A New Dual-bitstream Video Streaming System with VCR Functionalities Using SP/SI-frames

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Abstract With the proliferation of digital video and the popularity of video streaming applications, it is highly desirable to find and access video segments of interest by searching through the content of video at a speed that is faster than a normal playback. The key functions that enable quick browsing of video are fast-forward and fast-reverse playbacks. However, motion-compensated prediction adopted in the current video coding standards drastically complicates these operations. One approach to implement the fast-forward/reverse playback is to store an additional reverse-encoded bitstream in the server. Once the client requests a fast-forward/reverse operation, the server can select an appropriate frame for the client from either the forward-encoded bitstream or the reverse-encoded bitstream by considering the cost of network bandwidth and decoder complexity. Unfortunately, these two bitstreams are encoded separately. The frame in one bitstream may not be exactly identical to the frame in another bitstream. If one of these frames is then used as the reference for the requested frame, which is in another bitstream, it induces mismatch errors. In this paper, a novel H.264 dual-bitstream system aiming at providing the fast-forward/reverse playback based on SP/SI-frames is proposed. The proposed system can completely eliminate mismatch errors when the frame in the reverse-encoded bitstream replaces the frame in the forward-encoded bitstream and vice versa.

Experimental results confirm that the proposed system is effective in eliminating mismatch errors so as to enhance the performance of the dual-bitstream system.

Keywords Digital video cassette recording (VCR) · MPEG/H.264 · Streaming video · Dual-bitstream system

1 Introduction

Streaming video over the Internet becomes popular in recent years, mainly due to the continued advance of video compression and broadband networking technologies [1, 2]. These streaming applications such as video-on-demand allow users to ubiquitously access and retrieve various videos over networks using software players [3, 4] or digital set-top box devices [5, 6], which are currently ready to take place of obsolete analog-based devices and systems such as analog TV and Video Cassette Recorders (VCRs). Nowadays, the digital video coding standards such as MPEG-1/2/4 [7–9] and H.26x series [10, 11] were developed primarily for achieving high compression ratios by using motion-compensated prediction [12–14]. In order to complete the transition to digital video from its current analog state, it is highly desirable that users can browse video contents in a fast and user-friendly way [15–18]. Fast-forward and fast-reverse playbacks are two popular video browsing functions provided in many analog and digital video players. However, motion-compensated prediction is mainly designed and best suited for a normal playback in which frames are decoded and played back in a pre-determined frame order. The frame dependency severely complicates the fast-forward/reverse operations since a predicted frame can only be decoded when all its reference frames have already been decoded.

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Some works on the implementation of fast playbacks for video streaming were introduced in [15–22]. In [19], these operations are implemented at the client side by using pre-fetched video frames. However, this approach requires a huge buffer in the client machine, which is not desirable. Although the frame-skipping video transcoding methods proposed in [20, 21] can be used to support fast forward/reverse playbacks, they introduce much computation in the server and will cause drift due to the transcoding process. Omoigui et al. [22] suggested a number of client-server time-compression solutions for a fast-forward playback and video browsing. By using time-compression, the server stores multiple pre-encoded video bitstreams with various temporal resolutions and transmits a video bitstream with appropriate temporal resolution according to the speed-up factor required by users. This approach does not induce excessive buffers in the client but the speed-up granularity is limited by the number of pre-stored video bitstreams. In [15–17], some schemes proposed to store a forward-encoded bitstream and a reverse-encoded bitstream in the server. The idea is to switch frames between the forward-encoded bitstream and the reverse-encoded bitstream based on a frame-selection scheme, which is used to minimize the number of transmitted frames over the network for any speed-up factors. This dual-bitstream system can alleviate the decoder complexity while maintaining the low network bandwidth requirement in fast playbacks. However, this approach would cause a mismatch problem because a P-frame in the reverse-encoded bitstream may have to be approximated by an I-frame in the forward-encoded bitstream and vice versa.

In this paper, we utilize the concept of SP/SI-frame coding [23, 24] and provide an efficient solution for performing various fast playbacks in the dual-bitstream streaming system to eliminate the problem arising from the mismatch between the forward-encoded and reverse-encoded bitstreams. Our system is designed specifically for H.264 and can be adapted to any other coding standards that support SP/SI-frames. It is also a new application of SP/SI-frames. The organization of this paper is as follows. Section 2 of this paper presents an in-depth study of the problems on the dual-bitstream system. In Section 3, a brief

introduction of SP/SI-frame coding for H.264 is given and the proposed system is discussed in detail, where we describe how to adopt SP/SI-frames in the dual-bitstream system. We also illustrate how to modify the encoding processes of SP/SI-frames such that they work well with the newly modified dual-bitstream system. Experimental results are presented in Section 4. Finally, some concluding remarks are provided in Section 5.

2 Dual-bitstream MPEG Video Streaming System

To find a way to deal with the problem in different VCR trick modes of digital video, a dual-bitstream system was proposed in [15] which adds a reverse-encoded bitstream (RB) in the server in addition to the traditional forward-encoded bitstream (FB). The generation of the RB is simply encoding the video in reverse order. Figure 1 shows an illustrative example of the FB and the RB in which the video is coded in I/P-frames with a GOP size of 14 frames and I-frames in the RB is interleaved between I-frames in the FB. Note that B-frames are not used as references for later frames. It means they are not involved in decoding other frames. For simplicity but without loss of generality, we focus our discussions on the case that the video stream contains I/P-frames only. Once the server receives the VCR command or the requested frame number from the client, the server employs a frame-selection scheme to determine which frames in either the FB or the RB to be transmitted by minimizing the cost of decoding the next requested frame. In general, a larger number of frames to be sent induces much heavier network traffic and higher decoding complexity. For this reason, the cost can be approximated to the number of frames to be sent over the network [15]. The frame-selection scheme actually measures the distances from the next requested frame to the current displayed frame (d_C), the nearest I-frame in the FB (d_{FB}) and the nearest I-frame in the RB (d_{RB}). It then picks the frame with the minimum distance as the reference frame to the next requested frame to initiate the decoding. Since this selected reference frame has a shorter distance to the next requested

Figure 1 Fast-reverse operation with the speed-up ratio of 6 in the dual-bitstream video streaming system.

frame, a smaller number of frames is required to be sent. The frame-selection scheme may switch from the FB to the RB and vice versa according to the current play-direction, the requested mode and the distances d_C , d_{FB} and d_{RB} . In other words, it will determine which bitstream to be selected next and its decoding direction. To illustrate the scheme, let us recall the structure of dual bitstreams in Fig. 1 again. Assume that the previous mode was in the normal forward playback. At frame 20, fast-reverse playback with a speed-up factor of 6 is requested. In this case, frames 14, 8, and 2 should be displayed. If the requested frame is an I-frame in one of two bitstreams, the frame can be decoded by itself. Thus, in the above example, frame 14 will be decoded from the FB directly since it is an I-frame. Then, the next frame to be decoded is frame 8. Since the requested frame is a P-frame in both bitstreams, the current displayed frame, or the nearest I-frame either in the FB or the RB is firstly selected to initiate the decoding of the requested frames. In this example, frame 8 will be decoded from frame 7 of the RB (an I-frame) since d_{RB} has the smallest value among all distances. It implies the nearest I-frame of the RB (frame 7) is the closest reference to frame 8. Note that frame 7 of the RB (an I-frame) is used as an approximation of frame 7 of the FB (a P-frame) to reconstruct frame 8 of the FB, as depicted in Fig. 1. This I-to-P approximation will cause the drift problem due to the mismatch between the reference frames. Furthermore, the drift will not only be confined to the frame at the switching location, but will further propagate in time if it is used as reference for other frames. This is the case when the current fast-reverse mode is switched back to the normal playback at frame 8. In this situation, frame 9 will be decoded by using the drifted frame 8. This drift continues until the next I-frame in the FB. The quality degradation in this situation is depicted in Fig. 2 where the test video used for simulation is “Foreman” sequence. The “Foreman” sequence is encoded at 330 Kb/s with a frame-rate of 30 fps and the GOP length is 14 with an I-P structure. The starting point of the fast-reverse operation with a speed-up factor of 6 is at frame 20 and the normal-play operation is then requested at frame 8. This figure shows that the drift caused by the bitstream switching can be as large as 1.3 dB and will last until the next I-frame in the FB. Although the drift problem can be compensated by adding two drift-compensated bitstreams [15], it increases the storage requirements of the server.

3 Proposed Dual-bitstream Video System Based on SP/SI-frames

In the paper, we suggest an efficient solution for the drift problem by modifying the original structure of the dual

Figure 2 Quality degradation in the situation when the fast-reverse operation with a speed-up factor of 6 is requested at frame 20 and then the normal playback is issued at frame 8.

bitstreams with the help of SP/SI-frame coding. The new structure provides seamlessly approximation between frames in the FB and the RB for any VCR operation. SP/SI-frames are new picture types supported by H.264 [23, 24]. The traditional usage of SP/SI-frames is for drift-free switching between compressed bitstreams of different bit rates to accommodate the channel bandwidth variation [23–26]. Figure 3 shows an example in which a video is coded into two bitstreams (bitstream A and bitstream B) with different bit rates. Within each encoded bitstream, two SP-frames— $SP_{A,n}$ and $SP_{B,n}$, as shown in Fig. 3, are placed at frame n at which switching from one bitstream to another will be allowed. These SP-frames are referred to as primary SP-frames. Besides, for each primary SP-frame, a corresponding secondary SP-frame ($SP_{AB,n}$ in Fig. 3) is generated, which has the same reconstructed values as the primary SP-frame. Such a secondary SP-frame is sent only during bitstream switching. For normal transmission, either bitstream A or bitstream B is sent to the user depending on the current available bandwidth. When there is a need to switch from bitstream A to bitstream B at frame n , $SP_{AB,n}$ instead of $SP_{B,n}$ is transmitted. Note that, $SP_{AB,n}$ and $SP_{B,n}$ use different reference frames, $SP_{A,n-1}$ and $SP_{B,n-1}$ respectively, for prediction. After decoding $SP_{AB,n}$, the decoder can obtain exactly the same reconstructed values as normally $SP_{B,n}$ decoded at frame n , therefore it can continually decode bitstream B at frame $n+1$ seamlessly. The way to encode $SP_{AB,n}$ ensures that an identical reconstruction as that of $SP_{B,n}$ can be obtained even $SP_{AB,n}$ and $SP_{B,n}$ have different reference frames. Readers interested in learning how such property is achieved are encouraged to read the references [23, 24]. Similarly, an SI-frame can also be used in the bitstream-switching scenario. The only difference is that its prediction is formed using the intra-prediction modes from previously decoded samples of the reconstructed frame. The

Figure 3 Bitstream switching using SP pictures.

SI-frame may be used when the two bitstreams are completely different. In this case, it will not be efficient to use motion-compensated prediction because there is no correlation between these two sequences.

This property motivates us to adopt SP/SI-frames in the structure of dual bitstreams to prevent reference mismatch due to the I-to-P approximation during the fast playback operations. In the following, we provide a detailed description and formulation of the proposed dual-bitstream system.

3.1 Dual-bitstream Video System with SP/SI-frames

As mentioned in Section 2, the conventional dual-bitstream system suffers the drift problem due to the I-to-P approximation during fast playbacks. In our system, we propose to adopt the SP/SI-frame pairs at the switching points which are the points when a frame of one bitstream may be used to replace a frame of the other bitstream. This arrangement ensures that the I-to-P approximation will not happen at switching points for any fast-forward/reverse operation. Consequently, the new dual-bitstream system will not cause any mismatch at the decoder side.

The idea of utilizing SP/SI-frame coding for the purpose of the seamless approximation in VCR operations is introduced in Fig. 4. In the original structure of the dual bitstreams, I-frames represent the points of access to decode the sequence from any arbitrary position. In order to avoid the problem of reference mismatch, instead of using I-frames in the original dual bitstreams, SI-frames are adopted at the switching points. An SI-frame can be placed either in the FB or RB which is referred to as a forward-encoded SI-frame

(SI_{FB}) or a reverse-encoded SI-frame (SI_{RB}) respectively. For each SI_{FB}, there is a corresponding reverse-encoded SP-frame (SP_{RB}) and these two frames form an SI_{FB}/SP_{RB} pair. Similarly, there is a corresponding forward-encoded SP-frame (SP_{FB}) for each SI_{RB} and they form an SP_{FB}/SI_{RB} pair. Identical frame reconstruction can be allowed at these SI_{FB}/SP_{RB} and SP_{FB}/SI_{RB} pairs when an SI-frame of one bitstream is used to replace an SP-frame of the other bitstream. This facilitates the correctly predicted frame to be used if the replacement of SP with SI is needed in any VCR operation and hence no drift will occur. To illustrate the proposed system, we use the example in Fig. 1 again in which the current VCR is in the fast-reverse mode and this operation requires to display frames 14, 8, etc. After decoding and displaying frame 8, then a normal-play request is launched. Frame 8 will be decoded from frame 7 of the RB, which is an SI_{RB}. After decoding this SI_{RB}, the decoder can obtain exactly the identical reconstruction as normally decoding SP_{FB} at frame 7 in the FB, therefore it can decode frame 8 in the FB without any mismatch error and continue to decode the subsequent frames seamlessly when the normal playback is requested at frame 8. Hence, the proposed dual-bitstream system does not suffer the drift problem because no approximation between the SI-frame and the SP-frame on the dual bitstreams has been made.

3.2 Encoding and Decoding Arrangement of SP_{FB}/SI_{RB} and SI_{FB}/SP_{RB} Pairs

To ensure the identical reconstruction at switching pairs, this section provides a detailed description of how to encode the SP_{FB}/SI_{RB} and SI_{FB}/SP_{RB} pairs. Figure 5(a) shows the encoding processes of SP_{FB} at frame n (SP_{FB,n}) and its corresponding SI_{RB} (SI_{RB,n}). Similar to SP-frame encoding [23, 24], some additional quantization processes are required. For the sake of convenience, we use the superscript r to denote the reconstructed frame or the reconstructed prediction error, and the capital letter with superscript Q_p or Q_s to represent the coefficients in quantized transform domain with the quantization level Q_p or Q_s respectively for the rest of this paper.

A predicted frame is formed by motion-compensated prediction using the original frame n ($O_{FB,n}$) in the FB and

Figure 4 Structure of the proposed dual bitstreams with SP/SI-frame pairs.

Figure 5 Encoding and decoding of an SP_{FB}/SI_{RB} pair. (a) SP_{FB} and SI_{RB} encoding, (b) SP_{FB} decoding, and (c) SI_{RB} decoding.

the previously reconstructed frame $n-1$, $P_{FB,n-1}^r$, stored in the frame buffer. It can be written as $Interpred(P_{FB,n-1}^r, mv_{FB,n})$ where $Interpred(\cdot)$ is the motion-compensated prediction operator and $mv_{FB,n}$ represents the set of motion vectors of frame n in FB. The prediction error $e_{FB,n}$ between $O_{FB,n}$ and its prediction is

$$e_{FB,n} = O_{FB,n} - Interpred(P_{FB,n-1}^r, mv_{FB,n}) \quad (1)$$

Performing the transformation and quantization on $e_{FB,n}$ with Q_p , we get

$$E_{FB,n}^{Q_p} = Q_p(T(e_{FB,n})) \quad (2)$$

$E_{FB,n}^{Q_p}$ is then compressed into the bitstream $VLC(E_{FB,n}^{Q_p})$ with entropy coding. The above encoding process is exactly the same as normal P-frame encoding. To generate $SP_{FB,n}$,

an additional quantization process is applied to the P-frame. This additional quantization process ensures that the transform coefficients of the reconstructed frame $SP_{FB,n}^r$ can be quantized and de-quantized without loss at the quantization level Q_s , which is going to be used in the encoding process of $SI_{RB,n}$. Note that the server using the proposed dual-bitstream system with SP/SI-frames still stores $VLC(E_{FB,n}^{Q_p})$ instead of the bitstream generated by $SP_{FB,n}$. This $E_{FB,n}^{Q_p}$ can be used to generate $SP_{FB,n}^r$ in the local decoder loop of the SP-frame encoder as well as the decoder. In the following, we will describe how to generate $SP_{FB,n}^r$ which is used to update the frame buffers in both encoder and decoder to act as a reference for the next P-frame.

Before performing an additional quantization process on the P-frame, the reconstructed prediction error $e_{FB,n}^r$ are obtained by applying dequantization with the quantization level Q_p and then inverse transformation on $E_{FB,n}^{Q_p}$.

$$e_{FB,n}^r = T^{-1}\left(Q_p^{-1}\left(E_{FB,n}^{Q_p}\right)\right) \quad (3)$$

The reconstructed prediction error $e_{FB,n}^r$ is then added to $Interpred\left(P_{FB,n-1}^r, mv_{FB,n}\right)$ for computing the reconstructed P-frame $P_{FB,n}^r$, which can be written as

$$P_{FB,n}^r = e_{FB,n}^r + Interpred\left(P_{FB,n-1}^r, mv_{FB,n}\right) \quad (4)$$

$P_{FB,n}^r$ is then transformed again and the transform coefficients of $P_{FB,n}^r$ is quantized using the quantization level Q_s . The quantized transform coefficients of $P_{FB,n}^r$ become

$$SP_{FB,n}^{Q_s} = Q_s\left(T\left(P_{FB,n}^r\right)\right) \quad (5)$$

After performing dequantization with Q_s and inverse transformation on $SP_{FB,n}^{Q_s}$, we obtain an expression of the reconstructed frame $SP_{FB,n}^r$.

$$SP_{FB,n}^r = T^{-1}\left(Q_s^{-1}\left(SP_{FB,n}^{Q_s}\right)\right) \quad (6)$$

This reconstructed frame $SP_{FB,n}^r$, which is stored in the frame buffer of the encoder, acts as a reference frame for the next P-frame. Equations 5 and 6 indicate that the transform coefficients of $SP_{FB,n}^r$ can be quantized and de-quantized without loss at the quantization level Q_s . These represent the fundamental ideas of SP/SI-encoding to

ensure identical reconstruction of $SI_{RB,n}$ even when different predictions are used.

The decoding process of $SP_{FB,n}^r$ is shown in Fig. 5(b) in which $VLC(E_{FB,n}^{Q_p})$ is an input bitstream. The decoder actually is the local decoder loop of the encoding process for $SP_{FB,n}$ as shown in Fig. 5(a). Its decoding operation follows Eqs. 3–6. Finally, an identical $SP_{FB,n}^r$ to the encoder is reconstructed to update the frame buffer in the decoder which is used for decoding the next P-frame.

In order to avoid the problem of reference mismatch due to the replacement of $SP_{FB,n}^r$ with $SI_{RB,n}^r$, the reconstructed frame $SI_{RB,n}^r$ at frame n in the RB must be identical to $SP_{FB,n}^r$ in the FB. To achieve this, the quantized values of transform coefficients in both $SP_{FB,n}^r$ and $SI_{RB,n}^r$ must be synchronized to the same quantization level Q_s . By using the same encoder as shown in Fig. 5(a), $SP_{FB,n}^{Q_s}$ acts as an input instead of the original video frame in the RB, and the quantization operation is processed before calculating the prediction error of $SI_{RB,n}$, $EI_{RB,n}^{Q_s}$, which can be computed as

$$EI_{RB,n}^{Q_s} = SP_{FB,n}^{Q_s} - Q_s\left(T\left(Intrapred\left(SI_{RB,n}^r, Intra_Mode_{RB,n}\right)\right)\right) \quad (7)$$

where $Intrapred(\)$ is the intra-prediction operator and $Intra_Mode_{RB,n}$ represents Intra prediction modes. For coding $SI_{RB,n}$, the prediction is formed by using the intra-prediction modes from previously decoded samples of the reconstructed frame. Again the encoder compresses in the bitstream $VLC(EI_{RB,n}^{Q_s})$ with entropy coding. Since the same quantization level Q_s are used for $SP_{FB,n}^{Q_s}$ and $Q_s\left(T\left(Intrapred\left(SI_{RB,n}^r, Intra_Mode_{RB,n}\right)\right)\right)$ in Eq. 7, $EI_{RB,n}^{Q_s}$ is also synchronized at Q_s and then it can be quantized and de-quantized without any loss at Q_s .

By decoding the bitstream $VLC(EI_{RB,n}^{Q_s})$ in the decoder, the identical reconstruction to $SP_{FB,n}^r$ can be obtained as explained below. First, the transformed and quantized coefficients of different predictions will not introduce any mismatch, that is, the value at position C in the encoder and at position D in the decoder (Fig. 5(c)) are exactly the same. In other words, both positions C and D can create the prediction $Q_s\left(T\left(Intrapred\left(SI_{RB,n}^r, Intra_Mode_{RB,n}\right)\right)\right)$. Second, this prediction in the decoder adds the entropy decoded $VLC(EI_{RB,n}^{Q_s})$ to generate the reconstructed SI-frame $SI_{RB,n}^r$, which is given by

$$SI_{RB,n}^r = T^{-1}\left(Q_s^{-1}\left(EI_{RB,n}^{Q_s} + Q_s\left(T\left(Intrapred\left(SI_{RB,n}^r, Intra_Mode_{RB,n}\right)\right)\right)\right)\right) \quad (8)$$

By putting (7) into (8), we obtain

$$SI_{RB,n}^r = T^{-1} \left(Q_s^{-1} \left(SP_{FB,n}^{Q_s} \right) \right) \quad (9)$$

Equations 5 and 6 indicate that $SP_{FB,n}^{Q_s}$ is synchronized at Q_s , Eq. 9 can be written as

$$SI_{RB,n}^r = SP_{FB,n}^r \quad (10)$$

Now $SI_{RB,n}^r$ of the RB is used to replace $SP_{FB,n}^r$ of the FB, which is needed during VCR operations. In this case, $SI_{RB,n}^r$ is a reference frame for decoding the next P-frame, and such replacement will not introduced any mismatch error, as shown in Fig. 6(a).

Figure 6(b) shows the SI_{FB}/SP_{RB} pair which is used for switching from the FB to the RB at frame n . In this case, the reconstructed frame of $SI_{FB,n}^r$ ($SI_{FB,n}^r$) in the FB is used to replace the reconstructed frame of $SP_{RB,n}^r$ ($SP_{RB,n}^r$) in the RB. To avoid the problem of reference mismatch, the replacement of $SP_{RB,n}^r$ with $SI_{FB,n}^r$ should not introduce any mismatch error.

For encoding $SI_{FB,n}^r$ of the SI_{FB}/SP_{RB} pair, it is similar to encode $SP_{FB,n}^r$ and the only difference is that $SI_{FB,n}^r$ does not use any reference frame. The macroblocks in $SI_{FB,n}^r$ are coded by using intra prediction, which means that in the encoding diagram as shown in Fig. 7(a), the prediction is generated by intra prediction from neighboring blocks. The prediction error between $O_{FB,n}$ and its intra prediction in the quantized transform domain, $EI_{FB,n}^{Q_p}$, is

$$EI_{FB,n}^{Q_p} = Q_p \left(T(ei_{FB,n}) \right) \quad (11)$$

where $ei_{FB,n} = O_{FB,n} - \text{Intrapred} \left(SI_{FB,n}^r, \text{Intra_Mode}_{FB,n} \right)$ and $\text{Intra_Mode}_{FB,n}$ is an intra-prediction modes of the current block. To achieve identical reconstruction, $SI_{FB,n}^r$ should be synchronized at the quantization level Q_s . To do so, the prediction error $ei_{FB,n}^r$ are firstly reconstructed and then added to the prediction again. It can be written as

$$I_{FB,n}^r = ei_{FB,n}^r + \text{Intrapred} \left(SI_{FB,n}^r, \text{Intra_Mode}_{FB,n} \right) \quad (12)$$

where $ei_{FB,n}^r = T^{-1} \left(Q_p^{-1} \left(EI_{FB,n}^{Q_p} \right) \right)$. The reconstructed frame $I_{FB,n}^r$ is then transformed and quantized with Q_s . The quantized transform coefficients of $SI_{FB,n}^r$ and its reconstructed frame $SI_{FB,n}^r$ are

$$SI_{FB,n}^{Q_s} = Q_s \left(T \left(I_{FB,n}^r \right) \right) \quad (13)$$

and

$$SI_{FB,n}^r = T^{-1} \left(Q_s^{-1} \left(SI_{FB,n}^{Q_s} \right) \right) \quad (14)$$

respectively.

Figure 6 Frame replacement at (a) the SP_{FB}/SI_{RB} pair and (b) the SI_{FB}/SP_{RB} pair.

The lower part of Fig. 7(a) shows how to encode $SP_{RB,n}^r$ in the RB. The reference for which it uses is the reconstructed frame at frame $n+1$ ($P_{RB,n+1}^r$) in the RB and $SI_{FB,n}^{Q_s}$ acts as an input. Hence, the prediction error of $SP_{RB,n}^r$ in the quantized transform domain, $E_{RB,n}^{Q_s}$, is

$$E_{RB,n}^{Q_s} = SI_{FB,n}^{Q_s} - Q_s \left(T \left(\text{Interpred} \left(P_{RB,n+1}^r, mv_{RB,n} \right) \right) \right) \quad (15)$$

where $mv_{RB,n}$ is the motion vectors of frame n by using frame $n+1$ of the RB as the reference. This $E_{RB,n}^{Q_s}$ is then entropy encoded as $VLC(E_{RB,n}^{Q_s})$. The decoding processes of SI_{FB}/SP_{RB} pair are depicted in Fig. 7(b) and (c) which are quite similar to that of SP_{FB}/SI_{RB} pair. When the replacement of $SI_{FB,n}^r$ in the FB for $SP_{RB,n}^r$ in the RB is needed, the bitstream $VLC(E_{RB,n}^{Q_s})$ is decoded according to the block diagram in Fig. 7(c). Then $SP_{RB,n}^r$ is reconstructed as

$$SP_{RB,n}^r = T^{-1} \left(Q_s^{-1} \left(E_{RB,n}^{Q_s} + Q_s \left(T \left(\text{Interpred} \left(P_{RB,n+1}^r, mv_{RB,n} \right) \right) \right) \right) \right) \quad (16)$$

By using Eqs. 14 and 15, Eq. 16 can be further simplified as

$$SP_{RB,n}^r = SI_{FB,n}^r \quad (17)$$

This indicates that $SI_{FB,n}^r$ can exactly replace $SP_{RB,n}^r$ without any mismatch when switching from the FB to the RB is needed.

Figure 7 Encoding and decoding of an $\text{SI}_{\text{FB}}/\text{SP}_{\text{RB}}$. (a) SI_{FB} and SP_{RB} encoding, (b) SI_{FB} decoding, and (c) SP_{RB} decoding.

4 Experimental Results

In this section, we present some experimental results to evaluate the performance of the proposed dual-bitstream system. The H.264/AVC reference software JM [27] was employed to encode various video sequences with different spatial resolutions and motion characteristics. All test

sequences have a length of 200 frames. “Carphone” and “Claire” are typical videophone sequences in QCIF (176×144 pixels) format, while “Foreman”, “Football” and “Table Tennis” are in either CIF (352×288 pixels) format or SIF (352×240 pixels) format. For the original dual-bitstream system, each test sequence has been encoded into two bitstreams, FB and RB, and I-frames in the RB are

Table 1 Average PSNR and bitrate comparison for original and proposed dual-bitstream systems.

Sequences	Streams	Original		Proposed		Δ PSNR (dB)	Percentage increase in bitrate of the proposed system
		PSNR (dB)	Bitrate (kbits/s)	PSNR (dB)	Bitrate (kbits/s)		
Foreman (352×288)	FB	35.838	331.933	35.820	348.787	−0.017	5.08%
	RB	35.796	336.050	35.775	364.472	−0.021	8.46%
Football (352×240)	FB	33.461	946.258	33.459	961.187	−0.002	1.58%
	RB	33.432	938.954	33.433	967.981	0.001	3.09%
Table Tennis (352×240)	FB	32.824	528.680	32.805	545.380	−0.020	3.16%
	RB	32.644	530.878	32.709	564.649	0.065	6.36%
Claire (176×144)	FB	38.419	31.249	38.410	32.767	−0.009	4.86%
	RB	38.423	30.443	38.402	34.144	−0.022	12.16%
Carphone (176×144)	FB	35.537	93.846	35.524	97.141	−0.013	3.51%
	RB	35.534	93.469	35.500	103.368	−0.034	10.59%

interleaved between I-frames in the FB. Note that a total of 52 values of the quantization level are supported by the H.264 standard, indexed by a Quantization Parameter (QP) which is in the range of 0–51 and the quantization level doubles in size for every increment of 6 in QP. The wide range of the quantization levels makes it possible for an encoder to control the tradeoff accurately and flexibly between bit rate and quality. To encode the FB and the RB of the conventional system, QP was set to 30 for encoding I/P-frames. For all test sequences, the frame-rate of the video stream was 30 frames/s and the GOP length was fixed to 60 with an I-P structure.

Table 1 shows the PSNR and the bit rates of the FB and the RB for different sequences when the original system is used. In order to have a fair comparison between the original and proposed systems, we encoded the SP_{FB}/SI_{RB} and SI_{FB}/SP_{RB} pairs such that the reconstructed quality of the new dual bitstreams is similar to that of the original one. We also include in Table 1 the PSNR and the bit rates of different sequences when the new dual bitstreams are encoded using the proposed system. It can be observed in this table that the bitstream using SP/SI-frames have lower coding efficiency than the bitstream using P/I-frames. As a result, our system will introduce overhead in the bit rate, but it is not significant, especially in the normal playback. In this situation, only the FB is used and the increase in bit rate is fewer than 5.1%. Note, however, that the proposed dual-bitstream system provides better reconstruction quality for various VCR operations as discussed in the following.

Besides, we have also created the drift-compensated bitstreams [15] for the original dual-bitstream system. In [15], the drift compensation (DC) needs only to store the drift-compensated frames for all the I-frames of the dual bitstreams in order to reduce the storage requirement of the server. As mentioned before, since the coding efficiency of SP/SI-frames has lower than that of P/I-frames, our system

therefore introduces increase in the storage requirement (Δ bits), as shown in Table 2. But it is still smaller than that of the original system with DC.

Table 3 then gives our experimental results on the average PSNR for different systems on all possible switching points between the FB and the RB. It is clear that the original system introduces quality degradation as compared with the quality of the original FB or RB. This is due to the fact that an I-frame of the FB (RB) is used to approximate a P-frame of the RB (FB) at the moment of fast forward/reverse operations in the original system and this approximation leads to reference mismatch which affects the reconstructed quality of the next requested frame. However, the switching points of the proposed dual-bitstream system are at SI_{FB}/SP_{RB} and SP_{FB}/SI_{RB} pairs. These pairs can ensure identical frame reconstruction and no approximation is required. This means the reconstruction quality during the replacement of SP with SI is the same as that of the FB or RB. The advantage of the proposed system is indicated in the experimental results as shown in Table 3. This table shows that our proposed system has significant improvement over the original systems with and without DC for all video sequences.

Furthermore, for the original systems, the quality degradation will not only be confined to the frame at the

Table 2 Increases in the storage requirements of the original system with DC and the proposed system as compared to the original system.

Sequences	Original with DC	Proposed
Foreman	8.41%	6.78%
Football	2.62%	2.33%
Table Tennis	5.92%	4.76%
Claire	9.35%	8.46%
Carphone	8.74%	7.04%

Table 3 Average PSNR performance for conventional and proposed dual-bitstream systems on every possible switching between the FB and RB.

Sequences	Original		Original with DC (PSNR gain over original without DC)		Proposed (PSNR gain over original without DC)	
	FB→RB	RB→FB	FB→RB	RB→FB	FB→RB	RB→FB
Foreman	34.475	34.686	35.469 (0.994)	35.587 (0.901)	35.733 (1.258)	35.784 (1.098)
Football	33.107	33.212	33.372 (0.265)	33.649 (0.437)	33.850 (0.743)	33.916 (0.704)
Table Tennis	32.176	32.335	32.524 (0.348)	32.816 (0.481)	32.894 (0.718)	32.988 (0.653)
Claire	37.516	37.324	37.985 (0.469)	38.269 (0.945)	38.175 (0.659)	38.587 (1.264)
Carphone	34.218	34.583	35.112 (0.894)	35.500 (0.917)	35.536 (1.318)	35.642 (1.059)

switching point but can propagate and be accumulated in the subsequent P-frames. Figure 8 shows the amount of drift in PSNR using the various systems for the “Football” sequence in the situation where the fast-reverse mode is initially operated and subsequently a normal-play request is launched. Assume that the user requests a normal-play request at the start of each GOP in the RB. In this case, it has the longest drift propagation. This figure shows that drift caused by the I-to-P approximation of the original system is very serious and lasts until the next I-frame in the FB. Although the system with DC can reduce drift propagation, it still happens. As expected, our proposed system does not introduce any drift and it follows the same PSNR of the FB and the RB. This result indicates that the visual quality of the reconstructed frames in the proposed system for various VCR operations is exactly identical to that of the normal playback.

5 Conclusions

In this paper, we propose to adopt the concept of SP/SI-frame coding to improve the performance of the dual-bitstream system which has been proven to be an efficient approach for providing VCR functionality in video streaming. The original dual-bitstream system stores a forward-encoded bitstream (FB) and a reverse-encoded bitstream (RB) in the server in order to reduce the requirement of

network bandwidth significantly. However, a mismatch between encoding the FB and RB incurs. This induces the problem of drift when the I-to-P approximation is used for fast-forward and fast-reverse playbacks. Therefore, our novel dual-bitstream system is aimed at avoiding the problem of reference mismatch when a frame in the RB (FB) is selected as a reference for a frame in the FB (RB). The proposed system modifies the dual bitstreams using the main feature of SP/SI-frames which can provide an identical reconstruction even when different reference frames are used for prediction. To utilize this property, SP_{FB}/SI_{RB} and SI_{FB}/SP_{RB} pairs are added in the structure of dual bitstreams and this arrangement ensures that the I-to-P approximation will not happen in our system for various VCR operations. Consequently, the new dual-bitstream system will not cause any mismatch at the decoder side and the quality of reconstructed frames can be maintained. Besides, we have also shown how SP_{FB}/SI_{RB} and SI_{FB}/SP_{RB} pairs can be encoded such that identical frames can be reconstructed even when an SI-frame of one bitstream is used to replace an SP-frame of the other bitstream in any VCR operation. Experimental results show that the visual quality of all reconstructed frames in our new system for various VCR operations will be exactly the same as that of normal playback. Therefore, the proposed dual-bitstream system with SP/SI-frames is a promising solution for H.264 video streaming with VCR functionality.

Figure 8 Drift in PSNR of difference systems for the “Football” sequence. Negative value means PSNR drop of the reconstructed frame for the VCR operation as compared with that for the normal playback.

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