content. Based on the content index, a smart transmission system is designed to automatically select the most suitable error control mechanism for the input image and generate an optimal transmission policy to maximize the quality of the received image under the network constraints. Experimental results have demonstrated that the proposed approach is very effective to combat the packet loss during transmission to achieve a desirable quality of the received astronomical images.

This paper is organized as follows. Section 2 defines the optimization problem for astronomical image transmission. In Section 3, the joint optimization of content-based retransmission and error concealment is incorporated into a novel design of a smart streaming system for astronomical images. The experimental results of the system are shown in Section 4. Section 5 summarizes the findings described in this paper and draws conclusions.

2. Problem definition

2.1. Characteristics of Astronomical Image Transmission

In many astronomical research and educational activities, astronomers or other users need to browse a large number of images in a short timeframe. Therefore, a desirable transmission system should deliver the requested information in a timely fashion. In another words, delay constraints need to be considered. Due to the large volume of astronomical images, compression is necessary. In addition to the traditional compression method used for astronomical images such as RICE, H-Transform [6, 7], wavelet-based codecs have become popular because of its good compression performance and its ability to support progressive transmission. In our research, the transmission performance is optimized for astronomical images compressed by a wavelet-based codec.

The compression procedure can be briefly described by Figure 1. After the wavelet transform, zero-tree based encoding is applied. To increase the error resilience of the compressed image, Packetized Zero-tree Wavelet (PZW) is adopted [8, 9]. In PZW, each tree is coded independently. Therefore, multiple independent bitstreams can be generated where each bitstream comprises of a number of spatial-interleaved trees. These bitstreams are then packetized, so the most significant contents are placed in the same packets, while finer details are grouped together in different sets of packets. The structure of the output packetized bitstream is shown in Figure 1 as well. Apparently, the relationship between adjacent packets of the same bitstream is linear dependence. To optimize the error control performance in image streaming, these characteristics need to be taken into account.

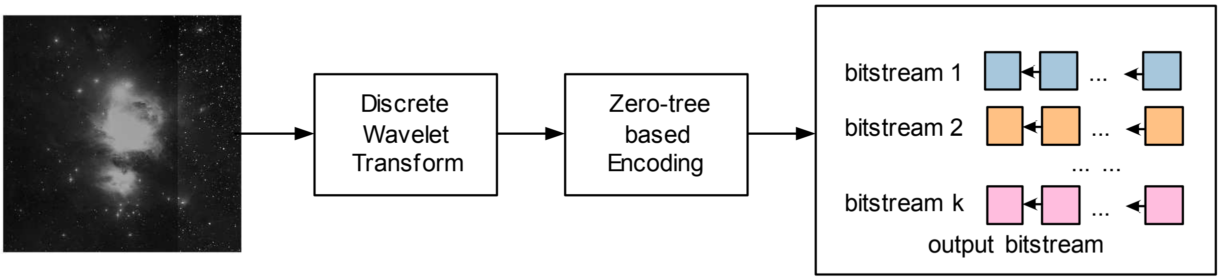


Figure 1. Procedure of wavelet compression for astronomical images

2.2 Problem formulation

The goal of an optimal transmission system is to achieve the maximum possible quality of the received image under given network resources. Assume the image quality is measured by end-to-end distortion. The optimization goal can be formulated by the following equation:

$$\pi = \arg\min_{\pi_k}\left(\sum D(P_{lost}(\pi_k))\right)$$

where $D(P_{lost}(\pi_k))$ is the resulting distortion under a certain transmission policy π_k, and π is the optimal policy that minimizes the distortion.

As stated above, the transmission is subject to the following rate and delay constraints:

$$\begin{cases} r_s \le R \\ \sum\limits_{j\in\Omega_T(\pi)} B_j \le r_s \cdot T_D \end{cases}$$

where r_s represents the average data sending rate, R the channel bandwidth, B_j the size of the j^{th} packet, and T_D the total allowable time delay.

3. Smart error control for astronomical image transmission

In order to design an optimal transmission system for astronomical images, their special characteristics have to be taken into account. In this section, the performance of joint error control on astronomical image transmission is analyzed. Based on the analysis results, a new content index is proposed to better represent the importance of an image packet, and a smart error control system is designed to achieve the best transmission quality under given channel constraints.

3.1 Joint optimization of content-based ARQ and error concealment

Joint optimization of content-based ARQ (CARQ) and error concealment (EC) has been proven to be very effective for general image and video streaming. Interested readers can refer to [5] for more details. However, when applying the same approach to astronomical image streaming, the results are not as good as expected. The following table compares the performance of the joint optimization on a general video and a test astronomical image when the channel packet loss rate is 20%.

Table 1. Averaged PSNR of received video and astronomical image with different error control mechanisms (20% loss)

	CARQ only	Joint optimization
Video sequence (Ms. America)	33.34 dB	34.33 dB
Astronomical image (deepfield)	26.33 dB	25.89 dB

Experimental results reveal that the joint optimization approach can always achieve the best result for general images and video, but it can lead to worse quality than content-based ARQ for some astronomical images (as illustrated by Table 1). The reason for the inferior performance of the joint-optimization approach on astronomical image streaming is that error concealment cannot always improve the image quality when used in conjunction with content-based retransmission. This is due to the noise-like nature of many astronomical images. It is well known that error concealment can repair the damaged image because of the correlation among the adjacent image blocks. However, for some of the astronomical images, the image content is very noisy such that there is very little correlation existing among adjacent regions. In this case, using received information to predict the lost neighbor block may not be able to improve the image quality; on the other hand, it may even deteriorate the image quality if the prediction error is larger than the distortion caused by packet loss. Hence, to achieve the best transmission quality for astronomical images, the error control mechanism has to be revised. The first step is to define an appropriate content index to measure the importance of each packet of an astronomical image.

3.2 Content index for an astronomical image packet

To select an optimal transmission policy to minimize the distortion, as presented in the optimization goal in Section 2, it is essential to define a quantitative measurement to reflect the impact of packet loss on the image quality.

In our previous research, a content index called reconstruction distortion was defined as follows [5]:

$$\Delta RD_i = \Delta D_i - \Delta d_i \qquad (1)$$

where Δd_i is the distortion reduction achieved by error concealment for packet i, and ΔD_i is the loss distortion of packet i [2].

The physical meaning of loss distortion ΔD_i is the end-to-end distortion caused by the loss of packet i. Therefore, it measures the importance of the packet content. Apparently, the reconstruction distortion reflects both the importance of the packet content and the effect of error concealment on the packet. Since error concealment may not always improve the quality of astronomical images when used with CARQ, the content index has to be revised. A suitable content index for astronomical image transmission should have the following features:

1) Ability to determine if error concealment is beneficial based on the characteristics of the input image;
2) Generate appropriate content measurement based on the above determination.

To facilitate the definition of the new content index, we first define a parameter called *Concealment Profit* to quantify the benefit brought by error concealment.

Definition: Concealment Profit

Concealment Profit (PF) is defined to be the expected distortion reduction achieved by error concealment when CARQ is used. The value of PF can be calculated using the following formula:

$$PF = \sum_{j \in \Omega_{lost}} \Delta D_j - \sum_{j \in \Omega_{lost}} \Delta E_j \qquad (2)$$

where Ω_{lost} is the set of dropped packets determined by CARQ, ΔD_j is the loss distortion of packet j, and ΔE_j is the prediction error when applying error concealment to packet j. Therefore, *Concealment Profit* PF can be viewed as the difference between the total loss distortion caused by packet dropping and the prediction error caused by error concealment for the dropped packets. When PF is positive, error concealment can effectively reduce the end-to-end distortion; when PF is negative, the prediction error caused by error concealment is even larger than the distortion caused by packet loss. Apparently, in the latter case, applying error concealment brings more damage than benefit.

In order to calculate PF, we need to know Ω_{lost}, ΔD_j and ΔE_j. Ω_{lost} can be easily obtained by the fast decision approach presented in [2]. The calculation methods for ΔD_j and ΔE_j is presented here briefly.

Since astronomical images are compressed by wavelet-based approaches like SPIHT, one or more progressive output bitstreams will be generated. Assuming that each progressive bitstream is enclosed in one packet, its loss distortion ΔD_j can be calculated using the following equation:

$$\Delta D_j = \sum_{(x,y)\in P_j} c_{xy}^2 \qquad (3)$$

where c_{xy} is the wavelet coefficient enclosed in the packet P_j.

To compute the expected prediction error of packet j of a given error concealment method, we first define the set of all packets that can be used in packet j's error concealment as its *neighbor packet set* and denote this by $\mathbf{N}(j)$. Then each packet in $\mathbf{N}(j)$ is a *neighbor packet* of packet j. Since the performance of error concealment depends on the receipt status of its neighbor packet set, $\mathbf{S}_{\mathbf{N}(j)}$, the expected prediction error can be expressed as

$$\Delta E_j = \sum_{\mathbf{S}_{\mathbf{N}(j)}} D_j^{EC}\left(\mathbf{S}_{\mathbf{N}(j)}\right) P\left(\mathbf{S}_{\mathbf{N}(j)}\right), \qquad (4)$$

where $D_j^{EC}\left(\mathbf{S}_{\mathbf{N}(j)}\right)$ and $P\left(\mathbf{S}_{\mathbf{N}(j)}\right)$ are the prediction error and probability when $\mathbf{N}(j)$ is at status $\mathbf{S}_{\mathbf{N}(j)}$, respectively. Of the two terms, $D_j^{EC}\left(\mathbf{S}_{\mathbf{N}(j)}\right)$ can be calculated from wavelet coefficient residuals after error concealment

$$D_j^{EC}\left(\mathbf{S}_{\mathbf{N}(j)}\right) = \sum_{xy\in P_j} \left(\hat{c}_{xy} - c_{xy}\right)^2$$

where c_{xy} is the original wavelet coefficient and $\hat{c}_{xy}$ is the predicted wavelet coefficient; $P\left(\mathbf{S}_{\mathbf{N}(j)}\right)$ (an independent packet erasure network is assumed) can be obtained by

$$P\left(\mathbf{S}_{\mathbf{N}(j)}\right) = P_e^{\,k} \left(1 - P_e\right)^{M-k}$$

where M and k are the numbers of the total and the lost neighbor packets, respectively.

With the definition of Concealment Profit, it is easy to judge if error concealment should be used in the transmission system. Thus an adaptive content index can be defined accordingly to meet the needs of different error control mechanisms. For input images with smooth content, error concealment is effective. Therefore the content index should reflect both the significance of the packet and the importance of error concealment. For input images with noise-like features, error concealment will not be used in the transmission system. Hence the content index shouldn't include the impact of error concealment.

Our new content index for astronomical image transmission, namely *Adaptive Reconstruction Distortion*, is defined as follows:

$$\Delta RD_i^A = \begin{cases} \Delta E_i, & PF > 0 \\ \Delta D_i & PF \le 0 \end{cases} \qquad (5)$$

where ΔRD_i^A is the *Adaptive Reconstruction Distortion* for packet i. The calculation of ΔD_i is the same as expressed in equation (3).

3.3 Smart image streaming system

3.3.1 Overview of system structure

Based on the newly defined content index, a smart transmission system has been designed to automatically provide the most suitable error control approach to the input image. The overall structure of the smart streaming system is depicted in figure 2.

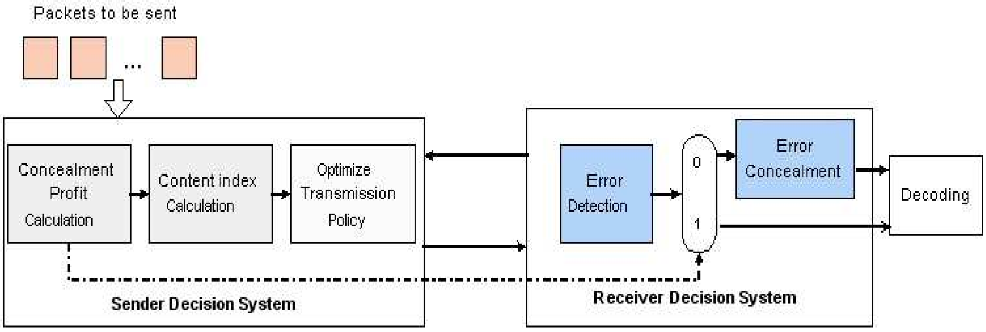


Figure 2. Overall structure of smart streaming system for astronomical images

The designed streaming system consists of two parts: 1) Sender decision system; and 2) Receiver decision system. The major function of the receiver decision system is to detect packet loss based on the gaps in the sequence numbers of the received packets, and send back retransmission requests if the delay constraint can be satisfied. The core of the smart streaming system is the intelligent sender. First, the sender will estimate the channel packet loss rate based on transmission statistics. Second, it will calculate the concealment profit for the input packets, and generate their corresponding content indices as described in equations (2) and (5). Based on the sign of concealment profit, the smart streaming system can determine if error concealment is suitable for the input image, and choose the most appropriate error control mechanism. Then, with the content index available, the sender decision system will select the optimal transmission policy to maximize the quality of the received image under the given error control mechanism and the network constraints.

3.3.2 Optimal transmission policy selection

As stated above, one of the major functions of the sender decision system is to select the optimal transmission policy to achieve the optimization goal specified in Section 2. Using our newly defined content index, the optimization goal can be rephrased as follows. An optimal transmission scheme is a policy π to choose a subset of packets (Ω_{lost}) to drop from the entire packet set (Ω_T) such that the total *adaptive reconstruction distortion* (ΔRD^A) is minimized:

$$\pi = \arg\min_{\pi}\Big(\sum_{j\in\Omega_{lost}} \Delta RD_j^A\Big) \qquad (6)$$

while subject to the following constraints:

$$\sum_{j\in\Omega_{lost}} B_j \geq B(\Omega_T) - r\Delta T_m \qquad (7)$$

where B_j is the size of packet j, $B(\Omega_T)$ is the total size of the packets to be transmitted, r is the rate constraint, and ΔT_m is the maximum transmission time allowed due to the delay constraint.

To solve this optimization problem, one can always use exhaustive search for the best solution. However, the computational complexity will be very high. To meet the requirement of real-time application, the fast decision approach proposed in [2] is adopted in the smart streaming system. The fast decision approach is a heuristic algorithm which uses $\Delta RD_i^A / B_i$ to order the importance of the packets. The physical meaning of $\Delta RD_i^A / B_i$ is adaptive reconstruction distortion per bit. Apparently, the lager the $\Delta RD_i^A / B_i$, the more important the packet. The basic principle of the algorithm is to drop from the least important packet until the constraint described in (7) is met. Experimental results show that this approach can achieve very good results with low computational complexity.

4. Performance evaluation

In order to evaluate the performance of our proposed smart streaming system for astronomical images, many experiments have been conducted. Our proposed approach has been compared with two other existing error control methods: 1) Error concealment; and 2) Delay-constrained retransmission. The PSNR of the received image is used to evaluate the delivery quality. To achieve a comprehensive evaluation, the performance comparison is conducted for various channel conditions with different packet loss rates. Figures 3 and 4 show the quality of received images under different transmission schemes for two different astronomical images with different contents. *Deepfield* is a noise-like image, while *Nebula3* is much smoother. From the experimental results, we can see that our proposed approach outperforms the transmission scheme with a single error control method regardless of the channel conditions and the image contents. Furthermore, more quality improvement can be achieved when the packet loss rate is higher.

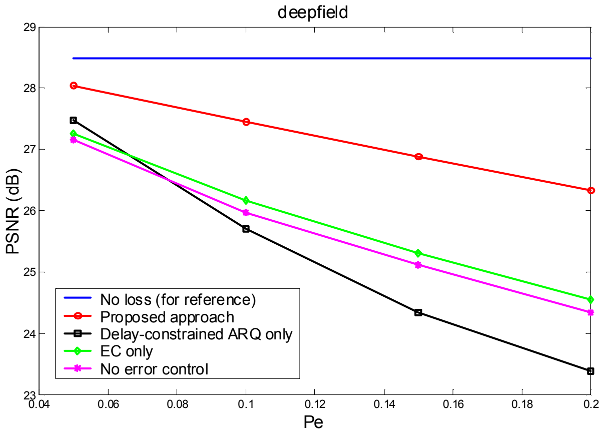


Figure 3. Quality comparison of received image (*deepfleld)* under different transmission schemes with various packet loss rates

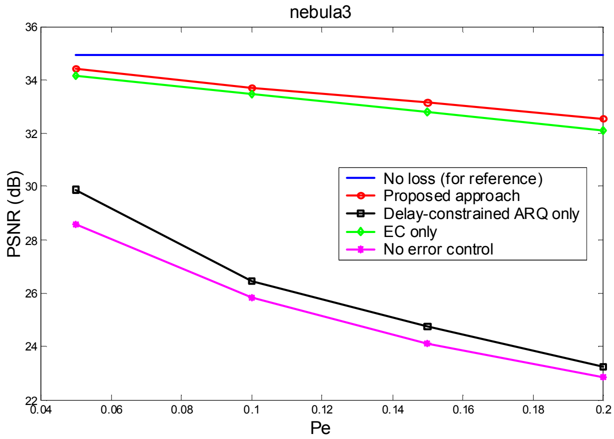
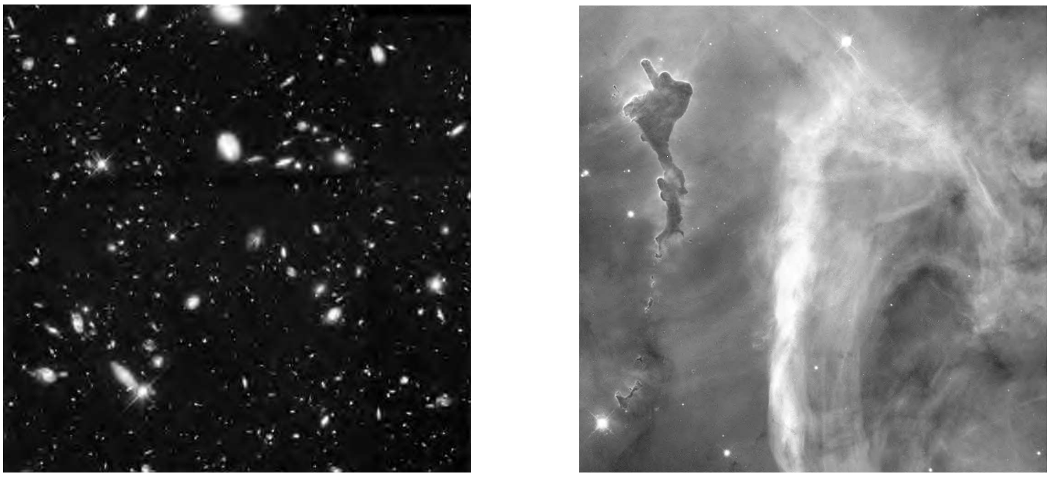


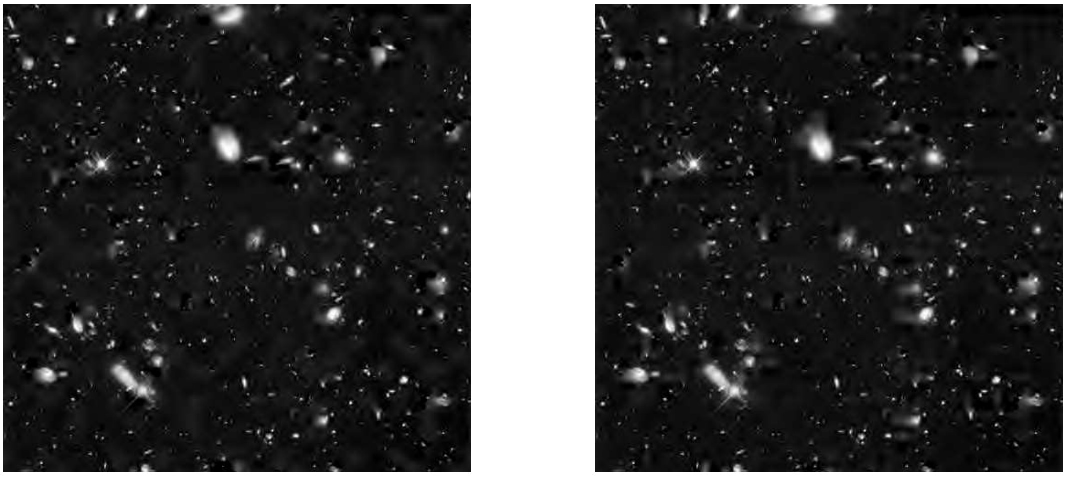
Figure 4. Quality comparison of received image (*nebula3)* under different transmission schemes with various packet loss rates

To show the different impacts of different transmission schemes on the visual effect, the reconstructed images are displayed below. For reference purposes, images without loss are shown in Figure 5. From Figures 6 and 7, it is clear that our proposed approach can minimize the distortion caused by packet loss, since Figures 6-(d) and 7-(d) are closest to the reference images in Figure 5-(a) and (b), respectively.

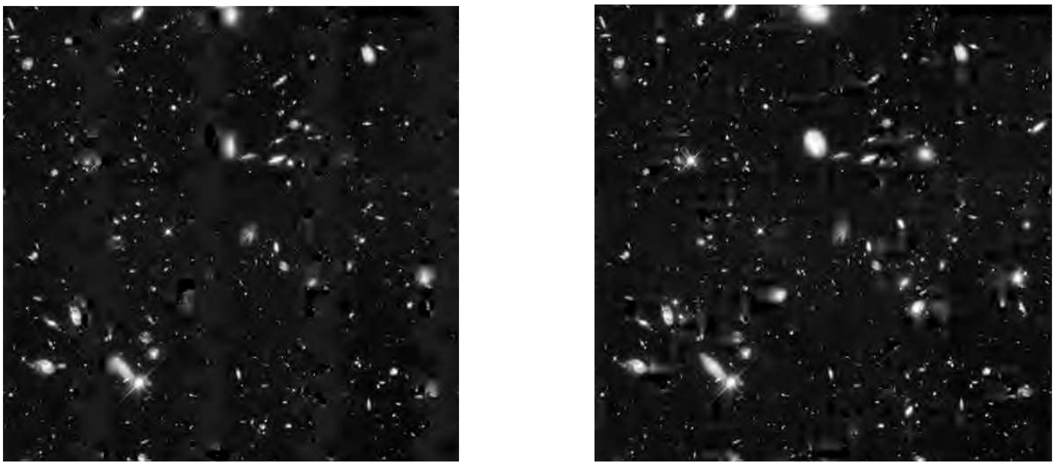


(a) (b)

Figure 5. Two test images used in experiments: (a) *deepfield*; (b) *nebula3*

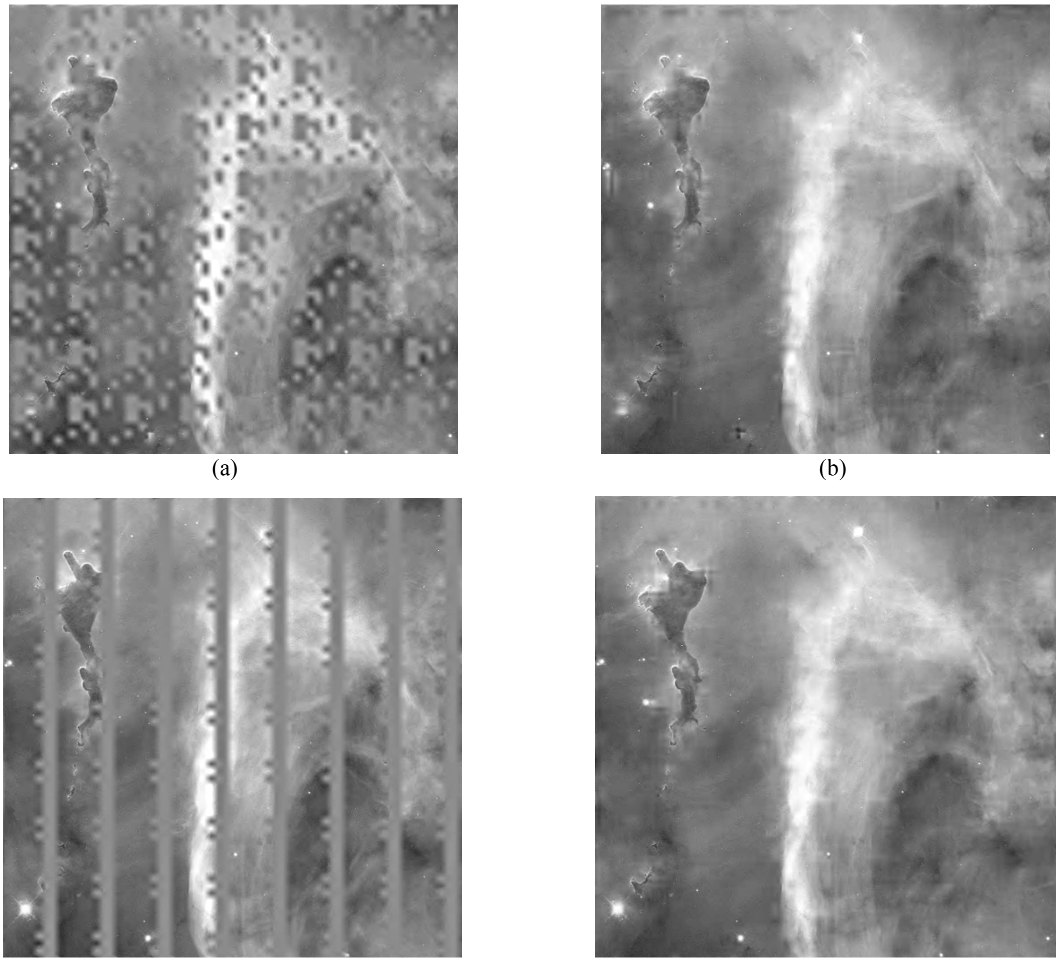


(a) (b)



(c) (d)

Figure 6. Reconstructed images of *deepfield* at a loss rate of 20% with: (a) no error control; (b) error concealment only; (c) delay-constrained ARQ only; (d) proposed approach.



(a) (b)

(c) (d)

Figure 7. Reconstructed images of *nebula3* at a loss rate of 20% with: (a) no error control; (b) error concealment only; (c) delay-constrained ARQ only; (d) proposed approach

5. Conclusions

This paper presented a smart streaming system for astronomical images, with the goal to maximize the quality of the received image over lossy channels. To automatically select the most suitable error control method for astronomical images with different contents, a novel measurement called *concealment profit* is proposed to quantify the expected distortion reduction achieved by error concealment when used in conjunction with CARQ. Accordingly, a new content index, namely *adaptive reconstruction distortion*, is defined. The smart streaming system is designed to select the optimal transmission policy based on the new content index to minimize end-to-end distortion. Experimental results demonstrate that the proposed system is very effective to combat packet loss.

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