Adaptive error-resilience transcoding using prioritized intra-refresh for video multicast over wireless networks

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Abstract

In this paper, we propose a two-pass error-resilience transcoding scheme based on adaptive intra-refresh for inserting error-resilience features to a compressed video at the intermediate transcoder of a three-tier streaming system. The proposed transcoder adaptively adjusts the intra-refresh rate according to the video content and the channel's packet-loss rate to protect the most important macroblocks against packet loss. In this work, we consider the problem of multicast of video to multiple clients having disparate channel-loss profiles. We propose a MINMAX loss rate estimation scheme to determine a single intra-refresh rate for all the clients in a multicast group. For the scenario that a quality variation constraint is imposed on the users, we also propose a grouping method to partition a multicast group of heterogeneous users into a minimal number of subgroups to minimize the channel bandwidth consumption while meeting the quality variation constraint. Experimental results show that the proposed method can effectively mitigate the error propagation due to packet loss as well as achieve fairness among clients in a multicast.
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1. Introduction

Transmitting video data over error-prone networks can be very unreliable due to packet loss, and still present many challenges to streaming video applications, especially for mobile video. In a non-live video streaming system, a server stores pre-encoded video bitstreams and transmits them to client terminals for decoding and playback. There are several existing video coding techniques developed to compress video sequences into bitstreams to reduce their data sizes. These video encoding techniques exploit spatial and temporal redundancy to achieve a high compression ratio, while making the compressed data very sensitive to transmission error. The packet-loss problem may lead to serious video quality degradation, which not only affects the quality of a corrupted frame, but also leads to error propagation to its subsequent frames due to the motion-compensated prediction technique used in standard video codecs. In practical applications

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where video contents are compressed and stored for future delivery, the encoding process is typically performed without enough prior knowledge about the channel characteristics of network hops between the encoder and the decoder. In addition, the heterogeneity of client networks also makes the encoder very difficult to adapt video contents to a wide range of different client channel conditions, especially for mobile client terminals. In order to achieve error robustness for transmitting video over wireless networks, the server located in an intermediate network node must be able to adapt or transcode the non-error-resilient compressed video bitstreams into error-resilience-capable bitstreams. To serve this purpose, a video transcoder can be placed in a network node (e.g., a mobile switch/base-station, a proxy server, or a video gateway) connected to a high-loss network (e.g., wireless network or highly congested network) to insert error-resilience features into the video bitstream to achieve robust video transmission over wireless channels [19,20].

A three-tier streaming system typically involves a streaming server, a media gateway (e.g., home server), and a number of client terminals (e.g., information appliances). In a home network, the communication links to heterogeneous client terminals may have different packet-loss characteristics and channel bandwidths, especially for mobile clients. The home server has to deploy different error-resilience features and regulate the bit-rate in order to match different channel characteristics. A transcoder [20,21] is usually located at the home server for adapting the incoming video bitstream to the varying channel conditions. Using the transcoder to handle the different demands (e.g., bandwidth, resolution, frame rate, and channel condition) from different client devices can reduce

the complexity and transmission cost from the streaming server to the home receivers. Fig. 1 shows the proposed error-resilience transcoder with feedback channels. The transcoder first extracts the video features (e.g., locations of video data that are likely to result in more serious error propagation if lost) from the incoming bitstream as well as estimates the client channel conditions according to the feedback channel statistics. The extracted features and the estimated channel condition are then used to guide the error-resilience transcoding policy that determines the allocation of source and channel coding resources. The features of video contents can also be pre-computed in the front-end encoding process and sent to the transcoder as auxiliary data (metadata) to assist the transcoding. In this work, we propose efficient error-resilience transcoding methods for such three-tier streaming architecture with the transcoder located at the home server for enhancing error robustness to video streams prior to delivering video data to the mobile users.

There have been a few research works about error-resilience video transcoding as surveyed in [19,20]. Intra-refresh [18,5,6,22,1] is one of the most commonly used error-resilience coding tools, because it does not need to make any change for standard video decoders, which is important in terms of cost and interoperability for many practical applications. Intra-refresh has therefore often been adopted in error-resilience transcoding. The content-based error-resilient coding (CBERC) scheme proposed in [1] takes video content into account in making intra-refresh decisions by using the zero-motion concealment error to identify important macroblocks. However, simply using error concealment error without considering motion information may not be able to capture the error-propagation
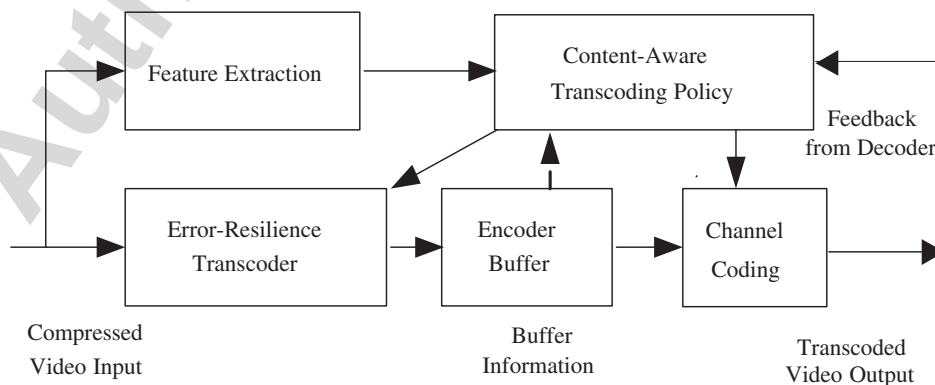

Fig. 1. Proposed system framework of error-resilience video transcoder.

effect very well. The method presented in [7] proposes a rate-distortion framework with analytical models that characterize the error propagation of corrupted video bitstream subjected to bit errors. These models are then used to guide the selection of spatial and temporal localization tools: synchronization marker and intra-refresh to achieve optimal combinations of spatio-temporal error resilience and transmission bit-rate under different conditions. Although the method achieves good performance, its computational complexity may be too high to meet real-time requirements. In [8], an error-resilience transcoder was proposed for general packet ratio services (GPRS) mobile-access networks. The transcoder is placed at a video proxy located at the edge of two or more networks. Two error-resilience tools: adaptive intra-refresh (AIR) and reference frame selection (RFS) with feedback control signaling (FCS), are exploited adaptively to reduce error effects, while preserving the transmission rate management feature of the video transcoders. In our previous work [4] a two-pass content-aware error-resilience transcoding scheme by using prioritized intra-refresh (CAIR) was proposed. The CAIR transcoder adaptively varies the intra-refresh rate according to the video content and the channel's packet-loss rate to protect the most important macroblocks against packet loss. In the off-line encoding process, the front-end encoder estimates the amount of error propagation at macroblock level, and then generates side information as transcoding hints for use at the transcoder. In real-time transcoding, the side information and the channel statistics are exploited to adaptively determine the intra-refresh rate and the locations of macroblocks to perform intra-refresh.

The problem of multicasting a video program to multiple clients with disparate channel-loss profiles is important and pratical. Cheung et al. [3] proposed a destination set grouping (DSG) protocol to improve inter-receiver fairness for multicast communication. The paper defined a single receiver fairness fuction that maps from the actual operating rate to a fairness value of users. The fairness function is in general application dependent. In [11] a single fairness function was also defined to deal with the inter-receiver fairness of receivers for multicast. The inter-receiver fairness was achieved by maximizing the weighted sum of the individual fairness values of receivers with different reception capabilities in a multicast group to perform max–min fair allocation. The method presented in [12] further extended the results in [11] to provide inter-session fairness among similarly controlled multicast sessions based on a specific two-group model. The method presented in [16] minimizes the maximum performance degradation for all users in video broadcasting. A gradient-based optimization scheme was proposed to find the optimal operating point. In our previous work [2], we proposed a MINMAX method to determine an appropriate intra-refresh rate in an error-resilience transcoder for the application scenario of video multicast with a single video bitstream. The proposed method was shown to reduce the mean and variance of PSNR distortion compared to three typical rate allocation methods: average, best case, and worst cast. In [15], in order to constrain the quality variation for a group of heterogeneous receivers, two multicast performance metrics, weighted average quality and MINMAX degradation, were evaluated. The proposed method dynamically adapts quantization parameters, intra frame rate, and channel coding rate to optimize a chosen multicast performance metric, based on the video quality curves achievable with different operating points for different possible channel conditions. However, how to select an applicable threshold to balance the fairness and the visual quality of users with various channel conditions was not yet well addressed.

In this paper, we propose a content-aware intra-refresh scheme with profit tracing to further improve the efficiency of intra-refresh allocation in our previous CAIR method [4]. Based on the prioritized intra-refresh scheme, we also propose efficient methods to cope with more general video multicasting situations involving heterogeneous clients with diverse channel conditions. As an extension of our work presented in [2], we propose a MINMAX loss rate estimation scheme to determine an appropriate intra-refresh rate for all the clients in a multicast group. We also propose a novel grouping method to partition a group of heterogeneous users into a minimal number of subgroups to meet a given quality variation constraint while minimizing the channel bandwidth consumption under the quality constraint.

The remainder of this paper is organized as follows. The proposed two-pass error-resilient transcoding scheme using prioritized intra-refresh with profit tracing is presented in Section 2. A MINMAX-based error-resilience transcoding strategy for video multicast in heterogeneous environments is proposed in Section 3. A grouping strategy

to divide a multicast group into smaller subgroups to meet the quality variation constraint is also presented. Section 4 shows experimental results. Finally the conclusions are drawn in Section 5.

2. Error-resilience transcoding using prioritized intra-refresh

Fig. 2 shows the proposed two-pass error-resilience transcoder architecture for home networking applications. At the first-pass front-end encoding, in addition to the standard encoding process, the encoder also utilizes the motion vectors generated in the encoding process and the estimated concealment distortion to evaluate the error-propa-

gation effect at the macroblock and frame levels within a GOP. The macroblocks are then ranked by the estimated amount of error propagation. As a result, the macroblock-level rank-order information and the frame-level error-propagation estimates are stored in the streaming server as the side information. This side information is sent to the intermediate transcoder as transcoding hints to guide the error-resilience transcoding operation while streaming the video to client terminals.

In the second-pass transcoding process, the transcoder uses the side information received from the streaming server and the channel statistics (e.g., the packet-loss rate) collected from a feedback channel to determine an intra-refresh allocation for

DCT : Discrete Cosine Transform
IDCT : Inverse Discrete Cosine Transform
Q : Quantization
IQ : Inverse Quantization

MC : Motion Compensation
MV : Motion Vector
F : Frame Memory
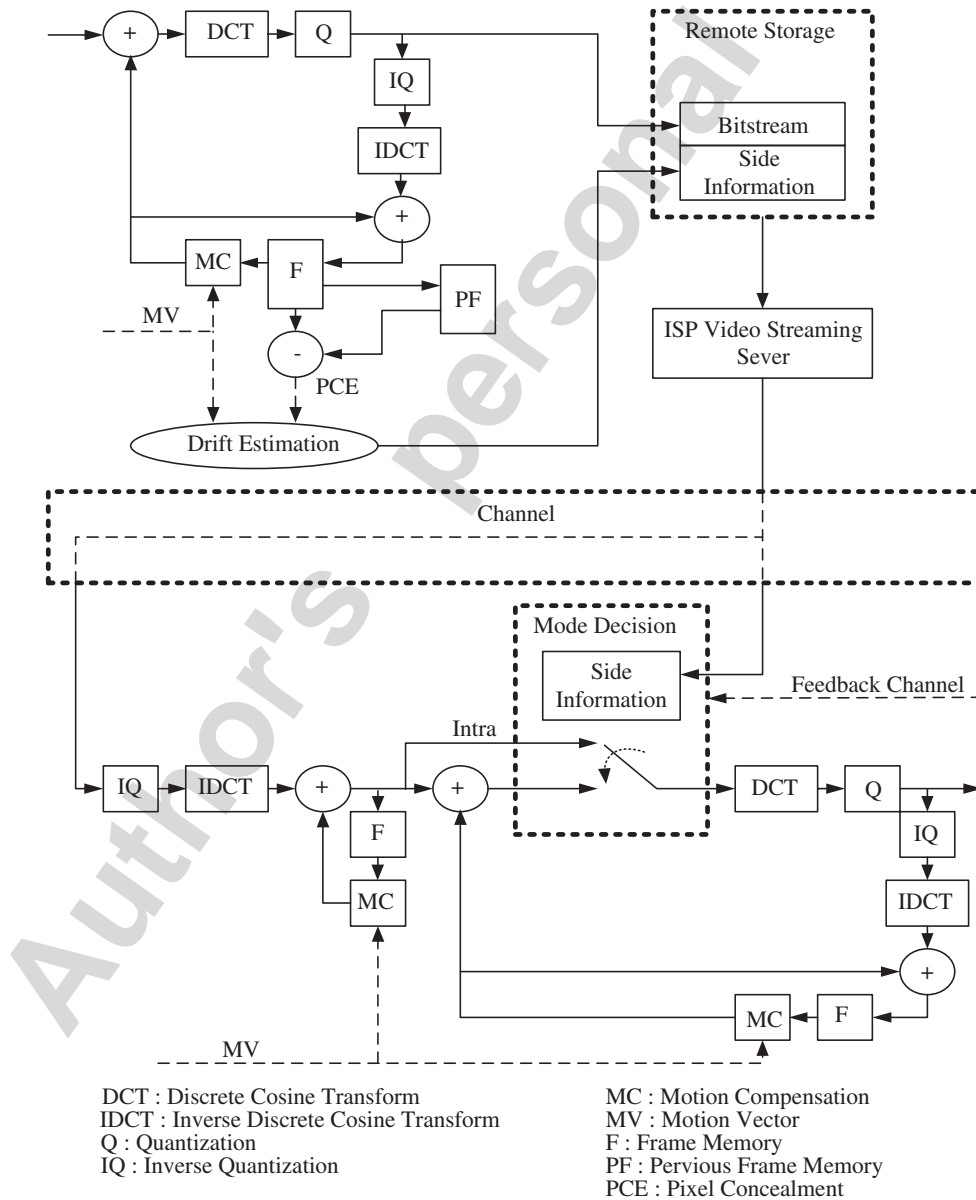PF : Pervious Frame Memory
PCE : Pixel Concealment

Fig. 2. Proposed architecture of two-pass error-resilience transcoder.

each frame of a GOP. The transcoder then performs intra-refresh on a number of high-priority macro-blocks with highest loss-impact factors according to the intra-refresh allocation. The key idea behind the proposed transcoding scheme is to stop the error propagation in the current frame by performing intra-refresh on those macroblocks which reference high loss-impact prediction blocks of the previous frame, thereby having a high possibility of being corrupted.

In the proposed scheme, most computation is done in the first-pass front-end encoding, which usually does not need to be done in real time for prerecorded video applications. Only a small amount of computation is left to the second-pass transcoding, which usually has to meet the real-time requirement. In the first-pass encoding, the major computation is to analyze the error-propagation effect using motion information and concealment error. The computational complexity for error-propagation estimation is relatively high, but usually can be done offline.

2.1. Estimation of loss impact

To estimate the error-propagation effect of a lost macroblock, we first define a pixel-level loss-impact (LI) metric as the product of two parameters: Pixel Reference Count (PRC) and Pixel Concealment Error (PCE), to characterize the amount of pixel-wise error propagation as follows:

$$LI(x, y, n) = PCE(x, y, n) \, PRC(x, y, n), \quad (1)$$

where $PRC(x,y,n)$ represents the frequency of pixel (x,y) in frame n being referenced by pixels in the succeeding frames within a GOP in the motion-compensated prediction process as illustrated in Fig. 3. It can be calculated recursively by summing up the individual reference counts of pixels in frame $n+1$ which reference the pixel (x,y) in frame n by tracking from the last frame back to the first frame of a GOP as follows:

$$PRC(x, y, n)$$
$$= \begin{cases} \sum_{(x',y',n+1) \text{ points to } (x,y,n)} PRC(x', y', n+1), & 1 \leqslant n < N_{GOP}, \\ 1, & n = N_{GOP}. \end{cases}$$
$$(2)$$

$PCE(x,y,n)$ denotes the norm of concealment error of pixel (x,y) of frame n should this pixel be corrupted:

$$PCE(x, y, n) = |f(x, y, n) - f(x, y, n - 1)|^2, \quad (3)$$

where $f(x, y, n)$ represents the pixel value of pixel (x, y) in frame n. In this work, the zero-motion error concealment scheme is adopted to compute the concealment error. More advanced spatio-temporal error concealment methods have been proposed, such as the side/boundary-match motion vector recovery scheme [18,13] and the model-based
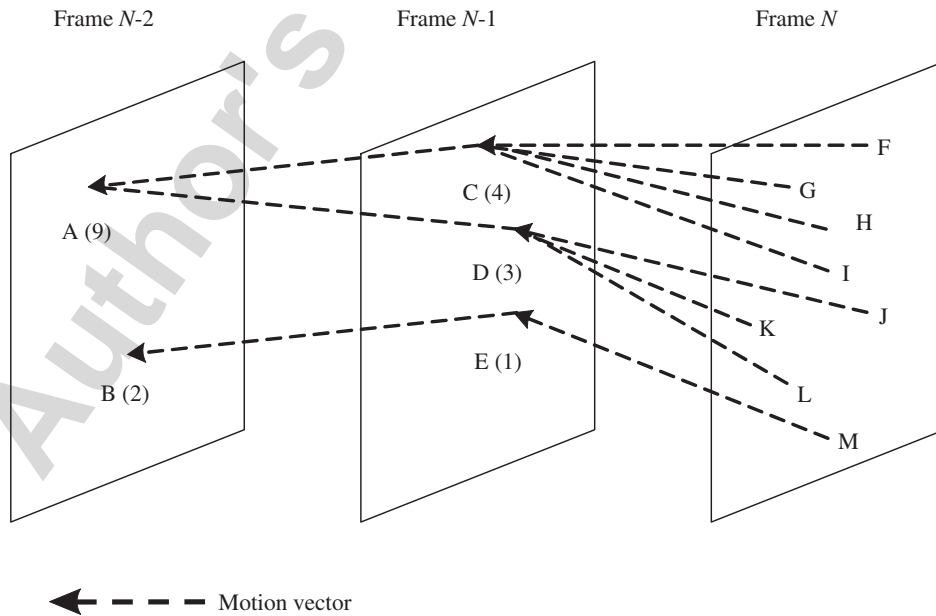

Fig. 3. An illustration of calculating the pixel reference count (PRC). Assume frame N is the last frame of a GOP, the number in the braces indicate the PRC of a pixel.

scheme presented in [17]. These methods can all substitute the zero-motion concealment scheme in CAIR-PT. However, in prestored video streaming applications, the off-line encoding process encoding process is typically performed without enough prior knowledge about what error concealment methods will be used in the decoders. Furthermore, different decoders in a multicast group may implement different error concealment schemes. The zero-motion error concealment scheme is a reasonable choice for evaluating the loss impact since it is considered the simplest error concealment scheme that is likely to be implemented in many decoders.

As depicted in Fig. 4, we then use the motion information to calculate the current frame's macro-block-level error propagation (from the previous frames) as follows:

$$\text{EP}_{\text{MB}}(m,n) = \sum_{(x,y)\in\text{MB}_m} \text{LI}(x + \text{MV}_x, y + \text{MV}_y, n-1), \tag{4}$$

where m denotes the macroblock index in a frame, n represents the time index, and $(\text{MV}_x, \text{MV}_y)$ represents the motion vector associated with pixel (x,y). Finally, all EP_{MB}'s in each frame are summed up to estimate the frame-level error propagation as follows:

$$\text{EP}_n = \sum_{m=1}^{N_{\text{MB}}^{\text{F}}} \text{EP}_{\text{MB}}(m,n), \tag{5}$$

where N_{MB}^{F} denotes the number of macroblocks in a frame. After obtaining the above features in the first-pass front-end encoding, EP_{MB}'s of macro-blocks and the frame-level EP_n are extracted and stored at the streaming server that will be sent to the intermediate transcoder as side information to enhance error resilience while streaming.

In this work, only the loss-impact values of the macroblocks belonging to P-frames need to be estimated, since a macroblock loss in a B-frame will not result in any error propagation outside this frame in most video coding standards. Moreover the loss-impact estimation of a macroblock is made based on the assumption that only the macroblock is lost in a GOP such that the corresponding macroblock in the previous frame can be decoded correctly and then used for the error concealment of this lost macroblock. It is difficult to make the estimation without this assumption. Since our prioritized intra-refresh scheme compares the "re-lative" loss-impact values of macroblocks in a GOP,

All pixel-level LI's in previous frame n-1

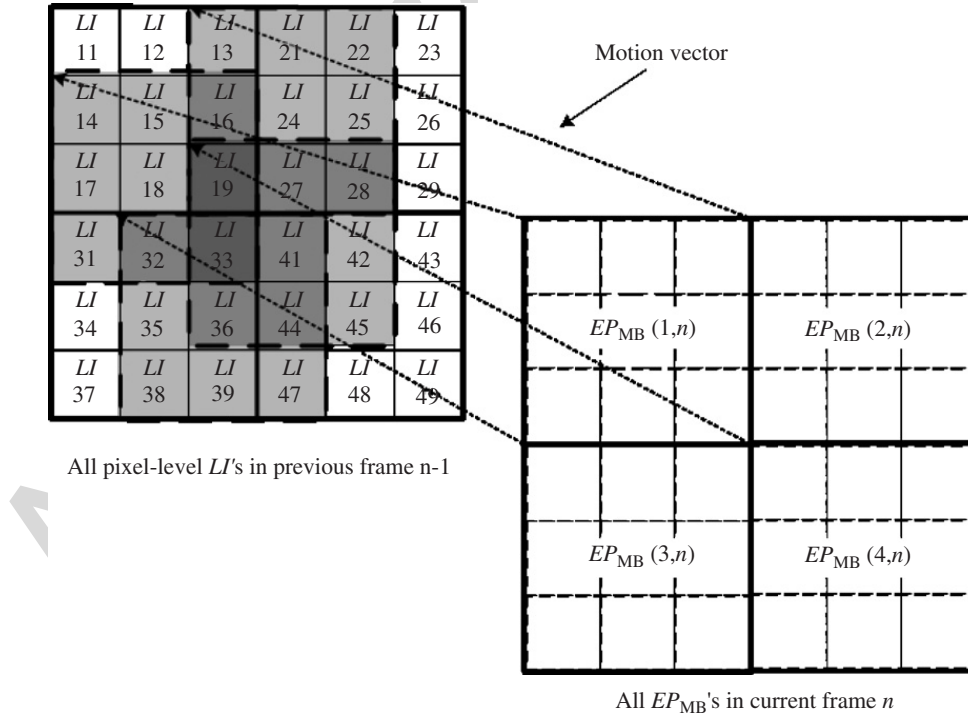All EP_{MB}'s in current frame n

Fig. 4. Illustration of using motion vectors to map pixel-level loss-impact values from the previous frame to obtain macroblock-level error-propagation impact values in the current frame.

accurate loss estimation may not be very important in our method.

2.2. Intra-refresh rate allocation of CAIR transcoding

In the second-pass transcoding, we propose a prioritized intra-refresh scheme to determine the intra-refresh rate and the intra-block allocation strategy for each GOP so as to adapt the transcoded video to varying network conditions. One key issue of the intra-refresh algorithm is to determine the number of macroblocks to be intra-coded in a GOP. We adopt the intra-refresh rate allocation scheme proposed in our previous work [4] as follows:

$$N_{\text{intra}}^{\text{GOP}} = \frac{\frac{1}{N_{\text{GOP}}} \sum_{n=2}^{N_{\text{GOP}}} \text{EP}_n \, \text{PLR}_{\text{TC}}}{\text{TH}_{\text{intra}}}, \qquad (6)$$

where $N_{\text{intra}}^{\text{GOP}}$ represents the total number of macroblocks of P-frames to be intra-refreshed in a GOP, N_{GOP} denotes the GOP size, PLR_{TC} represents the channel packet-loss rate estimated at the transcoder by using the client feedback information and is updated every GOP to capture frequently changing network conditions, and TH_{intra} is a scaling parameter.

The intra-refresh allocation is then distributed to a GOP using the following algorithm:

If $n = 2$ (i.e., the first P-frame in a GOP)

$$N_{\text{intra}}(n) = \frac{\text{EP}_n}{\sum_{i=n}^{N_{\text{GOP}}} \text{EP}_i} N_{\text{intra}}^{\text{GOP}}, \qquad (7)$$

else if $3 \leqslant n \leqslant N_{\text{GOP}}$

$$N_{\text{intra}}(n) = \frac{\text{EP}_n}{\sum_{i=n}^{N_{\text{GOP}}} \text{EP}_i} \left(N_{\text{intra}}^{\text{GOP}} - \sum_{i=2}^{n-1} N_{\text{intra}}(i) \right), \quad (8)$$

end if

where $N_{\text{intra}}(n) = \min(N_{\text{intra}}(n), k_{\text{MB}} N_{\text{MB}}^{\text{F}})$ denotes the number of macroblocks to be intra-coded in frame n, N_{MB}^{F} denotes the number of macroblocks in a frame, and k_{MB} ($0 \leqslant k_{\text{MB}} \leqslant 1$) is a control parameter to constrain the number of intra-coded blocks in a frame not to exceed an upper limit. For the nth frame of a GOP, we select a total of $N_{\text{intra}}(n)$ macroblocks with top-ranking EP_{MB} values to perform intra-refresh.

2.3. CAIR with profit tracing

In (4), the macroblock-level error propagation, EP_{MB}, is estimated by summing up the loss-impact values of the pixels in the previous frame that are referenced by this macroblock in the motion-compensated prediction process. However, it is very likely that temporally correlated macroblocks along a prediction path between successive frames all have high EP_{MB} ranks such that they are all selected to be intra-refreshed in these frames. For example, as illustrated in Fig. 5, suppose that $\text{MB}(i,n-1)$ (the ith macroblock of frame $n-1$) has a high EP_{MB} value: $\text{EP}_{\text{MB}}(i,n-1)$. The temporally correlated macroblocks of $\text{MB}(i,n-1)$ (e.g., $\text{MB}(i,n)$ and $\text{MB}(i+1,n)$ which reference in part the pixel values of $\text{MB}(i,n-1)$) will also likely have high EP_{MB} ranks since $\text{EP}_{\text{MB}}(i,n-1)$ is partially inherited by $\text{EP}_{\text{MB}}(i,n)$ and $\text{EP}_{\text{MB}}(i+1,n)$ according to (4). Encoding these temporally correlated macroblocks all in the intra mode will consume the intra-refresh budget rapidly, but may not be able to achieve comparable improvement on error resilience. The reason is that the error propagation along the prediction path may have already been terminated by intra-refreshing an earlier macroblock in the path such that intra-refreshing its succeeding macroblocks is not very useful, thereby reducing the efficacy of the CAIR scheme.

To address the above problem of CAIR, we propose a CAIR with profit tracing (CAIR-PT) scheme to improve the intra-block allocation strategy. First, we define a pixel-wise surplus refresh factor (SRF), which is inherited from a previous intra-coded macroblock. As illustrated in Fig. 6, $\text{SRF}(x,y,n)^-$ represents the intermediate SRF of pixel (x,y) in frame n before the transcoder decides the coding mode of the macroblock containing the pixel, which is defined as follows:

$$\text{SRF}(x, y, n)^- = \text{SRF}(x + \text{MV}_x, y + \text{MV}_y, n-1)^+ \\ \times (1 - \text{PLR}). \qquad (9)$$
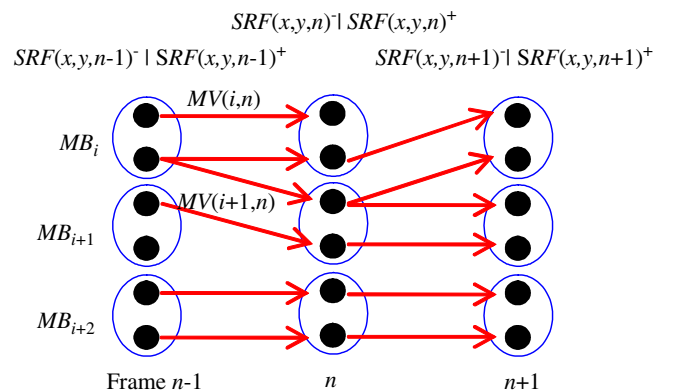

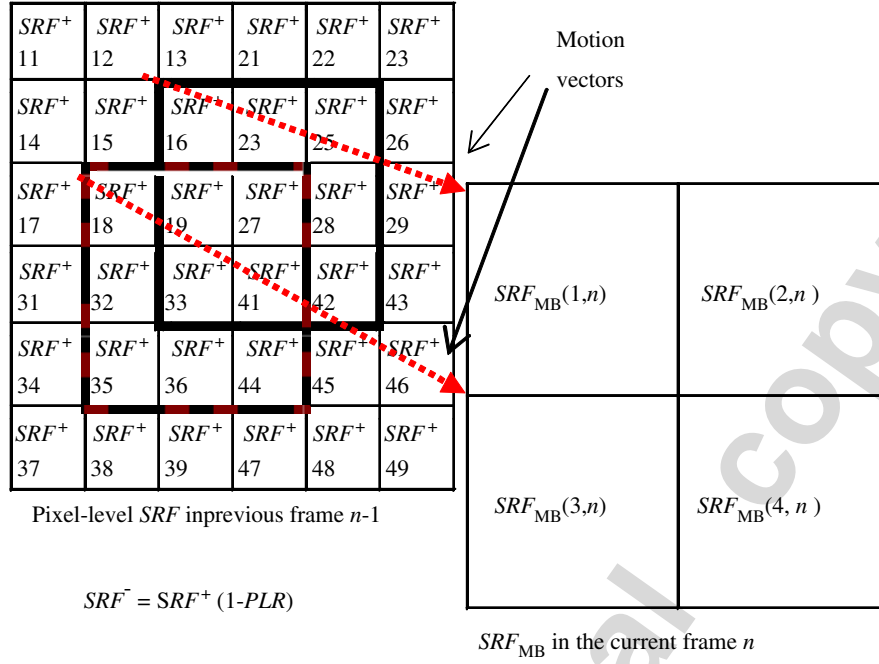Fig. 5. Profit tracing of each refreshed macroblock.

Fig. 6. Illustration of using motion vectors to map pixel-level SRF$^+$ of the previous frame to obtain macroblock-level SRF$^-$ in the current frame.

In (9), for the sake of simplicity, we use the packet-loss rate, PLR, to approximate the pixel loss rate in a GOP, since the two loss rates usually have close values for a sufficiently large amount of data (e.g., a GOP). As such, a pixel in frame $n-1$ has a probability of $(1-\text{PLR})$ to provide a correct reference value to the succeeding macroblocks of frame n which reference the pixel value. According to $\text{SRF}(x,y,n)^-$, the transcoder will determine the intra-block allocation for frame n. After the mode decision, the intermediate value $\text{SRF}(x,y,n)^-$ will be transferred to a refreshed value $\text{SRF}(x,y,n)^+$ based on the coding mode. $\text{SRF}(x,y,n)^+$ is set to be 1, if pixel (x,y) belongs to an intra-refreshed macroblock. Otherwise, $\text{SRF}(x,y,n)^+$ remains the same as $\text{SRF}(x,y,n)^-$. The initial values, $\text{SRF}(x,y,0)^-$, are all set to 0. Besides, in an initial I-frame, the values of $\text{SRF}(x,y,0)^+$ are all equal to 1. In summary, the SRF values are determined as follows:

$$\begin{cases} \text{SRF}(x,y,n)^+ = 1, & (x,y) \in \text{intra-MB} \\ \text{SRF}(x,y,n)^+ = \text{SRF}(x,y,n)^-, & (x,y) \in \text{inter-MB} \\ \text{SRF}(x,y,0)^- = 0 \\ \text{SRF}(x,y,0)^+ = 1 \end{cases}.$$

(10)

As depicted in Fig. 6, we use the motion information to map pixel-level $\text{SRF}(x,y,n-1)^+$ from the previous frame to obtain the macroblock-level $\overline{\text{SRF}}_{\text{MB}}(m,n)$ with a value ranging from 0 to 1, as follows:

$$\overline{\text{SRF}}_{\text{MB}}(m,n) = \frac{1}{\text{SIZE}_{\text{MB}}} \sum_{(x,y)\in \text{MB}_m} \text{SRF}(x,y,n)^-,$$

(11)

where $\text{SRF}(x,y,n)^-$ is calculated using (9), and SIZE_{MB} represents the number of pixels in a macroblock.

After computing $\overline{\text{SRF}}_{\text{MB}}(m,n)$, we select a total of $N_{\text{intra}}(n)$ macroblocks with top-ranking $\text{EP}_{\text{MB}}(m,n)\{1 - \overline{\text{SRF}}_{\text{MB}}(m,n)\}$ values to perform intra-refresh for the nth frame of a GOP.

3. Intra-refresh strategy for video multicast

In our proposed intra-refresh transcoding scheme described above, according to the estimated channel-loss rate PLR_{TC}, the transcoder determines an appropriate intra-refresh rate using (6) to reach a good tradeoff between error robustness and coding efficiency for a single client. In many practical applications, the bitstream may need to

be simultaneously delivered to multiple clients with diverse channel characteristics. The proposed intra-refresh rate allocation scheme, however, may not be directly applicable to such kind of video multicasting applications since the packet-loss rates of clients can be rather diverse such that no unique packet-loss rate can be derived for (6). We shall show that the mismatch between a client's actual packet-loss rate and the estimated transcoder parameter PLR_{TC} will lead to severe quality penalty for the client. Therefore, how to determine in the transcoder an appropriate parameter, PLR_{TC}, for a single multicast stream delivered to multiple clients with different channel-loss characteristics, PLR_{ch}'s, is a practical problem in video multicast applications. The optimal intra-refresh rate allocation for video multicasting is still an open problem, which, to our best knowledge, has not yet been well addressed. Moreover, should a constraint on quality variation be imposed for mobile clients with heterogeneous channel characteristics, sending a single bitstream may not be able to meet the constraint. How to partition the clients in a multicast group into a minimal number of subgroups so as to minimize the required channel bandwidth while meeting the

quality variation constraint for the clients is also of interest.

3.1. MINMAX penalty criterion

To characterize the amount of quality penalty due to adopting at the transcoder an estimated packet-loss rate, PLR_{TC}, that does not exactly match the packet-loss rate of a channel, PLR_{ch}, we define the following PSNR penalty metric:

$$\Delta PSNR_i(x|p_i) = PSNR(PLR_{TC} = x|PLR_{ch} = p_i) \\ - PSNR(PLR_{TC} = p_i|PLR_{ch} = p_i), \tag{12}$$

where we assume the packet-loss rate of the ith client is p_i, whereas the transcoder uses a different $PLR_{TC} = x$ to determine the intra-refresh rate for the outgoing video bitstream using (6). Fig. 7 shows an example of PSNR penalty plot for thee channels packet-loss rates: $PLR_{ch} = 5\%$, 10%, and 15%, respectively. In Fig. 7, the symbol '$\times$' marks the optimal PLR_{TC} value that leads to the minimal PSNR penalty for each client. With the proposed error-resilience transcoding method, the optimal PLR_{TC} for one channel is very
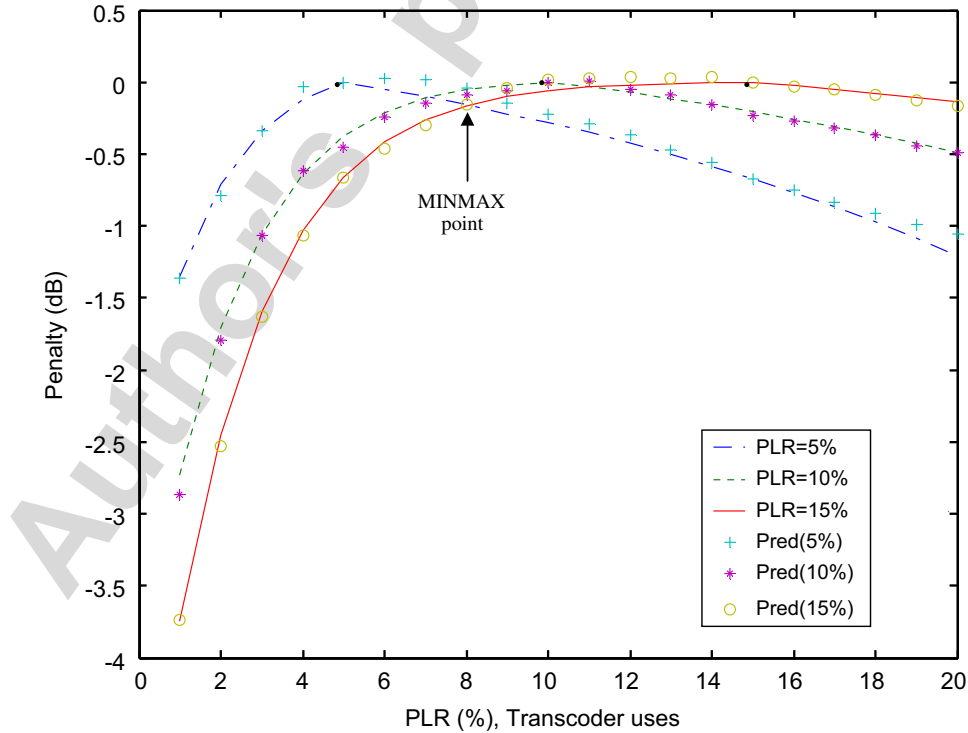

Fig. 7. Plot of PNSR penalty caused by using at the transcoder an estimated packet-loss rate, which does not match the packet-loss rates of individual channels ($PLR_{CH} = 5\%$, 10%, and 15%).

close to the channel's packet-loss rate. As shown in Fig. 7, if the transcoder adopts a PLR_{TC} different from the optimal value (i.e., the channel packet-loss rate PLR_{ch}), a PLR_{TC} value smaller than PLR_{ch} will lead to more severe error propagation caused by packet loss, since the intra-refresh rate is not sufficient to stop the error propagation effectively. On the other hand, a PLR_{TC} value higher than PLR_{ch} will lead to an excessive intra-refresh rate, resulting in poor coding efficiency which cannot be well compensated for by the performance gain obtained from the enhanced error resiliency.

When multicasting a video bitstream to multiple clients with diverse loss characteristics, the transcoder should not just maximize the received visual quality for some client since it may lead to quality degradation for the others. In such multicast scenario, we propose to determine PLR_{TC} based on the following MINMAX penalty criterion:

$$\text{PLR}_{\text{TC}}^{\text{opt}} = \arg\min_x \max_i \{|\Delta\text{PSNR}_i(x|p_i)|\}. \quad (13)$$

The transcoder then uses $\text{PLR}_{\text{TC}}^{\text{opt}}$ to determine the intra-refresh rate for the outgoing video bitstream according to (13). Such a single intra-refresh rate

will result in quality penalty $\Delta\text{PSNR}_i(x|p_i)$ for the ith channel due to the mismatch of channel-loss rates between PLR_{TC} and p_i. The intra-refresh rate $\text{PLR}_{\text{TC}}^{\text{opt}}$ is optimal for a multicast group in the sense of minimizing the maximum penalty distortion that any client will suffer, thereby tending to reduce the distortion deviation among all clients to achieve fairness.

We can observe from Fig. 7 that the MINMAX point for a multicast group will stay at the cross-point of two quality penalty curves of the lowest and highest PLRs of the group since they will have the maximum quality penalty. The reason is, in a multicast group for which the same intra-refresh rate $\text{PLR}_{\text{TC}}^{\text{opt}}$ is adopted, the receiver(s) with lowest PLR has the poorest coding efficiency due to its most excessive intra-refresh rate, whereas the receiver(s) with highest PLR has the poorest error resiliency.

In order to obtain $\text{PLR}_{\text{TC}}^{\text{opt}}$ analytically, we propose the following model to characterize the channel mismatch distortion:

$$\Delta\text{PSNR}(x|p) = \begin{cases} G_0(p-x)e^{-mx}, & x < p, \\ G_1(x-p)e^{n(x-a)}, & x \geqslant p, \end{cases} \quad (14)$$
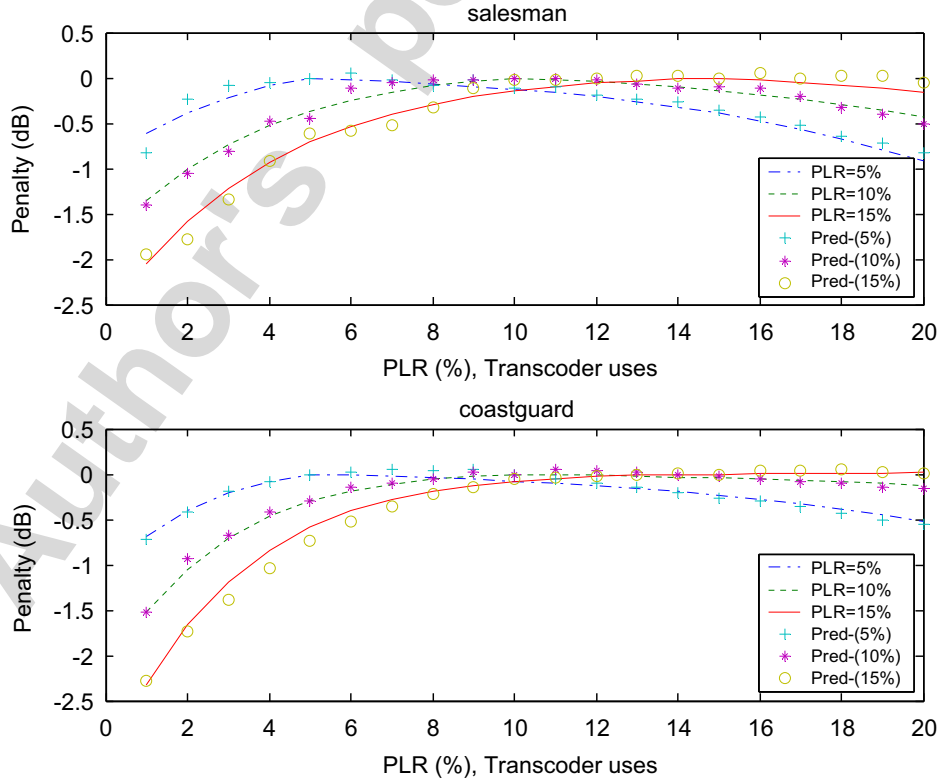
where $G_i = c_i - k_i p^b$.

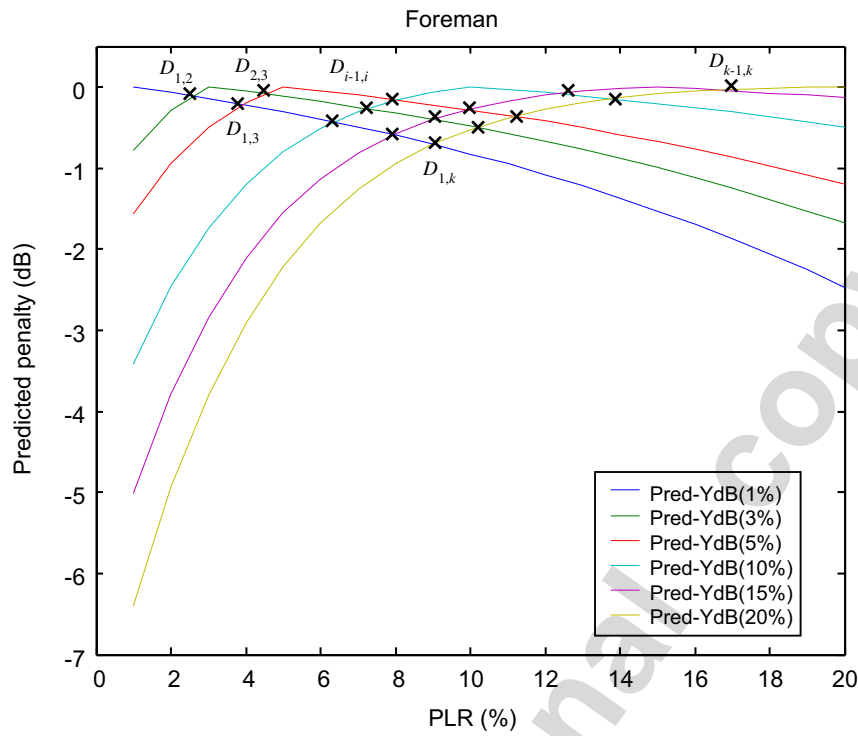Fig. 8. PSNR penalty function models for the *Salesman* and *Coastguard* sequences for $\text{PLR}_{\text{CH}} = 5\%$, 10%, and 15%.

Fig. 9. Cross points of the predicted PSNR penalty of any two receivers with different PLRs.

Fig. 10. A cross-point matrix records the penalty distortion values of each cross point.

As mentioned above, the penalty, $\Delta\text{PSNR}(x|p)$, is mainly caused by error propagation when $x < p$, and by coding efficiency loss when $x \geqslant p$. The amount of penalty is dependent on the mismatch distance of x from p. The parameters G_0 and G_1 are decreased by a scale k_i from c_i to indicate the slope of decay. e^{-mx} and $e^{n(x-a)}$ are used to fine tune the smoothness of penalty function. Fig. 7 illustrates the penalty models for the *Foreman* sequence under three channel packet-loss rates: $\text{PLR}_{\text{ch}} = 5\%$, 10%, and 15%, respectively. We use a fixed set of parameters, which can be computed beforehand and stored as side information, to model each individual video bitstream. For example, the set of model parameters used for *Foreman* is $(c_0, c_1, k_0, k_1, m, n, a, b) = (0.53, 3.29, 0.01, 1.15, 0.35, 0.035, 100, 0.33)$. The results of model fitting for the *Salesman* and *Coastguard* sequences are also illustrated in Fig. 8.

3.2. Fairness grouping

A video multicast session may involve a large number of receivers with heterogeneous channel conditions. This usually leads to a tradeoff between bandwidth utilization efficiency and granularity of error control. On one hand, sending a single video bitstream to all receivers in the multicast group achieves the best bandwidth utilization efficiency, but leads to the coarsest granularity of error control. On the other hand, sending an individual bitstream to each receiver leads to the finest granularity of error control but the worst bandwidth utilization efficiency. Considering the fairness among the receivers in a multicast group, it is usually undesirable to trade the visual quality of users with good channel conditions for the visual quality of users with significantly poor channel conditions, especially in WLAN environments where client mobility may temporarily result in rather unstable transient channel behaviors. In order to constrain the quality variation for a group of heterogeneous receivers, we propose to take into account the heterogeneity of the receivers' channel conditions to decide whether to divide the receivers with diverse channel characteristics into subgroups and then send video bitstreams of different intra-refresh rates to individual subgroups according to a MINMAX criterion. Based on the proposed penalty model, we attempt to partition receivers in a multicast group into a minimal number of subgroups so as to minimize the required channel bandwidth while meeting the quality variation constraint for each subgroup as well as achieving fairness among all subgroups.

As mentioned above, the MINMAX point for a multicast group stays at the cross-point of the two penalty model curves with the lowest and highest PLRs. Suppose there exist N receivers in the multicast group with K different classes of packet-loss rates, $\{\text{PLR}_1, \text{PLR}_2 \ldots, \text{PLR}_i \ldots, \text{PLR}_K\}$, where $\text{PLR}_{i-1} < \text{PLR}_i$ and $K \leqslant N$. Fig. 9 illustrates an example of the cross-points of penalty model curves, in which $D_{i,j}$ denotes the quality penalty value at the cross-point of the penalty model curves with the two packet-loss rates: PLR_i and PLR_j. Note that, $D_{i,i} = 0$ and $D_{i,j} = D_{j,i}$. Considering the efficiency of bandwidth utilization, our goal is to partition the K classes of PLRs into a minimal number of subgroups L $(1 \leqslant L \leqslant K)$ so as to maximize the channel utilization efficiency while meeting the constraint of quality variation (QV_{max}) for each subgroup. In our grouping strategy, as shown in Fig. 10, a cross-point matrix is used to record the PSNR penalty values of cross-points of every two penalty model curves. If the receivers with PLR_i, $\text{PLR}_{i+1} \ldots$, and PLR_j are grouped together as one subgroup, in our method, the penalty value for the subgroup becomes the MINMAX penalty value of the subgroup (i.e., $D_{i,j}$). In order to maintain fairness within all subgroups, we propose to minimize the maximum quality penalty value of the subgroups under the constraint of quality variation (QV_{max}) as follows:

$$
\begin{aligned}
&\text{QV}_{\text{min max}} \\
&= \min_{[i_{m-1}+1, i_m] \in m\text{th group}} \max_m \{D_{i_{m-1}+1, i_m}\} \quad \text{for} \quad m = 1, \ldots, L \\
&\quad \text{subject to } \text{QV}_{\text{min max}} \leqslant \text{QV}_{\text{max}},
\end{aligned}
\tag{15}
$$

where L represents the number of subgroups that the N receivers with K classes of packet-loss rates will be partitioned into. Furthermore, if the channel bandwidth is limited, the total bandwidth constraint should also be imposed in the optimization problem. The mth subgroup, which includes the receivers with packet-loss rates ranging from $i_{m-1}+1$ to i_m classes, has the MINMAX penalty value $D_{i_{m-1}+1, i_m}$, as shown in Fig. 11. $\text{QV}_{\text{minmax}}$ denotes the MINMAX quality penalty value of the L subgroups. In order to maximize the channel utilization efficiency, we would like to minimize the number of subgroups, while meeting the constraint that $\text{QV}_{\text{minmax}} \leqslant \text{QV}_{\text{max}}$. As shown in Fig. 11, the

proposed algorithm is summarized as follows:

Algorithm. Fairness grouping

Suppose there exist N receivers in a multicast group with K classes of packet-loss rates, $\{PLR_1, PLR_2\ldots, PLR_j\ldots, PLR_K\}$, where $PLR_{j-1} < PLR_j$ and $K \leqslant N$. The multicast group is partitioned into L subgroups.

Grouping procedure:

Increase the number of subgroups L to reduce QV_{minmax} until the condition $QV_{minmax} \leqslant QV_{max}$ is met.
{
  Iterate the following procedure to minimize the maximum quality penalty value of the L subgroups
  {
  Suppose the mth subgroup of $L^{(n)}$ subgroups at the nth iteration includes the receivers with packet-loss rate from $i_{m-1}^{(n)} + 1$ to $i_m^{(n)}$ classes, denoted as $[i_{m-1}^{(n)} + 1, i_m^{(n)}]$. At the next iteration (i.e., the $(n+1)$th iteration), we first divide the last subgroup $L^{(n)}$ into two subgroups with the packet-loss rate ranges $\left[i_{L^{(n+1)}-2}^{(n+1)} + 1, i_{L^{(n+1)}-1}^{(n+1)}\right] = \left[i_{L^{(n)}-1}^{(n)} + 1, \left\lfloor i_{L^{(n)}}^{(n)}/2 \right\rfloor\right]$ and $\left[i_{L^{(n+1)}-1}^{(n+1)} + 1, i_{L^{(n+1)}}^{(n+1)}\right] = \left[\left\lfloor i_{L^{(n)}}^{(n)}/2 \right\rfloor + 1, i_{L^{(n)}}^{(n)}\right]$, respectively.
  for $m = L$ to 1
  {
    move the receivers between the mth to $(m-1)$th group until $D_{i_{m-2}^{(n+1)}+1, i_{m-1}^{(n+1)}+1} > D_{i_{m-1}^{(n+1)}+2, i_m^{(n+1)}}$
    {
      move the receivers with packet-loss rate $i_{m-1}^{(n+1)} + 1$ from the mth subgroup to the $(m-1)$th subgroup, thereby changing the packet-loss rate ranges from $[i_{m-2}^{(n+1)} + 1, i_{m-1}^{(n+1)} + 1]$ to $[i_{m-1}^{(n+1)} + 2, i_m^{(n+1)}]$ and $[i_{m-1}^{(n+1)} + 1, i_m^{(n+1)}]$ to $[i_{m-1}^{(n+1)} + 2, i_m^{(n+1)}]$, respectively.
    }
  }
  }
}

4. Experimental results

In our experiments, three QCIF (176×144) test sequences, *Foreman*, *Salesman*, and *Coastguard*, are pre-encoded at 30 fps and 384 kbps with the IPPP…GOP (Group of Pictures) structure with a GOP size of 30. We implement a cascaded pixel-domain transcoder [13] using an MPEG-4 public-domain software codec [10] to perform the adaptive intra-refresh transcoding. The output bit-rate, after inserting intra-refresh macroblocks, is regulated to the same bit-rate of the input video (i.e., 384 kbps) by using the MPEG-4 TM5 rate control scheme. In our experiments, a slice containing one row of macroblocks is encapsulated into one packet. In this work, we use a two-state Markov model to simulate a packet-erasure channel. We adopt a simplified Gilbert channel at the packet level [9] to generate 10 packet-loss patterns for each of four packet-loss rates (PLRs): 5%, 10%, 15%, and 20%, respectively.

4.1. Performance of CAIR-PT

The proposed CAIR-PT scheme is compared with our previously proposed CAIR method [4], random intra-refresh [5], regular intra-refresh, [5] and CBERC [1] under the PLRs, respectively. Suppose the average number of intra-refreshed macroblocks in a frame is m. In the random intra-refresh scheme, the intra-refreshed positions are randomly selected independently for each frame. For regular intra-coding, the intra-refreshed positions are $1-m$ in the first frame, $m+1-2m$ in the second frame, and so on. If all macroblock positions have been refreshed once, the first positions will be intra-refreshed again. In the proposed method, the scaling factor of intra-refresh rate, TH_{intra}, in (6) is determined empirically. Fig. 12 shows the frame-by-frame PSNR with different TH_{intra} values for three test sequences when PLR = 10%. We adopt $TH_{intra} = 1200$ for all the sequences at different packet-loss rates as it stably achieves the best performance for every sequence.

The frame-by-frame PNSR performance comparisons of five different methods at PLR = 10% for the three test sequences are depicted in Fig. 13. Some reconstructed frames are illustrated in Figs. 14–16 for subjective performance comparison. Table 1 compares the average PSNR performances of the four methods computed from 10 loss patterns for each of the four packet-loss rates. In the above experiments, the average burst length is set to one to simulate random loss situations as in fast-fading channels. The experimental results show that CAIR-PT mitigates the
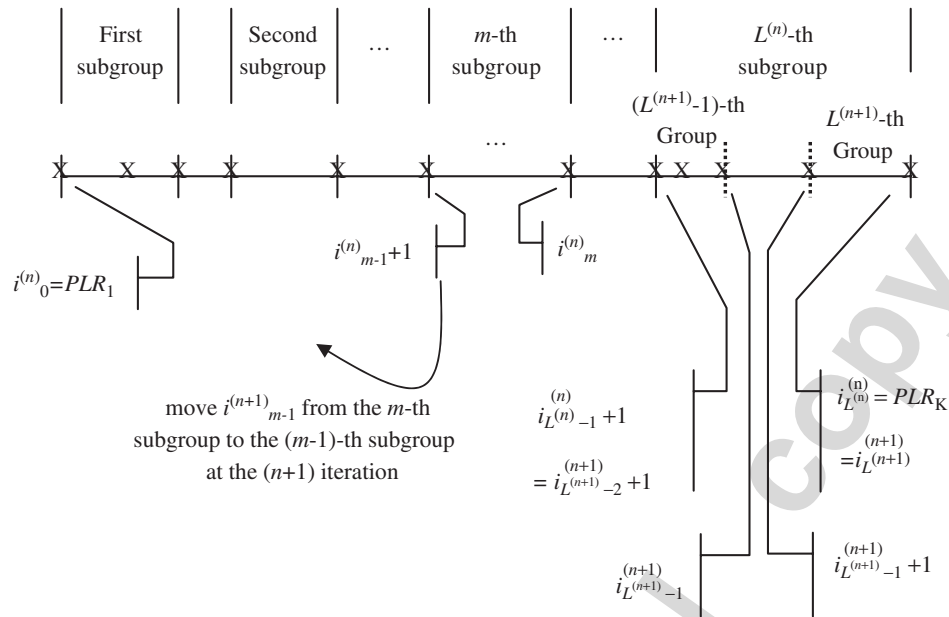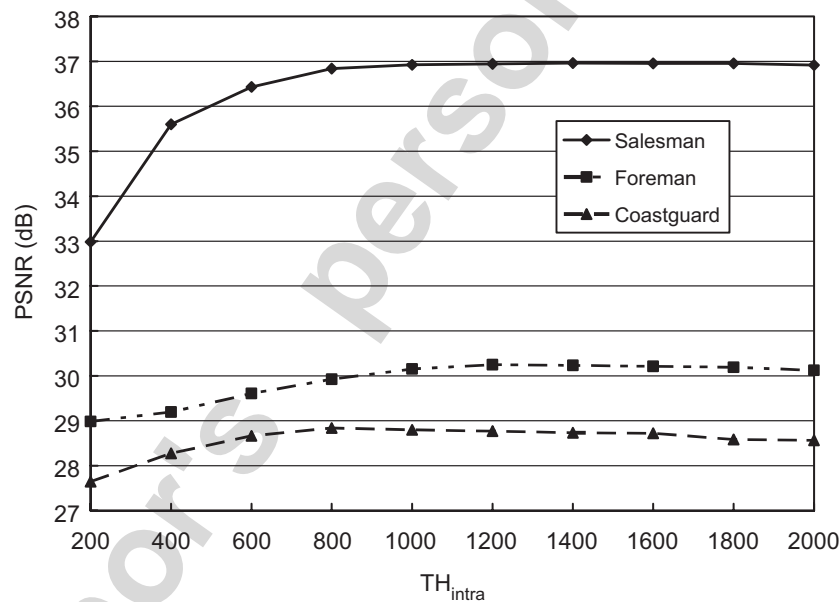
Fig. 11. Illustration of fairness grouping.

Fig. 12. Effect of changing the intra-refresh parameter (PLR = 10%).

error propagation due to packet loss more effectively than the other intra-refresh methods. For sequences of low motion activities such as *Salesman*, CAIR-PT achieves PSNR performance improvement over CAIR by up to about 0.92 dB, and even higher performance gain than the other three methods. Table 1 indicates that the CAIR-PT scheme achieves more significant improvement on low-activity video than on high-activity ones. This is because the EP_{MB} value

of a low-activity macroblock in a frame tends to be most inherited by a single macroblock rather than shared by several macroblocks in the following frame, thereby resulting in a longer sequence of high EP_{MB} macroblocks along a prediction path, which usually leads to poorer intra-refresh allocation efficiency in the CAIR transcoder. The results also show that the improvements under lower PLRs are typically larger than those under higher PLRs, because SRF will have a
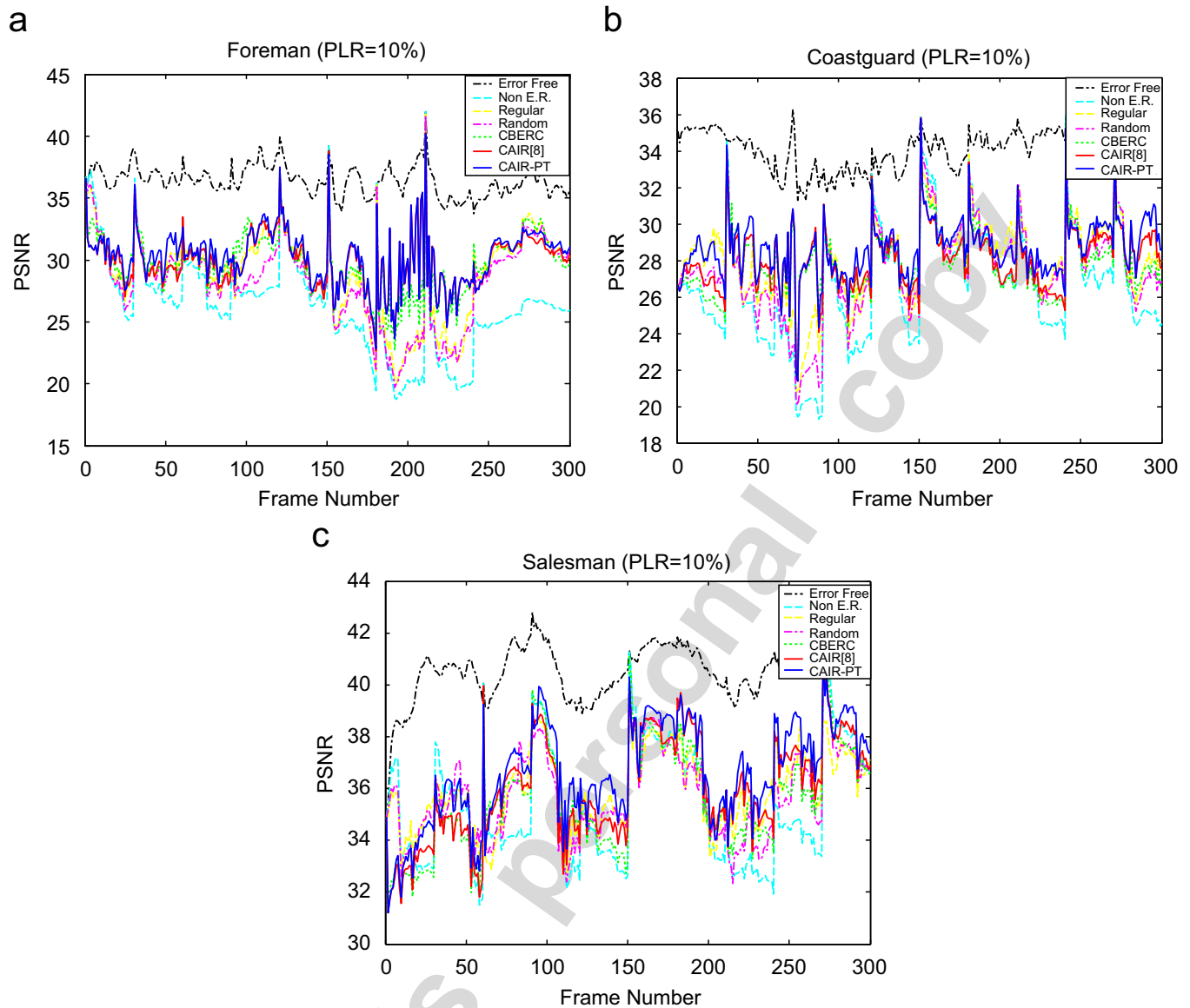
a

b

c

Fig. 13. Frame-by-frame PNSR performance comparison using various intra-refresh methods at PLR = 10% for three test sequences: (a) *Foreman*, (b) *Coastguard*, and (c) *Salesman*.

relatively higher probability of (1−PLR) to propagate to the following frames in situations with lower PLRs.

For video transmission over slow-fading wireless channels, burst packet losses, which usually result in severe video quality degradation, occur more frequently than transmission in fast-fading environments. In [14] a more accurate model about the error-propagation effect of a burst loss is presented, which shows that a burst loss of consecutive frames generally produces larger distortion than that produced by an equal number of isolated frame losses (namely, an additive model). Fig. 17 shows

the average PSNR performance comparison for the *Foreman* sequence at PLR = 10% with various burst lengths ranging from 1 to 50 packets corresponding to a loss of 1–5 consecutive frames, respectively. Ten loss patterns are used to obtain the average PSNR value for each burst-loss length. Evidently, for all the methods, the reconstructed video quality becomes significantly poorer as the burst loss length increases. The performance gain of CAIR-PT over CAIR becomes less significant for long burst-length situations. The reason is that CAIR-PT avoids allocating excessive intra-blocks along a prediction path with high loss impact
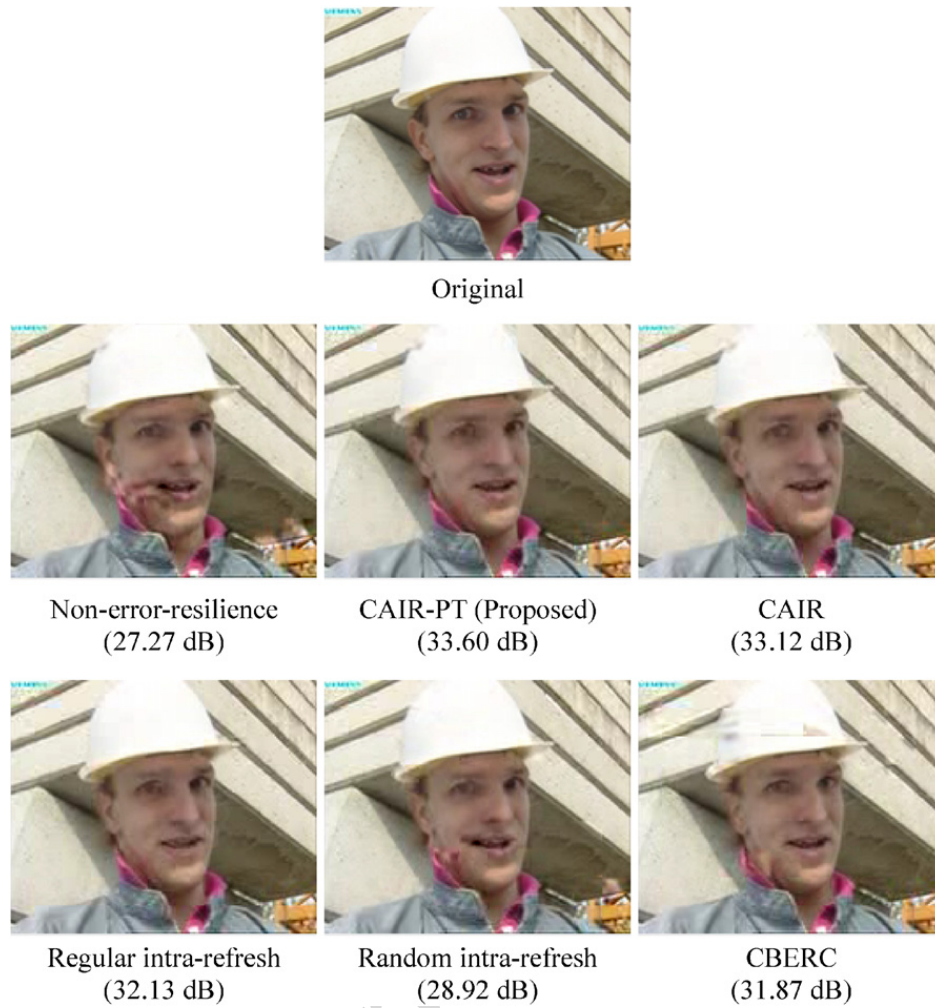
Fig. 14. Video snapshots for subjective quality comparison between six schemes with PLR = 10% (frame 110 of *Foreman*).

to make better use of intra-refresh resource. However, should a loss of long consecutive frames occur, the intra-refresh rate allocated by CAIR-PT for a high loss-impact path may not be sufficient for effectively terminating error propagation along the path. To resolve this problem, packet interleaving can be used to effectively spread out the long burst loss into short individual packet losses to facilitate the error control process if the introduced complexity and delay are acceptable [18].

Table 2 shows the run-time analysis of the first-pass encoding and second-pass transcoding on an Intel Pentium-III 1-GHz PC. With the proposed error-propagation estimation method, the first-pass encoding consumes significantly more time than the original one. On the other hand, the proposed method does not increase the computational complexity of second-pass transcoding. Actually some-

times it consumes even less time than the original transcoder for two reasons. First, the computation for intra-refresh decision in (6)–(8) in the second-pass transcoding is almost negligible compared to the whole transcoding process. Second, the error-resilience transcoding will increase the number of intra-coded macroblocks, thereby reducing the computation since the computational cost for intra-coding is much lower than that for inter-coding. For pre-recorded video streaming applications, the first-pass encoding and feature extraction can usually be done offline, thus having no impact on real-time transcoding.

4.2. Performance of multicast with one single bitstream

We apply the penalty model functions in (14) to compute the optimal PLR_{TC} which meets the
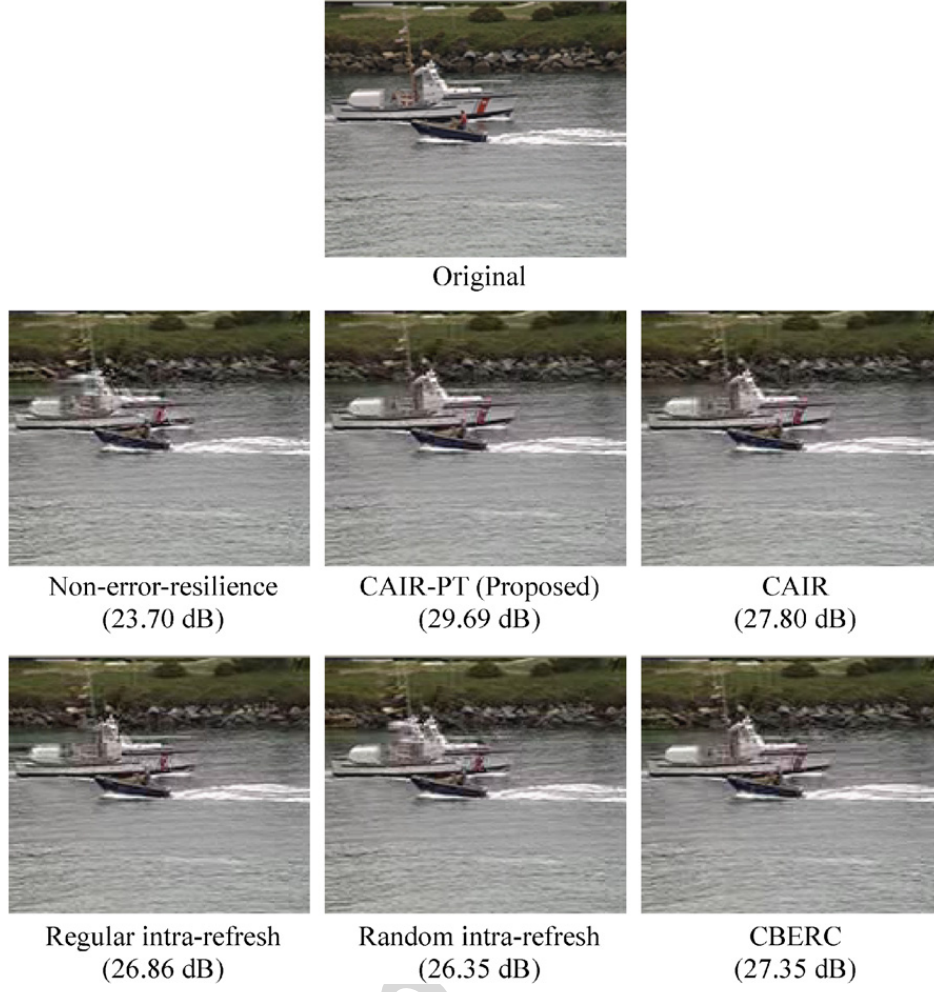
Fig. 15. Video snapshots for subjective quality comparison between six schemes with PLR = 10% (*Coastguard*, frame 55).

MINMAX criterion for the application scenario involving six receivers with different channel-loss rates as listed in Table 3. Table 3 also shows the numerical results of the penalty distortion $\Delta PSNR_i(x|p_i)$ for each user with channel-loss rate p_i, where 'Average' stands for $x = (\sum_{i=1}^{6} p_i)/6$, 'Worst' for $x = \max\{p_i\}$, and 'Best' for $x = \min\{p_i\}$, respectively. As shown in Fig. 18, the proposed MINMAX penalty criterion yields the best visual quality in terms of the mean and variance of PSNR penalty values among the four methods.

4.3. Performance of multicast with multiple bitstreams

In the experiments of video multicasting with multiple bitstreams, 13 users with heterogeneous PLRs, {1%, 1%, 1%, 1%, 1%, 3%, 3%, 3%, 5%, 5%, 10%, 15%, 20%}, are considered in the

multicast scenario. As shown in Fig. 11, $K = 6$, because there have six different PLR values: {1%, 3%, 5%, 10%, 15%, 20%}. Suppose the constraint of quality variation (QV_{max}) for each subgroup is 0.5 dB. In the case of sending only a single bitstream to all clients, the MINMAX penalty distortion value is $D_{16} = 0.71$ dB that exceeds the constraint of QV_{max}. The resulting MINMAX quality penalty value $QV_{min\,max}$, which is the maximum value of MINMAX penalty distortion values of *Subgroup* #1 ($D_{13} = 0.21$ dB) and *Subgroup* #2 ($D_{46} = 0.15$ dB), is 0.21 dB that can meet the constraint of QV_{max}. The result indicates that, in this case, partitioning the clients into two subgroups and sending two bitstreams for individual subgroups accordingly can achieve the best bandwidth utilization efficiency under the quality variation constraint of QV_{max}. As shown in Table 4, while sending two bitstreams, the fourth user with 1% PLR has a maximum PSNR
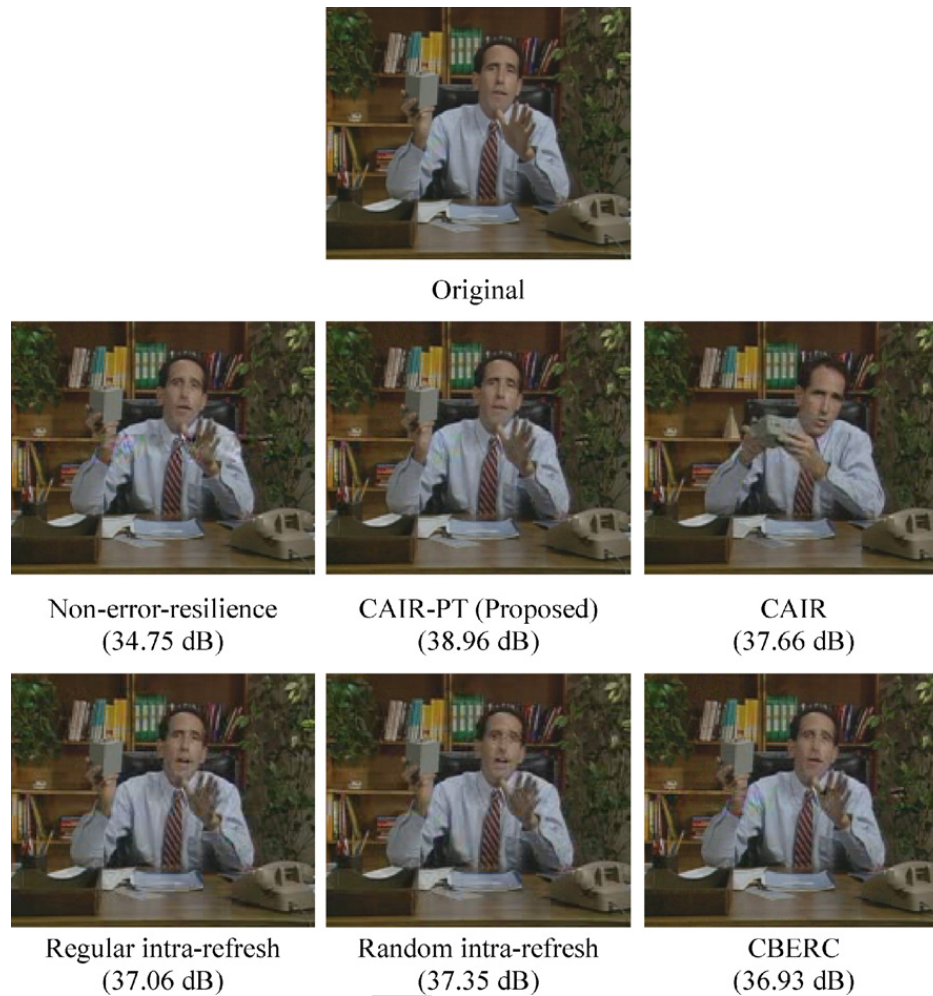
Fig. 16. Video snapshots for subjective quality comparison between six schemes with PLR = 10% (*Salesman*, frame 254).

penalty of 0.17 dB in *Group* #1 and the 13th user with 20% PLR has 0.1 dB penalty in *Group* #2, leading to 0.83 dB improvement compared to sending only one single bitstream that results in a maximum penalty of 1 dB. Sending two bitstreams, however, will double the bandwidth required.

5. Conclusion

In this paper, we proposed a novel two-pass error-resilience transcoding scheme with profit tracing by using prioritized intra-refresh. The profit tracing mechanism can improve the efficacy of intra-fresh allocation of the CAIR transcoder by avoiding wasting intra-refresh resources in macro-blocks of high error-propagation ranks in the same prediction path. Experimental results show that the proposed transcoder mitigates the error propagation due to packet loss much more effectively so as

to improve the visual quality significantly compared to the regular intra-refresh, random intra-refresh, and CBERC transcoders. Incorporating the proposed profit tracing mechanism into the CAIR transcoder can further achieve significant PSNR performance improvement over the CAIR scheme itself.

With the proposed scheme and fairness consideration, we also proposed an efficient method to cope with more general video multicasting situations involving heterogeneous clients with diverse channel conditions. We have proposed a MINMAX loss rate estimation scheme to determine an appropriate intra-refresh rate for all the clients in a multicast group. We have also proposed a grouping method to partition a group of heterogeneous users into a minimal number of subgroups to meet a given quality variation constraint while minimizing the channel bandwidth consumption under the quality

Table 1
Average PSNR values (in dB) of 10 packet-loss patterns using different intra-refresh transcoding schemes under four different PLRs

Sequence	Transcoding method	Average PSNR for various PLRs			
		5%	10%	15%	20%
Foreman	Error free	35.80			
	Non-E.R.	27.58	24.49	22.40	21.02
	CAIR-PT	**30.96**	**29.52**	**28.47**	**27.65**
	CAIR [4]	30.63	29.30	28.36	27.61
	Regular IR	28.78	27.05	25.99	25.28
	Random IR	28.41	26.51	25.93	25.37
	CBERC	29.55	28.84	27.44	26.25
Coastguard	Error free	33.53			
	Non-E.R.	28.26	25.65	24.12	22.80
	CAIR-PT	**29.88**	**28.48**	**27.71**	**27.10**
	CAIR [4]	29.40	27.99	27.41	26.94
	Regular IR	29.02	27.56	26.94	26.16
	Random IR	28.72	27.07	26.78	26.21
	CBERC	29.05	27.72	26.52	25.50
Salesman	Error free	39.81			
	Non-E.R.	36.84	34.32	32.24	30.60
	CAIR-PT	**37.33**	**36.29**	**35.39**	**35.40**
	CAIR [4]	37.14	35.90	35.17	34.48
	Regular IR	36.73	35.36	34.30	33.22
	Random IR	36.63	35.21	34.19	33.35
	CBERC	36.75	35.48	34.07	33.14

constraint. Simulation results show that the proposed scheme can effectively reduce the mean and variance of penalty distortion of all users to achieve fairness.

Table 2
Run-time analysis of the first-pass encoding and second-pass transcoding

Sequence	Encoding time		Transcoding time	
	Original (s)	Proposed (s)	Non-error-resilient (s)	Error-resilient (s)
Foreman	11.0	23.7	18.1	17.5
Coastguard	11.1	23.7	17.7	17.6
Salesman	11.2	23.7	17.6	17.3

Table 3
Comparison of penalty distortions of six individual users with different criteria

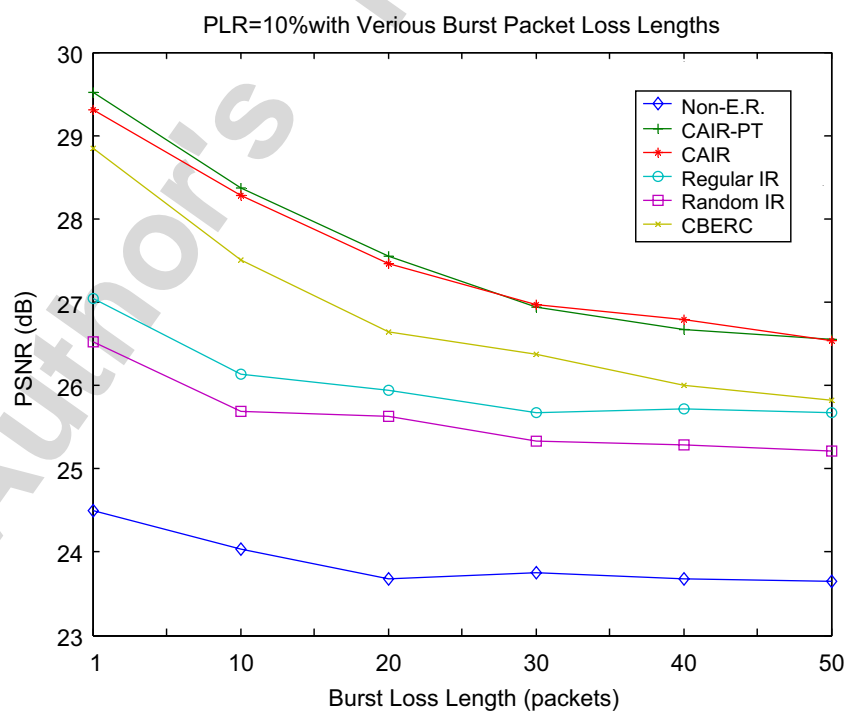| User	p_i (%)	MINMAX	Average	Worst	Best
1	3	0.03	0.01	**0.54**	0
2	3	0.01	0.06	0.36	0
3	3	0.05	0.03	0.60	0
4	5	0.03	0	0.22	0.34
5	5	0.01	0	0.28	0.43
6	10	**0.24**	**0.45**	0	**1.07**

Fig. 17. Average PNSR performance comparison for the *Foreman* sequence at PLR = 10% with various average burst loss lengths.
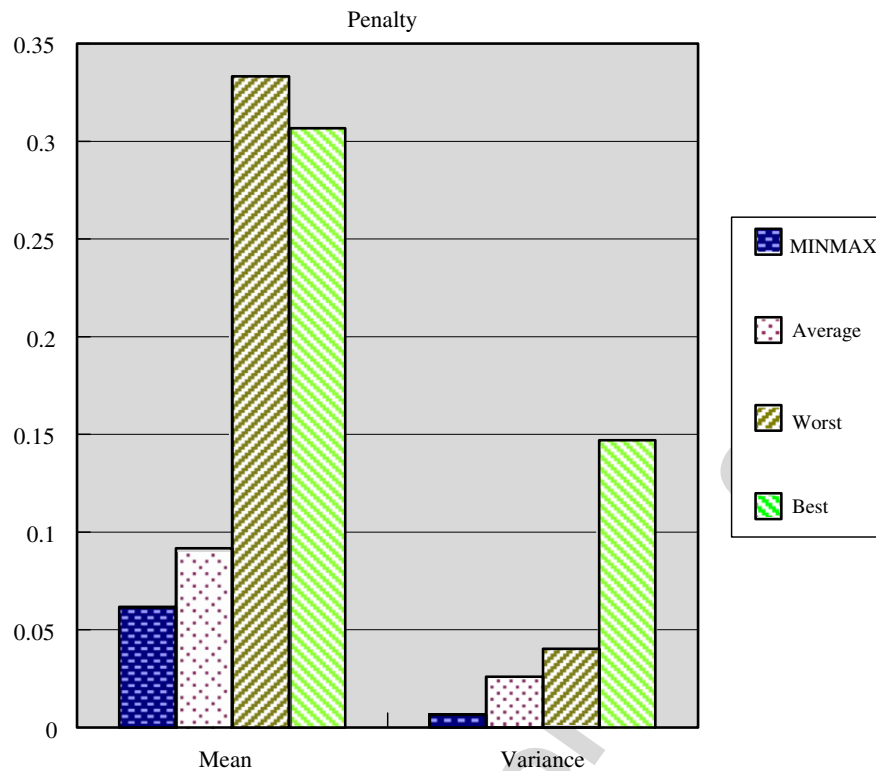
Fig. 18. Mean and variance of penalty of multiple users have disparate channel-loss characteristics.

Table 4
Penalty distortions of 13 users for one single and two streams

User	1	2	3	4	5	6	7	8	9	10	11	12	13
PLR (%)	1	1	1	1	1	3	3	3	5	5	10	15	20
Penalty													
Single stream	One single group												
	0.81	0.86	0.87	0.99	0.81	0.31	0.53	0.31	0.04	0.08	0.17	0.54	**1.00**
Two streams	*Group* #1										*Group* #2		
	0.05	0.04	0.13	**0.17**	0.05	0.04	0.05	0.04	0.03	0.15	0.09	0.02	**0.10**

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