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H.265/HEVC Video Coding Over Lossy Networks: Flexible or Fixed Mode in One CTU?

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ABSTRACT Flexible mode selection in one CTU, as one of the new technologies in H.265/HEVC video coding, can attain a high compression ratio. However, it may decrease the end-to-end PSNR for video communication over lossy networks. In this paper, we analyze the flexible prediction mode for the CTU in H.265/HEVC and find it causes more error propagation than fixed prediction mode in sub-pixel interpolation. Then, fixed mode-based error resilient encoding (FERE) is proposed to decrease the influence of error propagation. Experimental results show that the proposed FERE algorithm improves video quality by up to 5.56 dB compared with the baseline algorithms.

INDEX TERMS Error resilience, H.265/HEVC, video coding, rate-distortion optimization.

I. INTRODUCTION

The emerging video coding standard H.265/HEVC can attain high compression ratios for high definition (HD) video and the beyond-HD format. It introduces new hybrid video coding structures, such as the coding tree unit (CTU), coding unit (CU) and prediction unit (PU) [1]. Unlike the previous standard H.264, in which one macroblock (MB) had to be encoded by a particular prediction mode (inter or intra), H.265/HEVC can flexibly select the best prediction mode separately for each CU within one CTU. This kind of flexible mode can achieve high Rate-Distortion Optimization (RDO) performance. However, transmission errors may incur distortion when videos are transmitted over lossy networks. It is important to study H.265/HEVC video coding over lossy networks.

Methods of H.265/HEVC video coding have been widely researched. They mainly focus on complexity issues, such as fast intra and inter prediction ([2]–[5]) and fast CTU partitions ([6]–[8]). However, packet loss during transmission is not mentioned in these works.

Error resilient H.265/HEVC video coding has also been studied in recent years. In [9], the source and channel coding parameters are jointly optimized for video communication. The method of joint coding parameter selection and bit allocation was proposed in [10]. Carreira *et al.* [11] proposed an error resilient coding algorithm by transmitting predicted motion vectors as redundancy. In [12], the end-to-end distortion of variable size blocks is estimated in the DCT domain and then error resilient coding is proposed. In [13], two new modes, the unconstrained intra prediction mode and the soft-reset joint inter-intra prediction mode, are proposed for RDO coding mode selection, together with traditional inter and intra prediction modes. Thus, the algorithm with flexible control can trade-off error-resilience and compression. These algorithms aim to achieve better error resilience by considering the new technology of H.265/HEVC. However, the effect of flexible mode selection for the CUs within one CTU has not been studied for lossy networks.

When a video is transmitted in a lossy network, transmission distortion will propagate along the temporal and spatial prediction paths. As will be discussed later, the introduction of sub-pixels aggravates error propagation. In this paper, we focus on the problem of H.265/HEVC video coding over lossy networks. First, we analyze the error propagation in the reference sub-pixel interpolation when decoding a video with packet loss. It is illustrated that this error propagation will be reduced if we use the fixed prediction rather than the flexible prediction mode in H.265/HEVC to encode the CTU. Then, based on the well-known end-to-end distortion estimation method ROPE [14], we propose the fixed error resilient encoding (FERE) algorithm to decrease the influence of error propagation. Finally we give simulation results which compare the performance of FERE with two baselines, the ROPE-based RDO with flexible mode and random intra refreshing.

II. FIXED VS. FLEXIBLE CODING MODE FOR ONE CTU

Flexible mode selection in one CTU in H.265/HEVC video coding can attain a high compression ratio. However, when the video suffers from packet losses during transmission, errors will propagate more seriously when decoding.

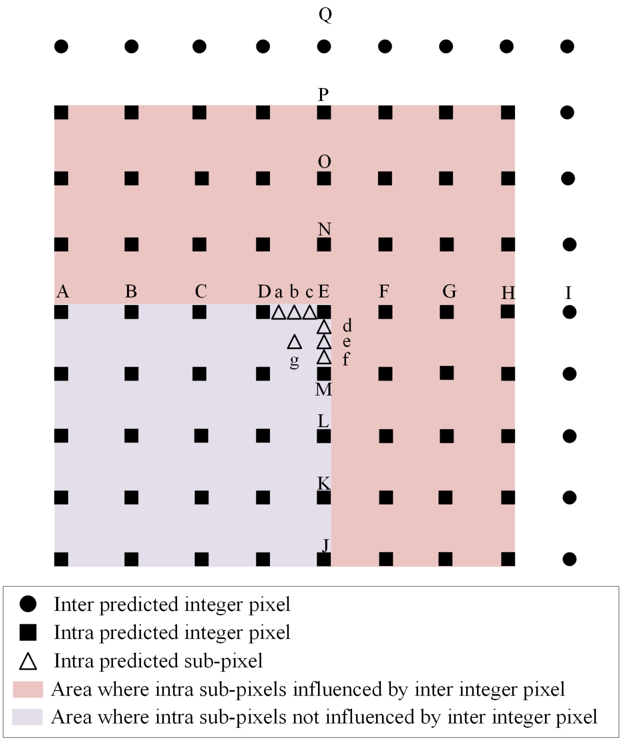


FIGURE 1. Error propagation from integer pixels to sub-pixels in the reference frame.

In H.265/HEVC encoders, 1/4-pixel-based motion estimation is used. In the reference frame, sub-pixels are interpolated from integer pixels, and the motion vectors are obtained at the 1/4 pixel level. Correspondingly, when an inter CU is decoded in the H.265/HEVC decoder, the reference CU should be matched by motion vectors at the 1/4 pixel level. Therefore, the reference frame needs to get the sub-pixels interpolated from integer pixels to create the reference CU. As shown in Fig. 1, the solid circles and squares denote inter and intra predicted integer pixels respectively, and sub-pixels are represented by triangles. In H.265/HEVC, given the weight by 8-tap filters, the 8 integer pixels in a line are used to interpolate the sub-pixels located in the middle. In Fig. 1, sub-pixels a∼c are interpolated from integer pixels A∼H, and d∼f are interpolated from integer pixels E and J∼P. A sub-pixel not in line with integer pixels, such as g in Fig. 1, needs to be interpolated from the 8 sub-pixels in the same line with it. Based on whether they are interpolated from inter integer pixels, the sub-pixels within an intra CU can be divided into two parts. The area where intra sub-pixels are influenced by inter pixels exists at the boundary between an inter and an intra CU with the width of 4 integer pixels.

Although inter mode generally achieves higher compression efficiency, it is more sensitive to channel errors as it promotes error propagation [14]. An error will spread into sub-pixels when they are interpolated using inter integer pixels. Besides the sub-pixels in an inter CU, the sub-pixels within an intra CU near the boundaries between an inter CU and an intra CU will also suffer from this error spread, as shown in Fig. 1. More boundaries between intra and inter CUs means more error will spread from inter integer pixels to intra sub-pixels.

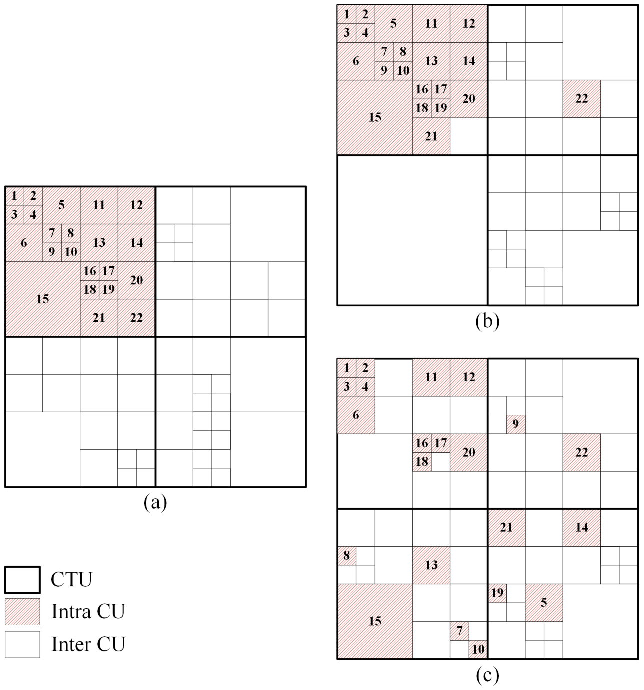


FIGURE 2. Illustration of (a) fixed mode, (b) flexible mode 1, (c) flexible mode 2.

When fixed and flexible prediction modes have the same proportion of intra pixels, there will be more boundaries in flexible mode than in fixed mode. In Fig. 2, we illustrate fixed mode in (a) and two different flexible modes in (b) and (c). The boundaries between inter and intra CUs can be regarded as the perimeters of the intra area here. An intra CTU of fixed mode is shown in Fig. 2(a). When a square is cut and separated into two parts as in Fig. 2(b), the perimeter will increase by twice the length of the nick while the area remains unchanged. Any set of CUs with the same area as the intra CTU in Fig. 1(a) can be regarded as cut and separated from the squared CTU. The perimeter of the set of CUs will be longer than the square CTU. Therefore, with the same intra proportion, the boundaries between intra and inter CUs for the fixed mode will be fewer than the flexible mode.

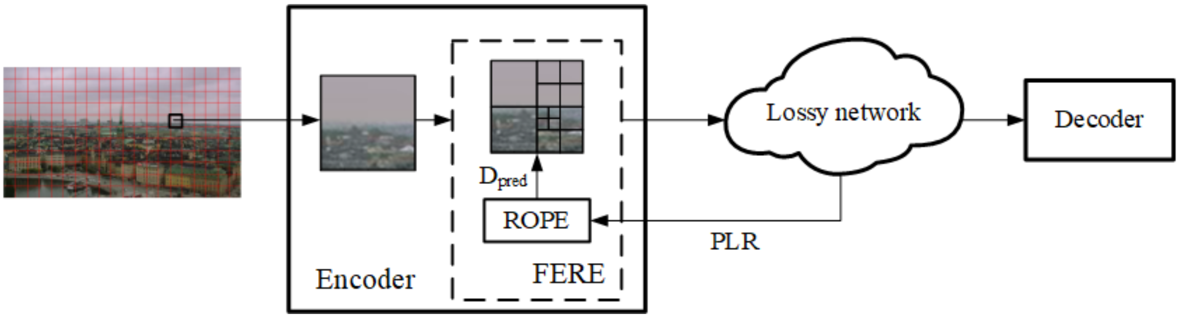


FIGURE 3. System architecture.

III. PROPOSED FIXED ERROR RESILIENT ENCODING (FERE) ALGORITHM

In our system architecture, shown in Fig. 3, video frames are encoded in the unit of a CTU with size 64 × 64. Given the packet loss rate (PLR) of the network, FERE estimates the end-to-end distortion by ROPE and determines the optimal CU partition mode and intra/inter prediction mode. We use either intra or inter prediction for each whole CTU in FERE. After transmission through the lossy network, some packets will be lost and the decoder conceals the error by copying the co-located pixels in the reference frame.

In our error resilient encoder, we use RDO to determine the optimal CU partition and intra/inter prediction mode for each CTU. The Lagrange minimization J_{CTU} is employed. We use C_1 and C_2 to denote the whole CU partition mode set of intra and inter prediction modes respectively, and c_1^* and c_2^* are the best CU partition modes for intra and inter encoding, respectively. The best prediction mode is represented by m^*. Thus, the best mode of a CTU is determined by

$$\left(c^*, m^*\right) = \begin{cases} \left(c_1^*, intra\right), & J_{CTU}\left(c_1^*\right) \le J_{CTU}\left(c_2^*\right) \\ \left(c_2^*, inter\right), & J_{CTU}\left(c_1^*\right) > J_{CTU}\left(c_2^*\right) \end{cases} \tag{1}$$

When the CTU is encoded by intra prediction, the best CU partition mode for intra encoding c_1^* can be obtained by

$$\begin{aligned} c_1^* &= \arg\min_{c_1 \in C_1} \left\{J_{CTU}\left(c_1\right)\right\} \\ &= \arg\min_{c_1 \in C_1} \left\{D_{CTU}\left(c_1\right) + \lambda R_{CTU}\left(c_1\right)\right\} \end{aligned} \tag{2}$$

When the CTU is encoded by inter prediction, the best CU partition mode for inter encoding c_2^* can be obtained by

$$\begin{aligned} c_2^* &= \arg\min_{c_2 \in C_2} \left\{J_{CTU}\left(c_2\right)\right\} \\ &= \arg\min_{c_2 \in C_2} \left\{D_{CTU}\left(c_2\right) + \lambda R_{CTU}\left(c_2\right)\right\} \end{aligned} \tag{3}$$

In Eq. (2) and Eq. (3), D_{CTU} is estimated using the ROPE method. Since ROPE estimates the distortion for each pixel,

$$D_{CTU} = \sum_{CTU} d_n^i \tag{4}$$

where d_n^i is the expected end-to-end distortion of pixel i in frame n in the decoder, which is calculated by

$$d_n^i = E\left\{\left(f_n^i - \tilde{f}_n^i\right)^2\right\} = \left(f_n^i\right)^2 - 2f_n^i E\left\{\tilde{f}_n^i\right\} + E\left\{\left(\tilde{f}_n^i\right)^2\right\} \tag{5}$$

where f_n^i is the original pixel value, and $\hat{f}_n^i$ and $\tilde{f}_n^i$ are the reconstructed values in the encoder side and the decoder side respectively. Let $\hat{r}_n^i$ be the reconstructed residue in the encoder. For an Intra-predicted pixel, the calculation of the first and second moments of the random variable $\tilde{f}_n^i$ are given by

$$E\left\{\tilde{f}_n^i\right\}(I) = (1-p)\left(\hat{f}_n^i\right) + pE\left\{\tilde{f}_{n-1}^i\right\} \tag{6}$$

$$E\left\{\left(\tilde{f}_n^i\right)^2\right\}(I) = (1-p)\left(\hat{f}_n^i\right)^2 + pE\left\{\left(\tilde{f}_{n-1}^i\right)^2\right\} \tag{7}$$

For pixel i in frame n, the reference is pixel j in frame $n-1$. For an Inter-predicted pixel, the distortion calculation will be

$$\begin{aligned} &E\left\{\tilde{f}_n^i\right\}(P) \\ &\quad = (1-p)\left(\hat{e}_n^i + E\left\{\tilde{f}_{n-1}^j\right\}\right) + pE\left\{\tilde{f}_{n-1}^i\right\} \end{aligned} \tag{8}$$

$$\begin{aligned} &E\left\{\left(\tilde{f}_n^i\right)^2\right\}(P) \\ &\quad = (1-p)\,E\left\{\left(\hat{e}_n^i + \tilde{f}_{n-1}^j\right)^2\right\} + pE\left\{\left(\tilde{f}_n^i\right)^2\right\} \\ &\quad = (1-p)\left(\left(\hat{e}_n^i\right)^2 + 2\hat{e}_n^i E\left\{\tilde{f}_{n-1}^j\right\} + E\left\{\left(\tilde{f}_{n-1}^j\right)^2\right\}\right) \\ &\qquad + pE\left\{\left(\tilde{f}_{n-1}^i\right)^2\right\} \end{aligned} \tag{9}$$

Eqns. (5) to (9) are from [14]. In Eq. (6) to (9), p represents the packet loss rate during transmission. Basic ROPE can be inaccurate since in motion estimation of inter pixels, the current pixels need to refer to the sub-pixels in the reference frame, which is acquired by the interpolation of integer pixels. However, in Eq. (8) and Eq. (9), $E\{\tilde{f}_n^i\}$ and $E\{(\tilde{f}_n^i)^2\}$ are the expected first and second moments of integer pixels, which have a difference from the values of sub-pixels. To avoid this inaccuracy, we use the method in [15] to interpolate the first and second expected moments of sub-pixels by those values of integer pixels. The interpolation filter here is an 8-tap filter which is the same as the sub-pixel interpolation filter in H.265/HEVC.

In a traditional H.265/HEVC encoder, the Lagrange multiplier is taken to be

$$\lambda_t = -\frac{\partial D_s}{\partial R} \tag{10}$$

where D_s represents the encoding distortion.

In Eq. (2-3) and Eq. (3), because the distortion contains both encoding distortion and packet loss distortion, the Lagrange multiplier here is not the same as in the traditional HEVC encoder. Based on the derivation in [16], the predicted distortion in Eq. (2) and Eq. (3) can be divided as

$$D_{CTU} = (1-p)\,D_s + (1-p)\,D_{ep} + pD_{ec} \tag{11}$$

where D_{ep} and D_{ec} denote error-propagated distortion and error-concealment distortion, which are not correlated with R. Therefore, as done in [16], the Lagrange multiplier is adjusted as

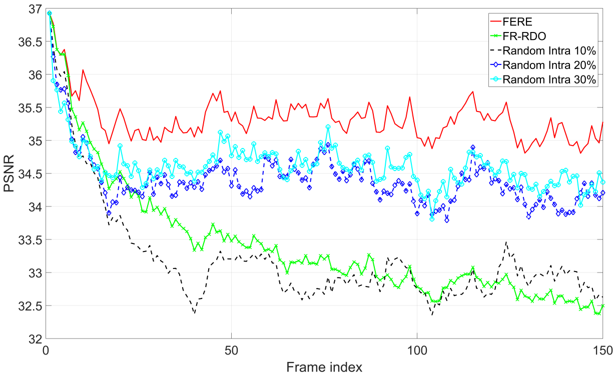
$$\lambda = -\frac{\partial D_{CTU}}{\partial R} = (1-p)\,\lambda_t \tag{12}$$

In this way, we obtain the best mode for error resilient coding based on FERE.

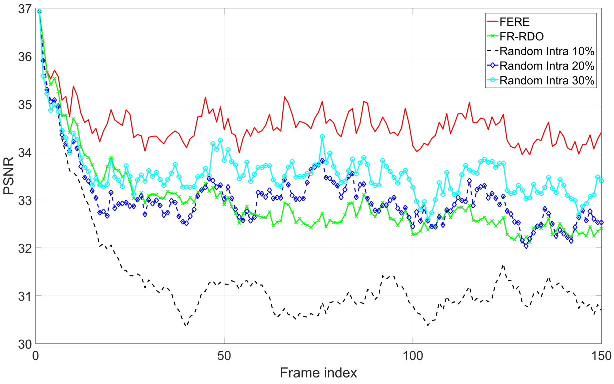
IV. SIMULATION RESULTS

In our experiments, FERE, flexible ROPE-based RDO (FR-RDO) and random intra refresh are implemented as three different error resilient encoding methods. In flexible ROPE-based RDO, the CUs within a CTU can flexibly select the best prediction mode in intra/inter like the mode selection in HEVC. In random intra refresh, we randomly set 10%, 20% and 30% of CTUs to be encoded by intra mode. Note that for random intra refresh, the prediction mode here is actually fixed mode. We use one NTSC video sequence (*Football*), one 480p video sequence (*Basketball drill*) and four different 720p video sequences (*Old town cross*, *In to tree*, *Stockholm*, *Ducks take off*) in our simulation. Each slice contains one CTU in our encoder and each CTU is packed in a separate packet. For each video sequence, the packet loss rates are set to be 3%, 5% and 10%, and a random packet loss generator is used to drop packets under the loss rate. For each packet loss rate, we simulate 30 different realizations of the lossy channel. Average PSNR is computed from the average value of the MSEs in the decoder for these channel realizations.

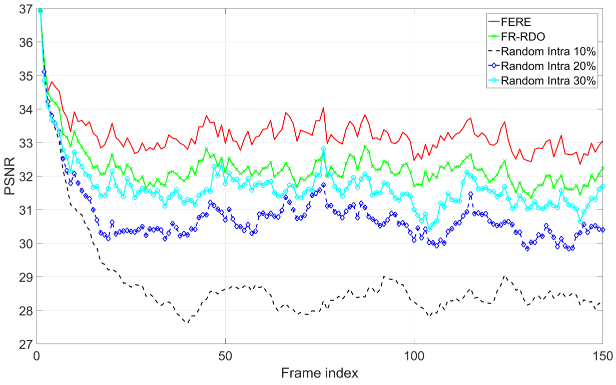
In Fig. 4, for *Old town cross* with the bitrate of 5 Mbps, we find that FERE produces a better end-to-end video quality than the baselines for all the different packet loss rates tested. At 3% and 5% packet loss rate, FR-RDO gets worse performance than 20% and 30% random intra refresh. The reason is that when packet loss rate is low, the advantages of FERE and FR-RDO which choose the best mode by RDO are not obvious. Due to the flexible mode in FR-RDO, the video quality will be influenced by more error propagation, thus in Fig. 4(a) and (b), random intra refresh performs better than FR-RDO.



(a) PLR=3%



(b) PLR=5%



(c) PLR=10%

FIGURE 4. Simulation results for ***Old town cross*** at different packet loss rates. (a) PLR = 3%, (b) PLR = 5%, (c) PLR = 10%.

Table 1 shows that for all video sequences in our experiment, FERE outperforms FR-RDO and random intra refresh by 0.4-5.56dB. For *Football* and *Basketball drill* at 2 Mbps, FERE improves the PSNRs by 0.48-1.63dB compared with FR-RDO, while for *Old town cross*, *In to tree* and *Stockholm* at 5 Mbps, the improvement is 0.73-1.99dB. For *Ducks take off*, which has complex content, we encode it at 8 Mbps to achieve an acceptable end-to-end video quality (average PSNR is higher than 30dB). FERE still yields a PSNR

TABLE 1. Comparison of average PSNRs at different packet loss rates.

Sequences	Algorithms	PSNR of Different PLRs (dB)		
		PLR=3%	PLR=5%	PLR=10%
Football NTSC, 2 Mbps	FERE	31.11	29.78	27.95
	FR-RDO	30.30	29.03	27.47
	Random Intra 10%	30.61	29.16	27.49
	Random Intra 20%	30.25	29.35	27.54
	Random Intra 30%	30.62	29.27	27.52
Basketball drill 480p, 2 Mbps	FERE	34.90	34.02	32.48
	FR-RDO	33.60	32.39	31.50
	Random Intra 10%	34.20	33.44	31.93
	Random Intra 20%	34.40	33.51	31.99
	Random Intra 30%	34.45	33.57	32.06
Old town cross 720p, 5 Mbps	FERE	35.32	34.54	33.19
	FR-RDO	33.33	32.89	32.22
	Random Intra 10%	33.14	31.25	28.66
	Random Intra 20%	34.39	33.01	30.73
	Random Intra 30%	34.61	33.54	31.61
In to tree 720p, 5 Mbps	FERE	35.26	34.63	33.55
	FR-RDO	33.77	33.33	32.69
	Random Intra 10%	33.05	31.44	29.08
	Random Intra 20%	34.29	33.07	31.02
	Random Intra 30%	34.60	33.70	31.96
Stockholm 720p, 5 Mbps	FERE	31.90	30.91	29.41
	FR-RDO	30.95	30.18	28.57
	Random Intra 10%	27.69	25.99	23.85
	Random Intra 20%	29.57	27.89	25.57
	Random Intra 30%	30.55	28.96	26.73
Ducks take off 720p, 8 Mbps	FERE	30.90	30.41	29.45
	FR-RDO	30.11	29.64	28.85
	Random Intra 10%	29.44	28.07	25.66
	Random Intra 20%	30.27	29.24	27.27
	Random Intra 30%	30.50	29.62	27.95

TABLE 2. Percentage of Intra CUs at different packet loss rates.

Sequences	Algorithms	Percentage of Intra CUs (%)		
		PLR=3%	PLR=5%	PLR=10%
Football NTSC, 2 Mbps	FERE	30.71	37.66	46.82
	FR-RDO	24.69	28.91	36.05
Basketball drill 480p, 2 Mbps	FERE	20.50	23.02	26.76
	FR-RDO	15.87	17.26	19.50
Old town cross 720p, 5 Mbps	FERE	10.50	13.80	19.95
	FR-RDO	9.27	11.82	16.38
In to tree 720p, 5 Mbps	FERE	17.97	21.38	25.85
	FR-RDO	12.32	14.74	18.62
Stockholm 720p, 5 Mbps	FERE	26.33	32.89	44.44
	FR-RDO	20.72	25.21	31.82
Ducks take off 720p, 8 Mbps	FERE	20.03	26.81	40.15
	FR-RDO	20.85	27.34	39.81

improvement of 0.60 to 0.79dB, although FR-RDO uses a high proportion of intra CUs.

We also present the percentage of intra CUs for FERE and FR-RDO at different packet loss rates in Table 2. The intra mode proportion depends on the packet loss rate and on the video content. Video sequences with complex contents such as *Stockholm* and *Ducks take off* tend to be encoded with more intra CUs. Moreover, the intra percentage in our proposed FERE is higher than the percentage in FR-RDO in most cases. However, at the packet loss rates 3% and 5% of *Ducks take off*, although the intra proportions in FERE are 0.82% and 0.53% lower than in FR-RDO, FERE still performs better by 0.79dB and 0.77dB due to less error propagation than FR-RDO.

V. COMPLEXITY ANALYSIS

In this section, we compare the number of possible encoding modes in fixed and flexible mode. In flexible mode, for a 16×16 CU, there exist 2 possible modes (intra and inter) if it is not split and 2^4 modes if it is split into four 8×8 sub-CUs. Thus the number of possible encoding modes for a 16×16 CU is $2 + 2^4 = 18$. In a similar way, there are $2 + 18^4 = 104978$ different modes for a 32×32 CU. So the total number of possible modes for the CTU in flexible mode is $2 + 104978^4 = 1.2145 \times 10^{20}$.

In fixed mode, for either intra or inter prediction, the numbers of CU partition patterns are equal. Based on whether it is split into four 8×8 sub-CUs, the 16×16 CU has 2 possible partition modes. Furthermore, there exists $1 + 2^4 = 17$ and $1 + 17^4 = 83522$ different partition modes for 32×32 and 64×64 CUs respectively. Therefore, the CTU in fixed mode has $83522 \times 2 = 167044$ possible encoding modes, which is far less than the number of modes in flexible mode.

VI. CONCLUSION

In this paper, an error resilient video encoding method FERE is proposed to improve the end-to-end video quality. The encoder selects the best fixed mode for each CTU, which can substantially reduce the influence of error propagation from integer pixels to sub-pixels when decoding. Experimental results show that the proposed method considerably improves the end-to-end quality of video with packet loss by 0.4-5.56dB when compared with FR-RDO and random intra refresh.

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