Packet Level Pre-FEC Interleaving for Robust JPEG2000 Video Streaming with Low Receiver Processing Delay

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ABSTRACT

A packet-level pre-FEC interleaving scheme for robust JPEG2000 video streaming over RTP is proposed. In this work, we introduce an efficient use of interleaving and FEC for protecting JPEG2000 images from network packet loss that leads to low receiver processing delay, which is the delay required for decoding the protected codestream at receiver. In addition, the proposed method offers high repair capabilities and is backwardly compatible with a non-FEC capable receiver. These features are achieved by utilizing FEC across packets, interleaving, RTP header extension, and JPEG2000 error resilient tools. Simulations were conducted to verify the robustness and processing delay of the proposed method with classical FEC and post-FEC interleaving approaches.

Keywords: Interleaved FEC, JPEG2000, packet loss, video transmission, RTP

1. INTRODUCTION

Real-time video streaming over the Internet has been very popular in recent multimedia communication. Obviously, streaming applications require robustness against channel error and short processing delays. For delay consideration, the real-time transport protocol (RTP), which is a protocol running over the user datagram protocol (UDP), is mostly used instead of the transport control protocol (TCP), which permits a retransmission mechanism with considerable delay. Forward error correction (FEC) has also been very popular as one solution to achieve channel robustness [1–12].

Unfortunately, transmission channel errors are bursty in nature [13, 14] and FEC alone is not able to cope with this burstiness. FEC can be coupled with interleaving to increase its repair capabilities [4–8, 15–18] and solve this problem. However, use of interleaving without proper consideration may introduce more processing delay.

The aim of this paper is to propose an interleaved FEC scheme for protecting JPEG2000 coded images against network packet loss, which requires less processing delay at the receiver in addition to having high repair recoverabilities. In general, existing work that has jointly utilized FEC and interleaving can be classified into two different approaches: pre-FEC interleaving [4, 6–8, 18] and post-FEC interleaving [5, 17]. As the name implies, pre-FEC applies interleaving to the media data prior to FEC coding, while post-FEC does the reverse. As will be discussed later, pre-FEC interleaving can provide more advantages when combined with our proposed method.

Even though FEC and interleaving can be applied either at the bit/byte level [4–6] or at the packet level [16–19], packet-level FEC is mostly used in network transmission [20, 21] as it is easier to control and combine with other techniques, such as limited retransmission in a hybrid ARQ system [10]. Therefore, we utilize packet-level FEC and interleaving in this work.

Packet level pre-FEC interleaving has been previously applied for MPEG-4 video multicasting [18]. Apart from MPEG-4 video, this previous work has taken neither the backward compatibility issue nor processing delay into consideration. Hence, it could not offer backward compatibility with standard RTP implementation. Furthermore, it did not offer any mechanism to achieve selective packet loss reconstruction that could reduce processing delay at receiver. Thus, other techniques in addition to pre-FEC interleaving are necessary to achieve backward compatibility and shorter processing delay for JPEG2000 images.

End-to-end delay of a video streaming system can be contributed by processing time at transmitter, transmission/propagation in network, and processing time at receiver. In this paper, we pay attention only to the receiver side by proposing a novel pre-FEC interleaving scheme for JPEG2000 video streaming with low processing delay at receiver. We focus on

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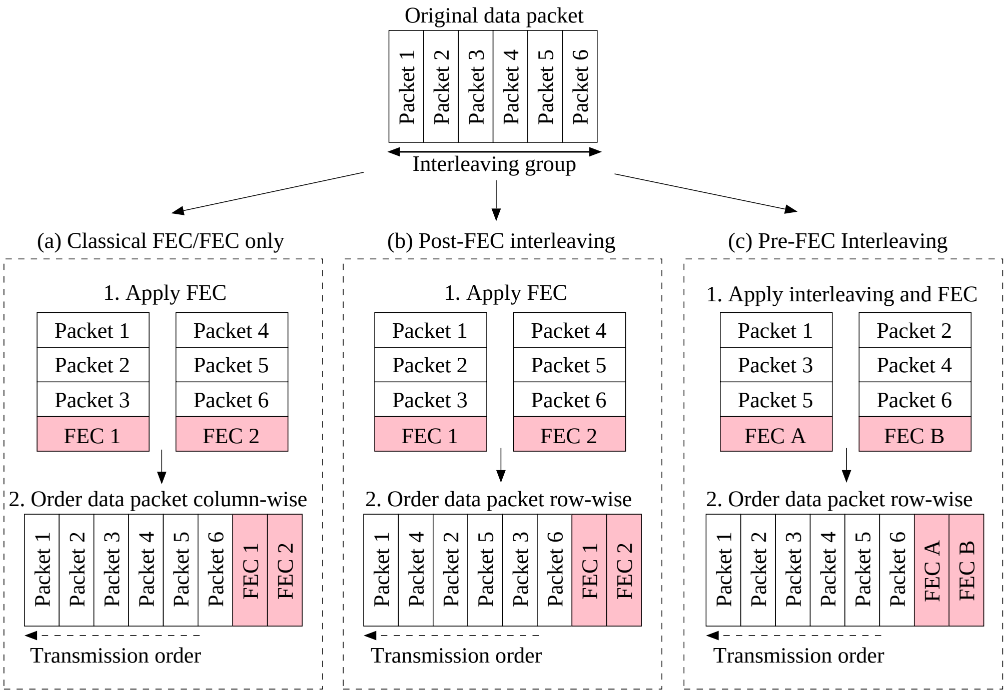

Fig.1: *Various approaches in combining FEC and interleaving. (a) Classical FEC, (b) Post-FEC interleaving, and (c) Pre-FEC interleaving.*

JPEG2000 since it offers several interesting features that can be blended into an efficient video streaming system, such as error resilient tools (ERT), quality scalability, and full intra-frame coding.

To summarize, our paper introduces an efficient way in utilizing the pre-FEC interleaving, RTP header extension, JPEG2000 features, and a selective repair algorithm (SRA) for JPEG2000 video streaming. Furthermore, the proposed method offers high repair capabilities, backward compatibility with a non-FEC capable receiver, and shorter receiver processing delay. The remainder of this paper is organized as follows. Section 2 presents some preliminary issues related to RTP-based network transmission using FEC and interleaving. In Sect. 3, a novel packet loss protection scheme for JPEG2000 video streaming is proposed including RTP header extension and the SRA. Section 4 presents the experimental results. Finally, concluding remarks are made in Sect. 5.

2. BACKGROUND

Here, background information on this work is briefly described, such as packet-level FEC, interleaving, RTP, burst channel model, and Motion JPEG2000.

2.1 Packet-level FEC and Interleaving

Packet-level FEC allows lost original data at the receiver to be reconstructed using redundant or parity information. This parity can be generated using techniques from coding theory, such as XOR-based operation, convolutional codes, and Reed-Solomon (RS) codes. In this work, we consider using the RS erasure codes since they have been widely used [3–5, 7–12]. Nevertheless, other techniques can also be applied along with the proposed method.

The RS(n, k) erasure code takes k original packets and generates $h = n - k$ parity packets. Given the position of the lost packets, the RS decoder can recover lost packets up to h out of n packets. When the code is systematic, the first k of the n encoded packets are the original packets, and the remaining h packets represent the parity. Detailed information on the RS-code and its implementation issues can be found in [22].

Packet interleaving re-sequences packets before transmission so that originally adjacent packets are separated by a certain distance, known as the interleaving depth or interleaving factor. Interleaving is useful because it makes bursts of consecutive packet losses appear as isolated losses when the original order is restored. The actual loss rate remains unchanged, but it is easier for the FEC decoder to recover a series of single-packet losses than it is to recover a longer burst of losses.

The interleaving function can be implemented in various ways, such as by random permutation, block-based interleaving, and other techniques [15]. In this paper, block-based interleaving is considered. We provide an example in Fig. 1(b), in which six packets are reordered with an interleaving factor $i = 3$.

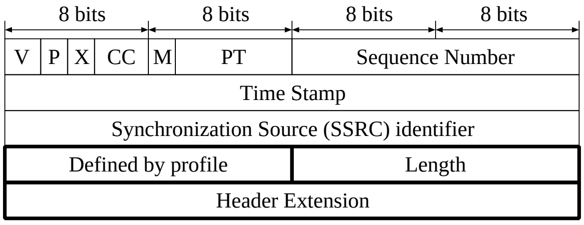

Fig.2: *RTP header format.*

2.2 Combining FEC and Interleaving

There are several approaches to jointly using FEC and interleaving. Let us assume media data is available at a transmitter and has been pre-packetized. With the aid of Fig. 1, we can classify the approaches into: (a) classical FEC or FEC only, (b) post-FEC interleaving and (c) pre-FEC interleaving.

a. Classical FEC.
With classical FEC, packet-level FEC coding is applied to adjacent data packets. In Fig. 1(a), three consecutive packets are protected resulting in 1 parity packet. After FEC coding, the packets are transmitted according to their original sequential order as we can see in the lower part of Fig. 1(a).
b. Post-FEC Interleaving.
When using post-FEC interleaving, the protected packets are interleaved before sending them to the network instead of sequential transmission as in classical FEC. In this case, the order of transmission is changed. In the lower part of Fig. 1(b), we can see that the second packet to be sent is *packet 4* instead of *packet 2* as in classical FEC.
c. Pre-FEC Interleaving.
Pre-FEC interleaving applies a reverse process to classical and post-FEC interleaving. As shown in Fig. 1(c), packets are first interleaved and FEC coding is applied after that. Prior to transmission, the packets are re-ordered into their original order as can be seen in the lower part of Fig. 1(c).

It is important to note that the resulting FEC packets in Fig. 1(c), *FEC A* and *FEC B*, are different from *FEC 1* and *FEC 2* in Figs. 1(a) and (b). The former are obtained from interleaved packets, while the later are generated from adjacent packets.

As described earlier, the pre-FEC interleaving transmit the network packets in their original sequential order. This is useful for backward compatibility with a non-FEC capable receiver. Moreover, it results in shorter processing delay at receiver when the packet loss rate is low. Because of that, in the proposed method, we will exploit the pre-FEC interleaving technique and combined it with SRA, RTP header extension, and JPEG2000 ERT, to achieve high repair recoverability.

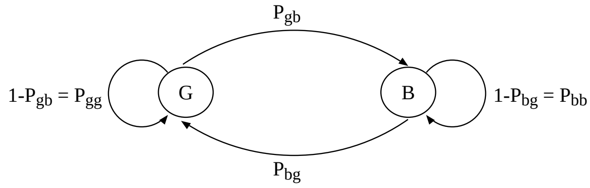

Fig.3: *Two-state Markov model for burst packet loss network.*

2.3 RTP: Real-time Transport Protocol [23]

RTP is the Internet-standard protocol for the delivery of real-time data, including audio, still images, and video. In RTP-based transmission, data is transmitted after being packetized into units called RTP packets. An RTP packet consists of a header and a payload. The header includes the data required for streaming playout. The structure of an RTP header is outlined in Fig. 2.

The *Sequence Number* in the header indicates packet ordering and is used for sorting the received packets and for detecting lost packets. The X (eXtension) in the RTP header is a flag that indicates the existence of an extended function, and the RTP header can be extended by setting this flag to '1'. The portion in bold in Fig. 2 can then be used as an extended function. As we will describe in Sect. 3, this extended function can be used to signal additional information for specific use, such as FEC information, and interleaving. It is worth noting that a receiver with standard RTP implementation can skip this information [23].

2.4 Burst Packet Loss Channel Model

We adopt a widely used two-state Markov model [12] to capture packet loss behavior in a network. In this paper, a packet switching network, such as the Internet, is assumed. Therefore, a lost packet is considered as a whole data loss in one packet and no bit error occurs. The Markov model with two states, Good (G) and Bad (B), is shown in Fig. 3. The G state represents the correct reception of packets, while in the B state, a packet is being lost. The transition probabilities are defined as P_{gb} (from G to B) and P_{bg} from (B to G). Consequently, the two most important characteristics of this channel, average packet loss rate (P_e) and average burst length (BL), can be derived using Eq. (1) below.

$$P_e = \frac{P_{gb}}{P_{gb} + P_{bg}} \quad and \quad BL = \frac{1}{P_{bg}} \tag{1}$$

2.5 Motion JPEG2000

Motion JPEG2000 is an extension of the JPEG2000 standard for video format. It utilizes the

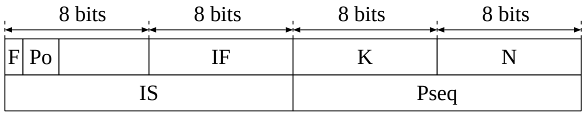

Fig.4: *Proposed RTP header extension.*

same coding engine as the JPEG2000 still coding scheme [24]. The streams of Motion JPEG2000 are formed as a continuous series of JPEG2000 still images. There are several features of JPEG2000 video that can effectively be used in streaming applications:

- The JPEG2000 standard is equipped with error resilient bit stream syntax and tools. Error resilience is achieved at the entropy coding level and at the JPEG2000 packet level.
- JPEG2000 scalability features can be utilized for progressive transmission, either by resolution or quality.
- Motion JPEG2000 is a full-intra frame format; each frame is independently compressed, and it therefore has low source encoding and decoding delay.

Our work takes advantage of these features to enable high quality JPEG2000 video streaming with low processing delay.

3. PROPOSED METHOD

The proposed method at the transmitting and receiving side are described in this section including RTP header extension, packet prioritization using JPEG2000 SNR scalability, and the selective repair algorithm (SRA). The pre-FEC interleaving we proposed offers high repair capabilities, low processing delay, and is backwardly compatible with standard RTP implementation and a standard JPEG2000 decoder.

3.1 Process at Transmission Side

The proposed system at the transmitting side can be described as follows.

3.1.1 RTP Header Extension

The receiver side needs to differentiate between packets containing source data and FEC information. Furthermore, the receiver should also be aware of interleaving related information. To accomplish this, we propose the utilization of RTP header extension as described in Section 2.3. Various bit flags for pre-FEC interleaving deployment are transmitted within this extended header. Figure 4 outlines the proposed RTP header extension to enable pre-FEC interleaving. The explanation for each item contained in the extended header is as follows.

- F (FEC flag): 1 bit

Denotes media packet or FEC packet. This flag will be set to '0' if the packet contains media data and '1' for FEC.

- Po (Position): 2 bits

Denotes packets position in one interleaving group.

- IF (Interleaving factor): 8 bits

Denotes interleaving factor i.

- K: 8 bits

Denotes the number of original protected data k in an RS code.

- N (FEC size): 8 bits

Denotes FEC size n. The number of redundant packets can be determined as $n - k$.

- IS (Interleaving group size): 16 bits

Denotes the number of packets in one interleaving group (IG).

- Pseq: 16 bits

Denotes the base packet position number before interleaving.

This header extension plays an important role in allowing backward compatibility with standard RTP implementation, as it can be ignored by receivers that do not understand an unrecognized header extension [23].

3.1.2 SNR Scalability and Packet Prioritization

When using SNR scalability in JPEG2000, the codestream is arranged in a layered structure according to its contribution to image quality. The most important part is placed at the beginning, while the least important one is placed at the tail of the codestream. Because of this structure, SNR scalability feature can be utilized to provide network packet prioritization; packets with a smaller packet number, which contain more important part of the codestream, are gaining more priority than those with a greater packet number. This packet prioritization is used for SRA implementation at the receiver and will be discussed in Section 3.2.1.

3.1.3 Transmission Algorithm

Since the JPEG2000 video format is fully intracoding, we consider one JPEG2000 video frame to be one independent interleaving group. Based on Fig. 5, the flow of the transmitting algorithm can be explained as follows.

1. JPEG2000 encoding.

Perform JPEG2000 source encoding on each frame. SNR scalability and ERT features are enabled during this step.

2. Frame fragmentation.

Fragment the JPEG2000 stream of each frame based on the RTP payload length.

3. Set FEC code and interleaving factor.

The required FEC code and interleaving factor are chosen. The strength of FEC determines the number of lost packets in one FEC block that can be restored, while interleaving factor i determines the gap between adjacent packets. Then, arrange packets according to the chosen interleaving factor i. At this point, the original packet order is changed.

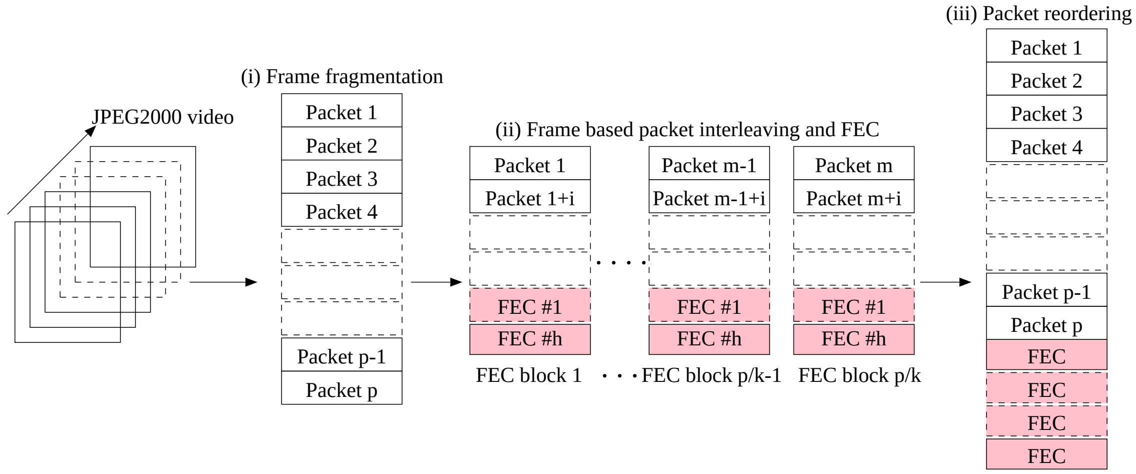

Fig.5: *Pre-FEC interleaving at transmitting side with RS(n, k) and interleaving factor of i. p is number of media packets in one frame and m = 1 + (p-k)/i.*

4. Packet level FEC.
Packet-level FEC is applied to the interleaved data packets resulting in several FEC blocks.
5. Packet reordering.
The protected packets are then re-sequenced in their original order with all the FEC packets placed in the last position, as can be seen in Fig. 5(iii).
6. RTP packetization.
Perform RTP packetization considering the header extension previously described in Sect. 3.1.1.
7. Send packets to network.
Packets are delivered into network.

3.2 Process at Receiver Side

The proposed system at the receiving side can be described as follows.
1. Identification of lost packets.
When all packets are received for each frame, lost packets are identified. This can be done by utilizing the sequence number field in the RTP header. The lost packets are detected by checking the gap between the two adjacent packets. There are two scenarios for the next steps, depending on network conditions.
2.a Perfect network condition.
If there are no packet loss during transmission, the received packets of each frame can directly be sent to the JPEG2000 decoder. No additional processing needs to be performed. This feature is advantageous compared with the limitations of post-FEC interleaving.
2.b Non-perfect network condition.
When packets are lost, recovery operation is executed as a reverse process to the one previously described in Sect. 3.1.3 , starting from packet interleaving, FEC decoding and packet re-sequencing. Instead of recovering all lost packets that can induce unnecessary delays, we propose a simple selective repair algorithm (SRA) to intelligently decide whether there is a need to perform packet recovery. A more detailed description of SRA will be discussed in subsection 3.2.1.
3. JPEG2000 decoding.
Using a standard JPEG2000 decoder with ERT, perform image decoding on the codestream of each frame.

3.2.1 Proposed Selective Repair Algorithm (SRA)

The SRA can briefly be described using the pseudo-code in Table 1. The basic idea is to prevent lost packets from being unnecessarily reconstructed to reduce processing delay at the receiver. As can be seen in Table 1, recovery is done when the following conditions are fulfilled:

- The number of lost packets in one FEC block is less than or equal to the FEC repair capabilities.
- If a lost packet in one FEC block cannot be recovered, there is no need to recover lost packets with a greater packet number in other FEC blocks.

Thus, the SRA manages the recovery process so that it is done efficiently according to the available resources. This SRA can be implemented due to various information in the RTP header extension, and the availability of JPEG2000 SNR scalability.

3.3 Backward Compatibility

By applying pre-FEC interleaving, RTP header extension, and JPEG2000 ERT as previously described, our proposed method is backwardly compatible with a receiver supported by standard RTP implementation. The process is as follows.

- A non-FEC capable receiver with standard RTP implementation skips the information contained in the RTP header extension. All packets, including FEC packets, are sent to the JPEG2000 decoder.
- JPEG2000 decoder can properly perform source decoding since the original data ordering in a codestream is preserved. When there is no lost packets,

Table 1: *Selective Repair Algorithm*

```
check lost packets;
IF (lost packets are detected)
   rearrange packets;
   for each FEC block
     IF (number of lost packets ≤ FEC repair
        capability)and (packet with smaller packet
        number in other blocks was not lost)
       attempt packet recovery;
       rearrange packets;
     ELSE
       skip packet recovery;
       rearrange packets;
     END
ELSE
   skip packet recovery;
END
```

the end of codestream (EOC) marker indicates the end of JPEG2000 data. Thus, the FEC data after EOC is discarded. When packet loss occurred, the remaining packets after the lost one are excluded during JPEG2000 decoding by the use of ERT.

Based on the above scenario, data packets generated at the transmitting side can be decoded by receiver with a standard RTP implementation. However, when packet loss occurs, the image quality may degrade because lost packets cannot be reconstructed. Backward compatibility feature is useful, such as to enable offering quality of service (QoS) among different users.

4. SIMULATIONS

To evaluate the effectiveness of the proposed method, several simulations were conducted. Simulation results and their interpretations are presented in this section.

4.1 Simulation Conditions

The simulation conditions are summarized in Table 2. We used 50 frames of "Football" and 40 frames of "Mobile&Calendar" sequences as the source video data, in which each frame was considered to be one interleaving group. Block-based interleaving with $i = 8$ was used. The RS(20,16) that can recover maximum 4 lost packets was tested in bursty packet loss environment with burst length of 3 (1 packet less than the maximum recovery of the chosen FEC) and 5 (1 packet exceeds the maximum recovery of the chosen FEC). In practice, both interleaving and FEC strength can be adjusted to match the measured loss pattern reported by the RTCP (RTP Control Protocol) [23].

Each frame of the test sequences consisted of 80 packets including FEC packets, and 4 FEC blocks. We, thus, had a total of 4000 packets with 200 FEC blocks for "Football" and 3200 packets with 160 FEC blocks for "Mobile&Calendar". JPEG2000 ERT was enabled during JPEG2000 encoding. The CPU time was measured on a PC with a 1.2 GHz processor and a main memory of 512 Mbytes for processing delay.

Table 2: *Simulation conditions.*

Test sequence (gray scale)	**Football** (50 frames), 720×486, 0.72 bpp/frame. **Mobile&Calendar** (40 frames), 720×576, 0.72 bpp/frame.
Transmission channel	Two-state Markov model
Packet loss rate	0.00, 0.01, 0.05, 0.10, 0.15
Average burst length	3, 5
FEC	RS(20,16)
Packet length	
-Football	500 bytes
-Mobile&Calendar	600 bytes
Interleaving factor (i)	8
Codec	JPEG2000 VM 8.6 [25]

4.2 FEC Repair Capabilities and Image Quality

Here, let us compare the FEC repair capabilities (measured by the percentage of FEC blocks successfully decoded) and decoded image quality (measured by average PSNR) of each approach. Tables 3(a) and (b) present the results at various loss rates with average burst lengths of 3 and 5 for "Football". We can see that classical FEC did not perform as well as the schemes utilized interleaving. This confirmed the usefulness of interleaving in increasing the FEC repair capabilities. The same tendency can be found in Tables 4(a) and (b) for "Mobile&Calendar".

Sample of decoded frames are presented in Fig. 6, in which the image protected by the classical FEC suffered from severe quality degradation. This is due to the lost of second network packet that contained important part of image data. The PSNR of image protected by the proposed method is 15 dB higher than the one protected by classical FEC.

4.3 Processing Delay

In addition to image quality, the performance of video streaming applications is also measured by end-to-end delay or latency from a frame being captured to its display. Most interactive video streaming, such as high quality video conferencing, allows a maximum latency of 200 ms [26]. However, some applications like video surveillance and live event video broadcasting have relatively loose latency requirement. Sources of end-to-end delay may include time to capture, time for compression, time for FEC encoding, and time for interleaving at transmitter, transmission and propagation time in the network, and time for decompression, FEC decoding, deinterleaving and display at receiver.

In this work, we focus only on the processing delay at receiver that consists of the processing time required for interleaving (T_i), FEC decoding (T_{fec}), and storing (T_{buf}). The processing time can be calculated considering two conditions; when there is no packet loss (perfect network condition) and when

Table 3: *Percentage of successful FEC blocks decoding and decoded image quality of each approach. Test sequence: football.*

(a) Percentage of repair capability and average PSNR, burst length = 3. Test sequence: football

314mmProtection Scenario	Packet Loss Rate							
	0.01		0.05		0.10		0.15	
	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)
Classical FEC	95.83	35.18	92.41	34.14	87.69	31.86	77.44	29.32
Post-FEC	100	35.31	99.04	35.10	95.68	34.04	84.24	30.82
Pre-FEC	100	35.31	99.04	35.08	95.68	34.09	84.24	30.71
Proposed	100	35.31	99.04	35.08	95.68	34.09	84.24	30.71

(b) Percentage of repair capability and average PSNR, burst length = 5. Test sequence: football

314mmProtection Scenario	Packet Loss Rate							
	0.01		0.05		0.10		0.15	
	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)
Classical FEC	88.24	34.94	62.30	31.94	62.07	27.99	56.59	22.88
Post-FEC	100	35.31	94.57	34.72	87.33	32.33	81.71	30.01
Pre-FEC	100	35.31	94.57	34.65	87.33	32.39	81.71	29.99
Proposed	100	35.31	94.57	34.65	87.33	32.39	81.71	29.99

Table 4: *Percentage of successful FEC blocks decoding and decoded image quality of each approach. Test sequence: mobile&calendar.*

(a) Percentage of repair capability and average PSNR, burst length = 3. Test sequence: mobile&calendar

314mmProtection Scenario	Packet Loss Rate							
	0.01		0.05		0.10		0.15	
	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)
Classical FEC	94.12	34.48	88.71	33.27	86.28	31.73	76.52	29.10
Post-FEC	100	34.54	97.50	34.29	96.24	33.71	85.43	31.08
Pre-FEC	100	34.54	97.50	34.05	96.24	33.89	85.43	30.74
Proposed	100	34.54	97.50	34.04	96.24	33.89	85.43	30.74

(b) Percentage of repair capability and average PSNR, burst length = 5. Test sequence: mobile&calendar

314mmProtection Scenario	Packet Loss Rate							
	0.01		0.05		0.10		0.15	
	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)	Repair (%)	PSNR (dB)
Classical FEC	91.67	34.47	64.71	32.51	60.00	28.89	56.78	24.54
Post-FEC	100	34.54	93.15	34.03	84.03	30.96	78.32	28.72
Pre-FEC	100	34.54	93.15	33.90	84.03	31.11	78.32	28.25
Proposed	100	34.54	93.15	33.90	84.03	31.11	78.32	28.25

packet loss occurs (non-perfect network condition), as summarized in Table 5. The average processing time required for each task at receiver was presented in Table 6. As shown, the time required for FEC decoding contributed to the most processing delay. It is worth noting that the processing delay due to interleaving and FEC decoding can be further decreased depending on the algorithm used.

a. Perfect Network Condition

Table 7(a) and 8(a) present the decoding delay of each approach for "Football" and "Mobile&Calendar" sequences when no packet loss occurred. Classical FEC and the proposed method required the same processing time. However, more time was required by post-FEC interleaving due to the need of packet reordering.

b. Non-perfect Network Condition

Table 7(b)–(c) and 8(b)–(c) present the processing time of each approach for "Football" and "Mobile&Calendar" respectively, at various packet loss rates with burst lengths of 3 and 5. As can be seen, classical FEC and our method required less processing time to repair lost packets at receiver.

Table 5: *Time processing unit required at receiver for each frame.*

Perfect network condition	
Classical FEC	T_{buf}
Post-FEC interleaving	$T_i + T_{buf}$
Proposed	T_{buf}
Non-perfect network condition	
Classical FEC	$T_{fec} + T_{buf}$
Post-FEC interleaving	$T_i + T_{fec} + T_{buf}$
Proposed	$T_i + T_{fec} + T_i + T_{buf}$

T_i = time required for packet rearrangement/interleaving
T_{fec} = time required for FEC decoding
T_{buf} = time required for stream buffering and storing

Thus, using the proposed method, we could gain both low processing delay and high repair capabilities. We note that the processing delay could be reduced by the proposed method due to the use of SRA. Instead of decoding all FEC blocks, as in classical FEC, post-FEC, and pre-FEC, the proposed method with SRA only treated the affected FEC blocks that led to successful decoding.

(a)

(b)

Fig.6: *Sample of decoded images taken from sequence no. 36 in packet loss rate of 10% with burst length = 3. (a) Image was protected with classical FEC (FEC only), PSNR = 19.67 dB. The second packet was lost and unrecoverable. (b) Image was protected with the proposed method, PSNR = 35.02 dB. Lost packet was perfectly recovered.*

Table 6: *Processing time required for each task per frame at receiver [ms].*

Time required for interleaving, T_i	0.7556
Time required for 4 blocks FEC decoding, T_{fec}	3.9867
Time required for buffering and storing, T_{buf}	3.3663

4.4 Backward Compatibility

Figure 7 compares the quality of images that were decoded by the proposed receiver and by a non-FEC capable receiver with standard RTP implementation, at a packet loss rate of 1% and a burst length of 3. As we can see, the codestreams generated at the proposed transmitting site could be decoded by a non-FEC capable receiver. However, the image quality was poor as there was no mechanism to recover the lost packets. Thus, the proposed pre-FEC interleaving is backwardly compatible with a non-FEC capable receiver that equipped with a standard RTP implementation and a standard JPEG2000 decoder.

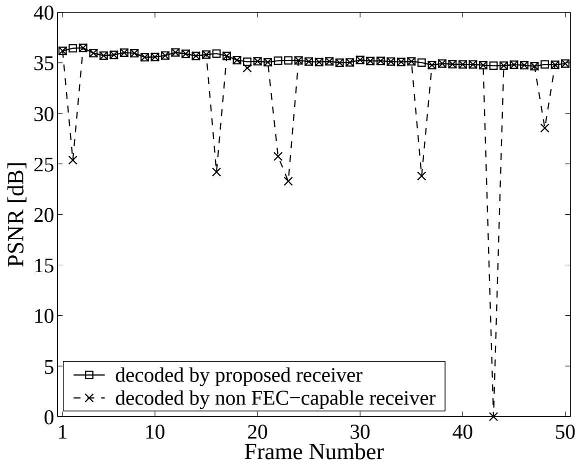

Fig.7: *Comparison of quality of images decoded by the proposed receiver and by a non-FEC capable receiver at packet loss rate of 1% and burst length of 3. PSNR = 0 dB indicates undecodable frame.*

5. CONCLUSION

A novel pre-FEC interleaving scheme with low receiver processing delay has been proposed for JPEG2000 video streaming. The proposed method combined a pre-FEC interleaving technique, RTP header extension, a selective repair algorithm, and JPEG2000 error resilient tools. The scheme is intended to combat burst packet loss during network transmission and it is backwardly compatible with non-FEC capable receivers.

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Table 7: *Total processing time at receiver [ms]. Packets were sent to network with various packet loss rates, burst lengths = 3 and 5, test sequence: football, number of frames = 50.*

(a) Perfect network condition.

Channel Rate	Classical FEC	Post-FEC	Pre-FEC	Proposed
0.00	168.3152	206.0946	168.3152	168.3152

(b) Non-perfect network condition, packet loss burst length=3.

Channel Rate	Classical FEC	Post-FEC	Pre-FEC	Proposed
0.01	200.2087	237.9882	212.2982	197.3481
0.05	279.9427	317.7221	326.2424	281.3920
0.10	351.7032	389.4827	421.2174	357.9448
0.15	359.6766	397.4561	432.2132	340.5191

(c) Non-perfect network condition, packet loss burst length=5.

Channel Rate	Classical FEC	Post-FEC	Pre-FEC	Proposed
0.01	188.2487	226.0281	195.8045	188.8278
0.05	275.9560	325.6955	322.2557	270.8784
0.10	307.8496	345.6290	366.2387	306.9204
0.15	347.7165	385.4960	415.7196	343.9590

Table 8: *Total processing time at receiver [ms]. Packets were sent to network with various packet loss rates, burst lengths = 3 and 5, test sequence: mobile&calendar, number of frames = 40.*

(a) Perfect network condition.

Channel Rate	Classical FEC	Post-FEC	Pre-FEC	Proposed
0.00	134.6521	164.8757	134.6521	134.6521

(b) Non-perfect network condition, packet loss burst length=3.

Channel Rate	Classical FEC	Post-FEC	Pre-FEC	Proposed
0.01	158.5723	188.7959	167.6394	156.6760
0.05	222.3595	252.5830	261.1033	223.2296
0.10	290.1333	320.3569	349.0693	296.2455
0.15	293.4996	324.4788	353.9468	285.1762

(c) Non-perfect network condition, packet loss burst length=5.

Channel Rate	Classical FEC	Post-FEC	Pre-FEC	Proposed
0.01	146.6122	176.8358	151.1458	147.1591
0.05	222.3595	264.5431	255.6054	214.7094
0.10	246.2797	276.5032	295.6017	243.2601
0.15	282.1599	312.3835	339.5847	275.7975

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