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REVERSE-PLAY TECHNIQUE ON COMPRESSED VIDEO ACROSS GOP BOUNDARIES

Chang-Hong Fu and Yui-Lam Chan
Centre for Signal Processing
Department of Electronic and Information Engineering
The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
enchfu@polyu.edu.hk and enylchan@polyu.edu.hk

ABSTRACT

In modern video coding standards, they are mainly designed for normal forward playback. Recently, we have developed a macroblock-based reverse-play scheme for compressed video bitstreams. By exploiting the motion relationship between two adjacent frames, this scheme can significantly reduce the requirements on the decoder complexity and network bandwidth during reverse playback. However, the MB-based technique does not works well on traversing GOP boundaries reversely since no inter-frame prediction takes place between the last frame of one GOP and the first frame of its succeeded GOP. In this paper, by utilizing a new SP picture type in the H.264, we can solve the GOP discontinuity problem by building linkages across GOP boundaries. Instead of arranging the primary SP-frame before the I-frame, a novel scheme is proposed to allocate various macroblocks within the GOP to be encoded as the SP type. This new arrangement for SP coding is specially designed for our macroblock-based reverse-play scheme and can be proved to eliminate the possible mismatch effect for reverse playback across GOP boundaries. With this allocation strategy, results from our experimental work confirm that the inherent GOP discontinuity problem can be avoided without introducing any mismatch between forward and reverse playback.

Index Terms: Video cassette recording (VCR), reverse playback, H.264 video, GOP boundary.

1. INTRODUCTION

For video browsing in today's Internet [1], it is desirable that interactive browsing can be provided at reasonable cost. Nevertheless, the current video standards such as H.264 [2] were mainly designed for encoding digital video in forward order which complicates reverse playback. Recently, some approaches have been proposed to support reverse playback for compressed video bitstreams [3-6]. The approach in [3] requires extra decoder complexity to perform the P-to-I conversion and higher storage cost to store the local bitstream in the client. In [4-5], the reverse transcoding process requires much computation in the server. In [6], a dual-bitstream approach was proposed. However, they approximately double the storage requirement of the server.

Recently, by exploring the motion relationship between two adjacent frames, a macroblock-based (MB-based) scheme [7] has been designed for efficiently implementing the reverse playback on compressed video bitstreams. Assume that MB_n^i represents the i^{th} MB in frame *n* and its corresponding motion vector is $mv_{n-1\to n}^i$, where frame *n* and frame *n-1* is the current frame and the reference frame respectively. With the motion vectors, the video server classifies MB_n^i into two categories – backward MBs (BMBs) and forward MBs (FMBs). A MB in frame *n* is defined as a BMB if its co-located MB in frame *n+1* is coded with zero motion vector, e.g. MB_n^i and MB_n^{i+2} in Figure 1. Otherwise, it is defined as a FMB, such as MB_n^{i+1}. For BMBs such as MB_n^i, it can be written as

$$MB_n^i = MB_{n+1}^i + (-e_{n+1}^i) \tag{1}$$

where e_{n+1}^i is the prediction error between MB_{n+1}^i and MB_n^i. Since pixels of MB_{n+1}^i have been already available at the decoder when the reverse-play operation is requested at frame *n+1*. From (1), the data required for the reconstruction of MB_n^i is $-e_{n+1}^i$, which can be extracted from the video bitstream, where $VLC\{Q[T(e_{n+1}^i)]\}$ exists. Since (1) does not hold true for FMBs, all the MBs related to FMBs from the previous nearest I-frame to frame *n* need to be sent.

This sign inversion scheme can significantly reduce the required decoding complexity and network bandwidth during reverse playback without introducing additional storage in the server. However, it suffers from one drawback. Since there is no inter-frame prediction between the last frame of one GOP and the first frame of its succeeded GOP, the motion relationship disappears and thus this technique cannot be applied in GOP boundaries, for instance, frame *L-1* and frame *L* in Figure 1. These high bitrate peaks in streaming video might result in dropped packets, which then causes jerky video during reverse playback.

In this paper, a novel scheme is proposed to cope with the GOP discontinuity problem of the H.264 bitstream by linking the boundary of two adjacent GOPs. The organization of this paper is as follows. In Section 2, various solutions for establishing the missing linkages across GOP boundaries are then proposed. Simulation results are presented in Section 3. Finally, some concluding remarks are provided in Section 4.

2. ESTABLISHMENT OF LINKAGES ACROSS GOP BOUNDARIES IN THE MB-BASED REVERSE-PLAY SCHEME

In order to establish the linkage between adjacent GOPs, e.g. frame *L-1* (P_{L-1}) and frame *L* (I_L), one possible way is to re-encode frame *L-1* as P'_{L-1} which uses I_L as the reference. As we know, due to the different reference frame of P_{L-1} and P'_{L-1}, there is mismatch between P_{L-1} and P'_{L-1} and it would not only be confined to a single frame but further propagate to frame *L-2* due to the use of sign inversion technique [7] for reverse playback.

2.1 The use of SP-frames across GOP boundaries

An SP-frame is a new picture type supported by H.264 for drift-free switching between compressed video bitstreams of different bit rates to accommodate the bandwidth variation [8-9]. The merit of SP-frames is to allow an identical reconstruction of the frames even when different reference frames are used for prediction. This property motivates us to adopt SP-frames across GOP boundaries for the linkage establishment between adjacent GOPs, as shown in Figure 2. In principle, SP-frames are encoded in pairs – a primary SP-frame and a secondary SP-frame. In Figure 2 , PSP_{L-1} is a primary SP-frame at frame *L-1* and it is encoded by using frame *L-2* as the reference. On the other hand, SSP_{L-1} is its corresponding secondary-SP frame predicted from I_L and this secondary SP-frame is decoded when reverse playback traverses the GOP boundary. The coding of PSP_{L-1} and SSP_{L-1} ensures that same reconstructed values of frame *L-1* be obtained for playing in both forward and backward directions.

The way to encode the i^{th} MB of PSP_{L-1}, $PSPMB^i_{L-1}$, is similar to that of a P-frame. First, the original MB^i_{L-1}, O^i_{L-1}, is coded in the same way as a normal P-macroblock. The pixel values of MB^i_{L-1} can be represented by

$$MB^i_{L-1} = MCMB_{L-2}(mv^i_{L-2\to L-1}) + T^{-1}\{Q_P{}^{-1}\{Q_P[T(O^i_{L-1} - MCMB_{L-2}(mv^i_{L-2\to L-1}))]\}\} \quad (2)$$

where $MCMB_{L-2}(mv^i_{L-2\to L-1})$ represents the motion-compensated MB of MB^i_{L-1} which is translated by the motion vector $mv^i_{L-2\to L-1}$ in frame *L-2*. For primary SP-frame encoding, additional transform/quantization and dequantization/inverse transform steps with the quantization level Q_S (enclosed within the dotted line in Figure 3 (a)) are performed on MB^i_{L-1}. These additional steps are required to avoid mismatch when different reference frames are used for reconstructing frame *L-1*, and a more detailed treatment of the additional quantization process can be found in [8-9]. The i^{th} MB of PSP_{L-1}, $PSPMB^i_{L-1}$, is then stored in the frame buffer, and can be written as

$$PSPMB^i_{L-1} = T^{-1}\{Q_S{}^{-1}\{Q_S[T(MB^i_{L-1})]\}\} \quad (3)$$

To encode the corresponding MB in SSP_{L-1}, $SSPMB^i_{L-1}$, $Q_S[T(MB^i_{L-1})]$ is taken from the primary SP encoder as the input data of the secondary SP encoder, as depicted in Figure 3(b). Its motion-compensated MB from frame I_L, $MCMB_L(mv^i_{L-1\leftarrow L})$, is also transformed and quantized using Q_S before generating the prediction error with $Q_S[T(MB^i_{L-1})]$. Note that $mv^i_{L-1\leftarrow L}$ is the motion vector of $SSPMB^i_{L-1}$ by using I_L as the reference. The prediction error in the quantized transform domain ($SSPE^i_{L-1}$) can then be computed as

$$SSPE^i_{L-1} = Q_S[T(MB^i_{L-1})] - Q_S\{T[MCMB_L(mv^i_{L-1\leftarrow L})]\} \quad (4)$$

which is then entropy encoded as its binary representation $(VLC(SSPE^i_{L-1}))$. Both $Q_S[T(MB^i_{L-1})]$ and $Q_S\{T[MCMB_L(mv^i_{L-1\leftarrow L})]\}$ are thus synchronized to Q_S and there is no further quantization from this point. It means that $SSPE^i_{L-1}$ is also synchronized to Q_S. On traversing the GOP boundary reversely, the decoder receives $VLC(SSPE^i_{L-1})$ with $mv^i_{L-1\leftarrow L}$. Besides, I_L is already in the decoder buffer, $Q_S\{T[MCMB_L(mv^i_{L-1\leftarrow L})]\}$ is then generated in the same way as the encoder and summed up with $SSPE^i_{L-1}$, as shown in Figure 3(c). After dequantization and inverse transformation, $SSPMB^i_{L-1}$ can be obtained as

$$SSPMB^i_{L-1} = T^{-1}\{Q_S^{-1}\{Q_S\{T[MCMB_L(mv^i_{L-1\leftarrow L})]\} + SSPE^i_{L-1}\}\} \quad (5)$$

Substituting (4) into (5), we obtain

$$SSPMB^i_{L-1} = T^{-1}\{Q_S{}^{-1}\{Q_S[T(MB^i_{L-1})]\}\} \quad (6)$$

From (3) and (6), we can conclude that

$$SSPMB^i_{L-1} = PSPMB^i_{L-1} \quad (7)$$

In this way, when the reverse playback traverses the GOP boundary as shown in Figure 2, after displaying frame *L*, $VLC(SSPE^i_{L-1})$ and $mv^i_{L-1\leftarrow L}$ are going to be transmitted and decoded to reconstruct pixel values of SSP_{L-1}, which is exactly equal to that of PSP_{L-1}. This means that the mismatch between the forward and reverse playback at frame *L-1* can be eliminated due to the use of SP-frames at the GOP boundary.

Although this coding arrangement can achieve identical reconstruction of frame *L-1* for forward and reverse playback, it will lead to quality degradation of each MB in reverse playback as compared with the MB which is P-frame encoded. For example, consider the i^{th} MB of frame *L-1* as shown in Figure 2. If frame *L-1* is encoded as an SP-frame, during reverse playback across the GOP boundary, $SSPMB_{L-1}^{i}$ is reconstructed as $T^{-1}\{Q_S^{-1}\{Q_S[T(MB_{L-1}^{i})]\}\}$. This signifies that $SSPMB_{L-1}^{i}$ is equal to $PSPMB_{L-1}^{i}$ instead of MB_{L-1}^{i}. In other words, the pixel values stored in the decoder buffer, $SSPMB_{L-1}^{i}$, is no longer equal to MB_{L-1}^{i}. On reconstructing frame *L-2* by adopting the sign inversion technique, (1) indicates that exact MB_{L-1}^{i} is required in the decoder buffer. Otherwise, the decoder encounters the mismatch problem between MB_{L-1}^{i} and $PSPMB_{L-1}^{i}$. This mismatch again introduces distortion of MB_{L-2}^{i} and will influence the quality of the subsequent P-frames within the same GOP for reverse playback. The extent of mismatch caused by the SP frame will be illustrated later in the experimental results.

2.2 The strategy of allocating PSPMBs

For reverse playback, the above discussion notifies that the sign inversion technique cannot be used for PSPMBs/SSPMBs due to the extra quantization. This means that the primary SP-frames and their corresponding secondary SP-frames placed before I-frames are not enough to achieve mismatch-free video reconstruction between forward and reverse playback after traversing GOP boundaries. Instead of arranging the primary SP-frame before the I-frame, we propose a novel strategy to allocate different PSPMBs within the GOP to cope with the mismatch problem.

From (3) and (6), it points out that (1) does not hold true for PSPMBs/SSPMBs. To avoid the mismatch due to use of the sign inversion technique in PSPMBs/SSPMBs, we make a special arrangement for SP coding. In the new arrangement, only the last BMB (in the backward direction) of the BMB chain is PSPMB-encoded. For illustration, Figure 4 shows the BMB chain at the ith position, in which it consists of three BMBs consecutively - MB_{L-2}^{i}, MB_{L-3}^{i}, and MB_{L-4}^{i}. Only the last BMB, MB_{L-4}^{i}, is allowed to be PSPMB-encoded ($PSPMB_{L-4}^{i}$). Since it is at the end of the BMB chain, MB_{L-5}^{i} in this example is a FMB and no sign inversion technique is applied to MB_{L-5}^{i} by using $PSPMB_{L-4}^{i}$. In other words, $PSPMB_{L-4}^{i}$ would not be used to reconstruct MB_{L-5}^{i} and the mismatch does not happen during reverse playback. Similarly, in Figure 4, MB_{L-2}^{i+2} is also PSPMB-encoded as $PSPMB_{L-2}^{i+2}$. On the other hand, no MB is encoded as PSPMB at the $i+1^{\text{th}}$ position since MB_{L-2}^{i+1} is already a FMB. This strategy for distributing PSPMBs in different frames within the same GOP can guarantee no mismatch to be appeared during reverse playback and the PSPMB-encoded MBs will have no influence on the use of the sign inversion technique.

In the following, we again use the MB at the i^{th} position as an example to provide a detailed formulation of how this strategy can provide mismatch-free solution. In this BMB chain, only MB_{L-4}^{i} is PSPMB-encoded as $PSPMB_{L-4}^{i}$ since it is the last BMB (in the backward direction). According to the encoding structure in Figure 3(a), MB_{L-4}^{i} needs to pass through extra quantization/dequantization and $PSPMB_{L-4}^{i}$ can be computed as

$$PSPMB_{L-4}^{i} = T^{-1}\{Q_S^{-1}\{Q_S[T(MB_{L-4}^{i})]\}\} \tag{8}$$

It is interesting to note that its subsequent co-located MBs in the forward direction (MB_{L-3}^{i}, MB_{L-2}^{i} and MB_{L-1}^{i}) are not necessary to be PSPMB-encoded. For instance, MB_{L-3}^{i} is encoded by using the normal P-frame encoding procedure. The prediction of MB_{L-3}^{i} is $PSPMB_{L-4}^{i}$ since the motion vector of MB_{L-3}^{i} is zero. MB_{L-3}^{i} can then be reconstructed as

$$MB_{L-3}^{i} = PSPMB_{L-4}^{i} + T^{-1}\{Q_P^{-1}\{Q_P[T(e_{L-3}^{i})]\}\} \tag{9}$$

where e_{L-3}^{i} is the prediction error between MB_{L-3}^{i} and $PSPMB_{L-4}^{i}$, and its prediction error coefficients are quantized and dequantized using the quantization level Q_P. These quantization/dequantization are the normal processes defined in the P-frame encoding. Similarly, MB_{L-2}^{i} and MB_{L-1}^{i} can be represented by

$$MB_{L-2}^{i} = MB_{L-3}^{i} + T^{-1}\{Q_P^{-1}\{Q_P[T(e_{L-2}^{i})]\}\} \tag{10}$$

and

$$MB_{L-1}^{i} = MB_{L-2}^{i} + T^{-1}\{Q_P^{-1}\{Q_P[T(e_{L-1}^{i})]\}\} \tag{11}$$

respectively. Putting (9) – (10) into (11), it becomes

$$MB_{L-1}^{i} = PSPMB_{L-4}^{i} + \sum_{k=1}^{3} T^{-1}\{Q_P^{-1}\{Q_P[T(e_{L-k}^{i})]\}\} \tag{12}$$

Performing the transformation on both sides and taking into account the linearity of transformation, (12) can be re-written as

$$T(MB_{L-1}^{i}) = T(PSPMB_{L-4}^{i}) + \sum_{k=1}^{3} Q_P^{-1}\{Q_P[T(e_{L-k}^{i})]\} \tag{13}$$

Referring to (8), we see that the transform coefficients of the first term in the right-hand side of (13), i.e. $T(PSPMB_{L-4}^{i})$, is divisible by Q_S. On the other hand, $\sum_{k=1}^{3} Q_P^{-1}\{Q_P[T(e_{L-k}^{i})]\}$ in (13) is only divisible by Q_P. If we set $Q_S = Q_P$ during SP-frame encoding, the terms inside the summation in (13) are also divisible by Q_S. Therefore, $T(MB_{L-1}^{i})$ is now divisible by Q_S if Q_S is set to Q_P. The divisibility of Q_S in $T(MB_{L-1}^{i})$ provides the fundamental for solving the mismatch problem for reverse playback across GOP boundaries. Note that, as comparing to the SP-frame arrangement mentioned in Section 2.1, $T(MB_{L-1}^{i})$ in (2) is impossible to be divisible by Q_S since the motion-compensated MB in the transform domain $T[MCMB_{L-2}(mv_{L-2\rightarrow L-1}^{i})]$ in (2) is not divisible by Q_S.

Figure 4 also shows SSP_{L-1} which is necessary to build the linkage between two successive GOPs. To reconstruct $SSPMB_{L-1}^{i}$ during reverse playback, $SSPE_{L-1}^{i}$ is required. In the proposed primary and secondary SP-frame coding arrangement, the PSPMBs and SSPMBs are no longer at the same frame. For instance, at the i^{th} MB in Figure 4, $PSPMB^i_{L-4}$ is at frame *L-4* while $SSPMB^i_{L-1}$ is at frame *L-1*. From (4), $SSPE^i_{L-1}$ can be generated by computing the difference between $Q_S[T(MB^i_{L-1})]$ and $Q_S\{T[MCMB_L(mv^i_{L-1\leftarrow L})]\}$. Again, $SSPE^i_{L-1}$ is synchronized to Q_S. According to (6), during traversing across the GOP boundary in reverse frame order, the decoder with I_L, $SSPE^i_{L-1}$, and $mv^i_{L-1\leftarrow L}$ can perfectly reconstruct $SSPMB^i_{L-1}$ as $T^{-1}\{Q_S^{-1}\{Q_S[T(MB^i_{L-1})]\}\}$. From (13), since all transform coefficients in $T(MB^i_{L-1})$ are quantized and dequantized without loss at Q_S given $Q_S = Q_P$, the term $T^{-1}\{Q_S^{-1}\{Q_S[T(MB^i_{L-1})]\}\}$ is equal to MB^i_{L-1}. Therefore, we obtain

$$SSPMB^i_{L-1} = MB^i_{L-1} \tag{14}$$

As mentioned in Section 2.1, only $SSPMB^i_{L-1}$ is available in the decoder buffer after the reverse play traverses the GOP boundary. But now, $SSPMB^i_{L-1}$ in the buffer is exactly the same as MB^i_{L-1}. This means that the sign inversion technique can then be applied to reconstruct MB^i_{L-2} from $SSPMB^i_{L-1}$ without introducing any mismatch. During reverse playback, the sign inversion technique continues to be used until the last BMB of this chain. To reconstruct MB^i_{L-5}, the sign inversion technique is no longer applied since it is a FMB. Therefore, the mismatch does not happen although $PSPMB^i_{L-4}$ is not equal to MB^i_{L-4}, as formulated in (8).

By encoding the last BMB of the BMB chain to be PSPMB-encoded, ($PSPMB^i_{L-4}$ and $PSPMB^i_{L-2}$ in Figure 4), the linkage across the GOP boundary between frame *L* and frame *L-1* is established without mismatch. As shown in Figure 4, when reverse playback passes across the GOP boundary, $SSPMB^i_{L-1}$, MB'^{i+1}_{L-1}, and $SSPMB^{i+2}_{L-1}$ are transmitted and decoded as frame *L-1*. For $SSPMB^i_{L-1}$ and $SSPMB^{i+2}_{L-1}$, their decoded pixel values are the same as compared with MB^i_{L-1} and MB^{i+2}_{L-1} for forward play, as formulated in (14), which ensures that the sign inversion technique be applied on these MBs without any mismatch to further decode frame *L-2* during reverse play. In contrast, MB'^{i+1}_{L-1} is encoded as a normal P-macroblock. The decoded pixel values of MB'^{i+1}_{L-1} are thus not equal to MB^{i+1}_{L-1}. This will not introduce mismatch for reverse playback since there is no BMB at this position, and the sign inversion technique will not be used for MB^{i+1}_{L-2}. Therefore, the mismatch between MB^{i+1}_{L-1} and MB'^{i+1}_{L-1} has no influence on reverse playback. Although MB^{i+1}_{L-1} and MB'^{i+1}_{L-1} can be encoded as $PSPMB^{i+1}_{L-1}$ and $SSPMB^{i+1}_{L-1}$, respectively, to avoid mismatch, it is not necessary for the sake of better performance for forward playback. It is due to the fact that the additional quantization step with Q_S introduces quality degradation of MB^{i+1}_{L-1} during forward playback.

3. SIMULATION RESULTS

In this section, we evaluate the performances of various methods for linkage establishment across GOP boundaries. H.264 JVT JM 10.1 encoder [10] was employed to encode various sequences with different spatial resolutions and motion characteristics. All the test sequences have a length of 100 frames. “Claire”, “Carphone”, and “Foreman” are typical videophone sequences in QCIF (*176×144 pixels*) format. “Tabletennis” and “Football” are in SIF (*352×240* pixels) format. For all testing sequences, the frame-rate of the video stream was *30* frames/s and the GOP size was 15.

Tested schemes include the conventional scheme, the recently developed sign inversion (SI) scheme [7] and two varieties for building linkages across GOP boundaries, called Link-SP and Link-PSPMB. Link-SP uses SP-frames for building linkages across GOP boundaries. For Link-PSPMB, the proposed PSPMB allocation strategy suggested in Section 2.2 was adopted to avoid the mismatch problem. The starting point of the reverse-play is at the end of the sequence. The frame-by-frame comparison for sequence “Claire” is shown in Figure 5. It is obvious that the peaks caused by the last frame of GOP in SI can be smoothed away by using the proposed Link-SP and Link-PSPMB. Building the linkages across GOP boundaries is thus efficient in reducing burstiness of the network traffic and decoder complexity during reverse playback across GOP boundaries.

The mismatch between the forward and reverse playback for different schemes is shown in Figure 6. This figure shows that except the frames before I-frame, all frames cause serious quality degradation for reverse playback when Link-SP is employed. It is not unexpected since $SSPMB^i_{L-1}$ is equal to $PSPMB^i_{L-1}$ instead of MB^i_{L-1}, as illustrated in Figure 2. In this case, the sign inversion technique introduce mismatch for reconstructing frame *L-2*. This problem can be alleviated by using Link-PSPMB because $SSPMB^i_{L-1}$ is now equal to MB^i_{L-1} when the PSPMB allocation strategy is adopted. The degradation for SI and Link-PSPMB are almost the same since both of them will not introduce mismatch theoretically and the quality degradation comes only from the clipping and rounding operation of the H.264 video when the sign inversion technique is used [7]. Therefore, the proposed Link-PSPMB can avoid the quality degradation due to the adoption of PSPMB and SSPMB while smoothing out the burstiness of decoder complexity and network traffic.

4. CONCLUSION

In this paper, we have designed a technique to improve the MB-based reverse-play scheme for H.264 video bitstreams. Since the inter-frame dependency between the last frame of one GOP and the first frame of its succeeded GOP disappears, the sign inversion technique for the MB-based scheme cannot work well. As a result, when reverse playback traverses GOP boundaries, the required number of MBs to be decoded and the required number of bits to be sent increase significantly. In order to handle the GOP discontinuity of the video bitstream, SP-frames have been adopted to establish the missing linkage to a previous GOP thereby ensuring continuity of reverse playback across GOP boundaries. Through a novel arrangement of the PSPMBs inside the GOP, a new allocation strategy has been proposed to encode the last BMB of the BMB chain as PSPMB. This arrangement is able to ensure that the reverse playback retains nearly the same reconstruction quality as that of the forward playback. Experimental results show that the proposed algorithm can smooth out the burstiness of decoder complexity and network traffic which is beneficial to the MB-based reverse-play scheme.

6. ACKNOWLEDGEMENTS

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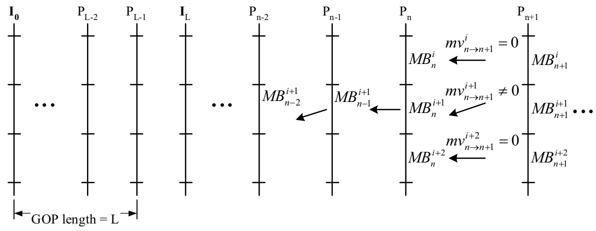

Figure 1. The MB-based scheme for reverse playback in [7].

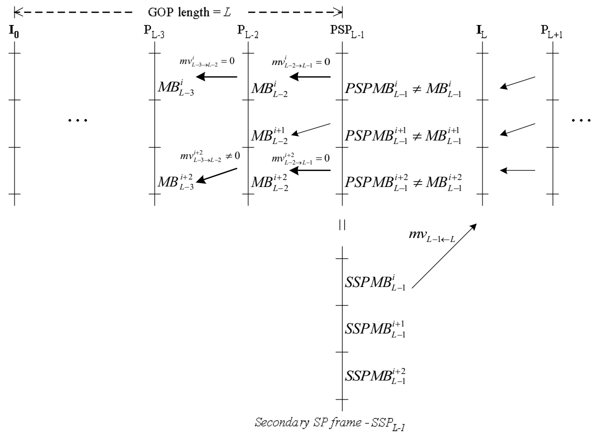

Figure 2. Establish the linkage across the GOP boundary by using SP frame.

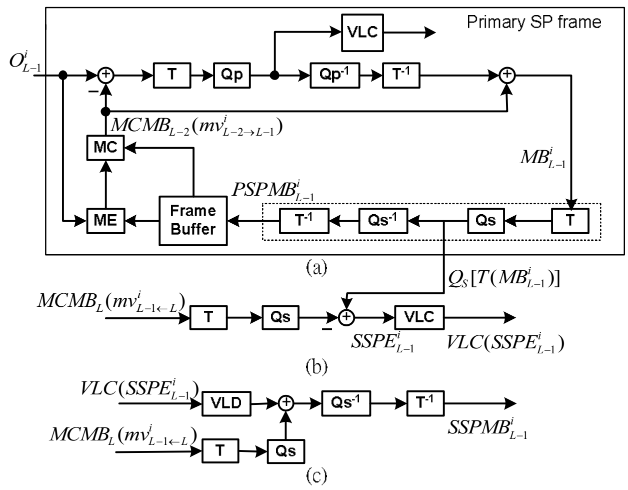

Figure 3. The block diagrams of (a) primary SP-frame encoding, (b) secondary SP-frame encoding, and (c) secondary SP-frame decoding.

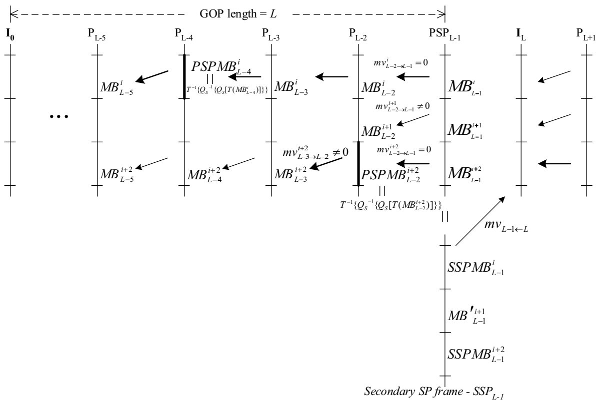

Figure 4. The strategy of allocating PSPMBs in the proposed scheme.

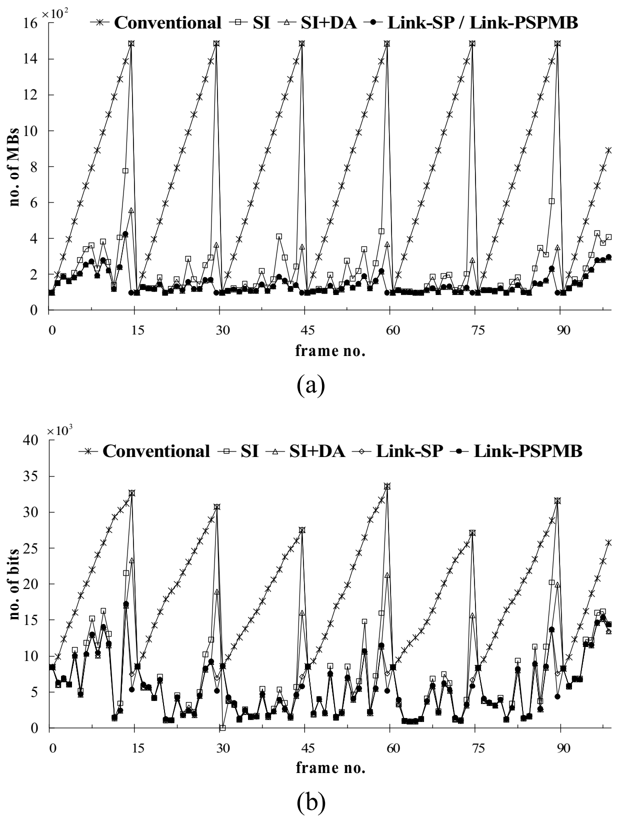

Figure 5. Performance of the conventional, SI, SI+DA, Link-SP, and Link-PSPMB schemes for the "Claire" sequence in the reverse playback. (a) Number of MBs to be decoded by the decoder, and (b) number of bits to be sent over the network.

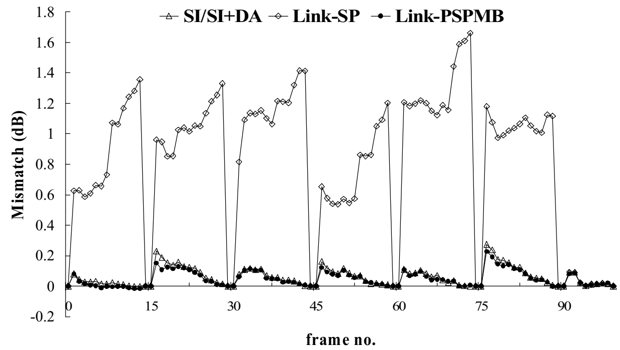

Figure 6. Mismatch between forward and reverse playback in terms of ΔPSNR for the "Claire" sequence.