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REGULAR PAPER

Lossless video coding based on pixel-wise prediction

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Abstract The state-of-the-art H.264/AVC was designed for lossy video coding in the beginning. Recently, the H.264/AVC FRExt was developed by removing transformation and quantization for lossless coding. In this paper, we propose an efficient intra lossless coding method based on a pixel-wise prediction. The proposed algorithm introduces an additional intra prediction mode that employs the LOCO-I predictor of JPEG LS. We found that the proposed lossless coding algorithm achieved approximately 22.0, 2.6, and 10.7% bit saving in terms of compression ratio, compared to the H.264/AVC FRExt, lossless intra 4:4:4, and Takamura's lossless coding methods, respectively.

Keywords H.264/AVC · Lossless video coding · DPCM · Intra prediction · FRExt

1 Introduction

Recently, there has been an increasing demand for lossless video coding for medical image archiving and professional content productions. To accommodate these market-driven demands, the H.264/AVC, standardized by the joint video team (JVT), a collaboration of ISO/IEC moving picture experts group (MPEG) and ITU-T video coding experts group (VCEG) [1] has recently been extended to a fidelity range extension (FRExt) [2,3].

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The H.264/AVC is based on intra-frame and inter-frame coding similar to prior coding standards. The H.264/AVC makes use of quantization and transformation of residual signals produced by intra and inter predictions [4,5]. For the intra frame coding, intra prediction with previously coded blocks plays an important role in achieving high coding gain. Intra prediction of the H.264/AVC is known to be effective for lossy video coding, however, this is not the case for lossless video coding because intra coding cannot remove all of the inter-pixel redundancy for lossless video coding. Several lossless coding algorithms have been proposed based on prediction and entropy coding [6–12]. Among existing lossless coding algorithms, the JPEG LS is known to be the most effective for lossless image compression. However, the lossless intra 4:4:4 coding based on the H.264/AVC [6,7] is known to be the most effective among lossless coders supporting video coding functionality. The lossless 4:4:4 coding utilizes inter-pixel prediction along the horizontal or vertical direction according to a selected intra prediction mode. However, it might not be able to remove all the inter-pixel redundancy. In this paper, we propose a lossless intra frame coding method utilizing a pixel-based prediction rather than a block-based prediction. In the proposed algorithm, an additional inter-pixel prediction mode is added to the H.264/AVC's nine intra prediction modes. We call this option the DPCM prediction mode. In our experiments, the proposed algorithm is shown to be approximately 11–30% better than the conventional H.264/AVC FRExt in terms of compression ratio.

In Sect. 2, we will introduce the conventional intra prediction of the H.264/AVC. In Sect. 3, we will present the proposed lossless video algorithm. In Sect. 4, we will show the effectiveness of the proposed algorithm with several video sequences. Finally, we will state our conclusion and further study plans are given in Sect. 5.

2 The H.264/AVC intra prediction and mode decision

The intra prediction method of the H.264/AVC is based on likelihood of neighboring pixels being similar to a current pixel. The intra-prediction approach of the H.264/AVC is different from the MPEG-4 Part 2 and prior video standards in the sense that the H.264/AVC prediction is conducted on an image domain, not a frequency domain [13]. Furthermore, it is performed on a 4×4 block or a 16×16 block. Recently, the fidelity range extension (FRExt) of the H.264/AVC has allowed it to use an 8×8 block intra prediction. For both the 4×4 and 8×8 block cases of the H.264/AVC, one of nine different prediction modes can be used according to the corresponding prediction direction. Figure 1 shows the nine intra direction modes of the H.264/AVC. For example, if mode 0 (vertical) is selected, all pixels of each column are predicted by the corresponding upper pixels A, B, C or D. This prediction method can be considered as a zero-order prediction, meaning that several target pixel values are predicted by one single value. This prediction method leaves an opportunity for some redundancy to remain between inter pixels in the block. This redundancy could be reduced by pixel-wise prediction for lossless coding.

The best mode among the nine prediction directions can be determined based on rate-distortion optimization using the Lagrangian cost function [14], defined by

$$J = \text{distortion} + \lambda_{\text{MODE}} \times \text{rate}$$
$$\text{MODE} \in [\text{INTRA}4 \times 4, \text{INTRA}16 \times 16], \quad (1)$$

where the distortion term is absolute difference between original and reconstructed signals, and the rate term represents the amount of actual bits produced by the H.264/AVC entropy coding. λ_{MODE} is the Lagrangian constant depending on a quantization level. For lossless coding, criterion for selecting the best mode can be simplified into

$$\text{Best\_mode} = \text{Arg}_{\text{MODE}}\text{MIN}[\text{Rate}_{\text{MODE}}]$$
$$\text{MODE} \in [\text{INTRA}\,4 \times 4, \text{INTRA}\,16 \times 16] \quad (2)$$

because the distortion of lossless coding is zero. MIN[$\cdot$] represents a minimum value of costs. Even if the best intra mode is selected by the mode having a minimum rate, residual signal could still have redundancy between consecutive pixels in a block. The rationale for this redundancy is that four consecutive pixels in a block are predicted by the one single value of their neighboring block. In this paper, we propose a lossless coding mode based on inter-pixel prediction for the H.264/AVC video coder.

3 Proposed lossless intra coding methods

Recently, as demands for medical images or professional digital content authoring applications have been rapidly increasing, lossless compression has become a topic of interest. The H.264/AVC FRExt was standardized to support a lossless coding mode. The lossless mode of the H.264/AVC FRExt employs the nine-directional prediction modes and context-adaptive entropy coding for encoding image sample

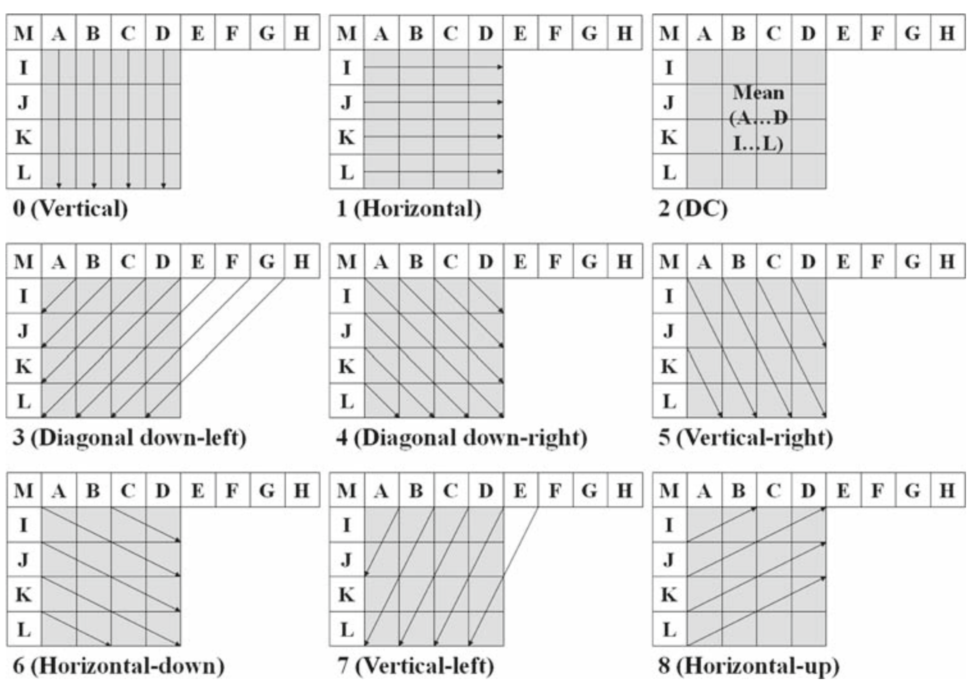


Fig. 1 Nine intra prediction modes

values, excluding integer transform and quantization [15]. However, the intra prediction of the H.264/AVC could not be the most effective in removing redundancy between inter pixels, as mentioned before. To reduce the redundancy between adjacent pixels in a block, we propose an additional DPCM prediction mode based on the MED predictor inside at each block. This algorithm is presented as follows:

3.1 Proposed DPCM prediction mode (DPCM PM)

To verify the efficiency of utilizing DPCM for residual signals, we applied pixel-wise prediction to residual signal of the H.264/AVC intra prediction. The residual signal obtained by the H.264/AVC intra prediction is selectively predicted to remove inter-pixel redundancy by the DPCM [16,17]. We call this approach selective residual DPCM (SR DPCM). Figure 2 shows the block diagram of the SR DPCM lossless intra coding by embedding a DPCM in the H.264/AVC coder, following the intra prediction. In our experiment, we found that the SR DPCM is selected for the majority of blocks in a frame. The encoder transmits one signaling bit per 16×16 block (or 4×4 block) (mode flag as shown in Fig. 2) to indicate whether DPCM is used or not. Based on combined prediction using the inherent coding efficiency of the H.264/AVC intra prediction as well as the inter-pixel prediction, the proposed lossless coding can outperform the state-of-the-art H.264/AVC FRExt lossless coding mode. In addition, the transform and quantization were not employed as in the H.264/AVC FRExt lossless coding mode. Note that F_n and F'_n in Fig. 2 are the same in lossless coding mode.

Figure 3 shows the proposed DPCM prediction mode as a new intra prediction mode of the H.264/AVC for lossless video coding. The existing H.264/AVC employs nine intra prediction modes and we propose to add one more DPCM prediction mode useful for lossless video coding. The DPCM PM is based on inter-pixel prediction on image domain and each pixel value in the block is predicted with an adjacent pixel value. The pixel values at the top column and the most left row in the block are predicted with those at neighboring blocks. This modified lossless intra video coding can be chosen in addition to the existing prediction modes to determine the best prediction mode by minimizing rate, defined by

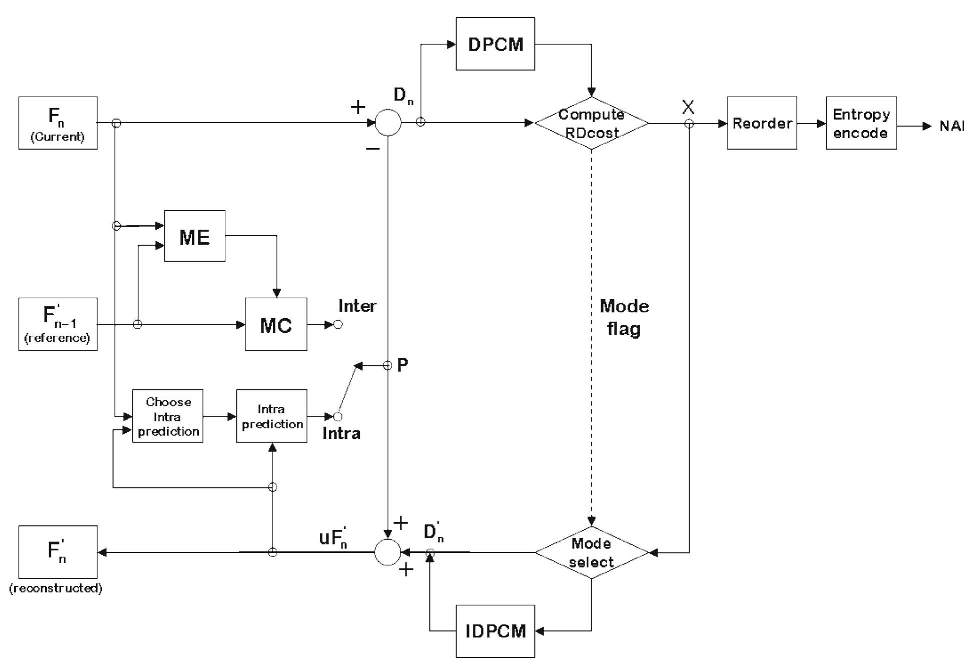
$$\text{Best\_Mode} = \text{Arg}_{\text{MODE}}\text{MIN}[\text{Rate}_{\text{MODE}}] \tag{3}$$

$$\text{MODE} \in [\text{INTRA}\,4 \times 4,\ \text{DPCM PM}(4 \times 4),$$
$$\text{INTRA}16 \times 16,\ \text{DPCM PM}(16 \times 16)].$$

For 4×4 block cases, the best mode would be selected not only among the existing nine intra prediction modes, but also the additional DPCM prediction mode. For the 16×16 cases, the 16×16 DPCM prediction mode will compete with four INTRA16×16 modes of the H.264/AVC. As a result, a best prediction mode among the 15 modes would be determined and coded. Then, it would be referred to an intra prediction on a decoder side.

Note that the pixel-wise prediction was used in the JPEG lossless image coding because it was known to be effective in removing inter-pixel redundancy. However, our proposed lossless intra coding makes use of the pixel-wise prediction

Fig. 2 Block diagram of the proposed SR DPCM for lossless video coding



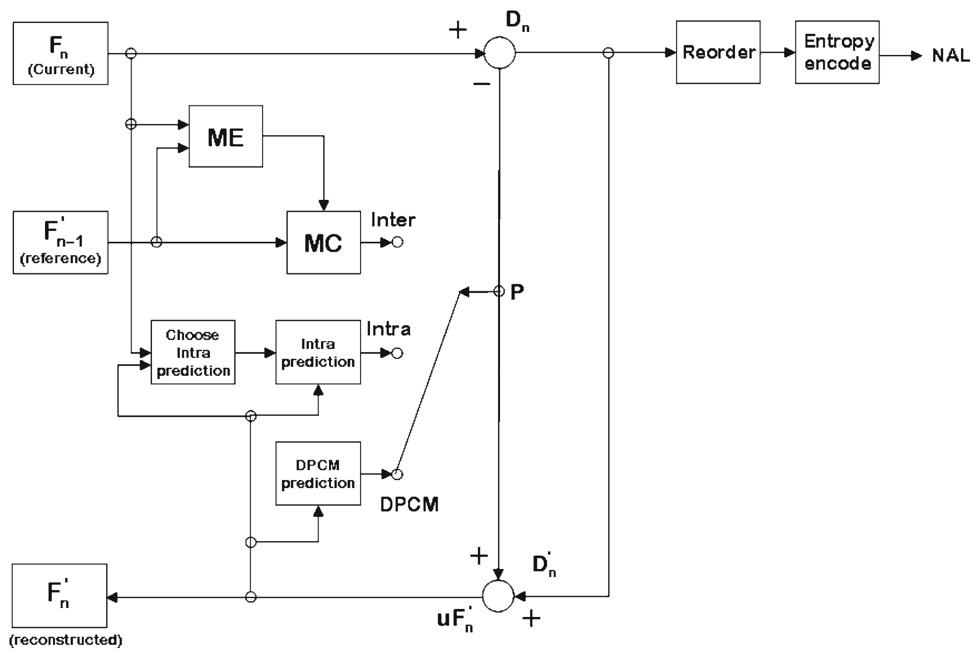


Fig. 3 Block diagram of the proposed DPCM PM for lossless video coding

as well as the H.264/AVC zero-order prediction at the same time according to minimum rate [18].

3.2 Pixel-wise predictor for lossless coding

In our proposed lossless intra coding, the pixel-wise prediction is carried out in a 4 × 4 block or a 16 × 16 block. For example, the current pixel x is predicted by its neighboring pixels, as shown in Fig. 4. The pixel-wise prediction is performed using the location of the pixel in a block, as shown in Fig. 5. For example, the most upper left pixel cannot be predicted because there are no available neighboring pixels. Except for the upper left pixel, each pixel on the first line in a block is predicted with the left pixel value in the same line. In a similar fashion, the pixel on the first vertical column is predicted with the above pixel of the current pixel x. Otherwise, the current pixel value can be predicted with the previously coded a, b, and/or c.

In our experiment, we employ the LOCO-I predictor [18] as the DPCM, as shown in Figs. 2 and 3. The LOCO-I operator is defined by

$$\hat{x}_{\mathrm{LOCO-I}} = \begin{cases} \min(a,b) & \text{if } c > \max(a,b) \\ \max(a,b) & \text{if } c < \min(a,b). \\ a+b-c & \text{otherwise} \end{cases} \tag{4}$$

If the pixel value c is larger than the two-pixel values: a and b, the LOCO-I decides $\min(a,b)$ as the predicted value. That means, the value c and $\max(a,b)$ are considered to be in the same object and the value x and $\min(a,b)$ are considered to be in the same object, making the assumption that there is an edge between $(c, \max(a,b))$ and $(x, \min(a,b))$. If the pixel value c is smaller than the others, $\max(a,b)$ is used as a prediction value for the current pixel x. Thus, the pixel x and $\max(a,b)$ are considered to be the same object. Otherwise, the prediction value of the current pixel x is defined by $a+b-c$.

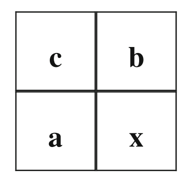


Fig. 4 Pixel to be predicted and its neighboring pixels

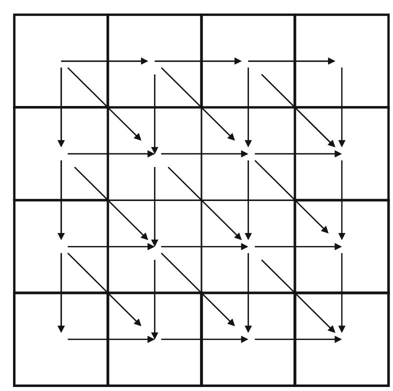


Fig. 5 4 × 4 intra prediction directions

3.3 Pixel-wise prediction of chrominance components

We applied two inter-pixel prediction methods not only to the luminance, but also to the chrominance components (Cb and Cr). Intra prediction for chrominance components is conducted by selecting one of four modes in an 8×8 block. For the SR DPCM, the DPCM is performed on the residual signal obtained by the best 8×8 intra prediction mode. For the DPCM PM, the DPCM prediction competes with the H.264/AVC's four prediction modes, defined by

$$\begin{aligned}&\text{Best\_Mode} = \text{Arg}_{\text{MODE}}\text{MIN}[\text{Rate}_{\text{MODE}}]\\&\text{MODE} \in [\text{INTRA } 8 \times 8,\ \text{DPCM PM } (8 \times 8)].\end{aligned} \quad (5)$$

4 Experiments

In order to show the effectiveness of the proposed lossless intra video coding, we have implemented the proposed algorithms in the JM reference software version 9.8 [19]. We used "Container", "News", "Silent", and "Stefan" sequences of 176×144 pixels (QCIF format, 4:2:0) and "Coastguard", "Foreman", "Mobile", "Paris", and "Silent" sequences of 352×288 pixels (CIF format, 4:2:0). Frame rates of these sequences are all 30 frames per second (fps). Each sequence consists of 100 frames and all the sequences are encoded as intra frames. In our experiments, we used the CABAC for entropy coding.

Table 1 shows the energy of residual signals for luminance and the chrominance components separately. Here, the energy is measured by mean square error (MSE) of the residual signal. The proposed algorithm significantly reduced energy of the original residual signals. At first, we found that up to 44% energy reduction was achieved by SR DPCM for luminance components. For the chrominance component,

Table 1 Reduction ratios of signal energy for luma and chroma components (*QCIF, +CIF)

Test sequence	MSE			Residual energy reduction ratio (%)	
	H.264/AVC FRExt	SR DPCM	DPCM PM	SR DPCM	DPCM PM
Container*					
Luma	268.31	150.08	132.69	44.1	50.5
Chroma	55.00	1.22	1.03	97.8	98.1
News*					
Luma	341.50	186.55	180.31	45.4	47.2
Chroma	105.69	1.98	1.65	98.1	98.4
Silent*					
Luma	126.01	55.51	60.10	55.9	52.3
Chroma	31.55	1.62	1.65	94.9	94.8
Stefan*					
Luma	576.79	361.09	344.58	37.4	40.3
Chroma	134.09	4.66	4.11	96.5	96.9
Coastguard+					
Luma	171.63	75.15	71.79	56.2	58.2
Chroma	41.83	0.41	0.36	99.0	99.1
Foreman+					
Luma	77.06	45.28	42.40	41.2	45.0
Chroma	17.60	0.96	0.88	94.6	95.0
Mobile+					
Luma	731.98	471.13	467.10	35.6	36.2
Chroma	177.09	12.36	11.04	93.0	93.8
Paris+					
Luma	367.01	219.97	199.33	40.1	45.7
Chroma	82.83	2.67	2.23	96.8	97.3
Silent+					
Luma	81.68	48.90	49.23	40.1	39.7
Chroma	19.83	1.00	0.94	95.0	95.2
Average					
Luma	304.66	179.30	171.95	44.01	46.12
Chroma	73.94	2.99	2.66	96.18	96.52

Table 2 Selection ratios of proposed methods

Test sequence	Selection ratio (%)	
	SR DPCM	DPCM PM
QCIF		
Container	89.6	57.7
News	93.6	68.2
Silent	99.6	78.2
Stefan	98.8	63.2
CIF		
Coastguard	99.9	90.2
Foreman	81.4	55.2
Mobile	95.4	52.9
Paris	96.5	59.7
Silent	93.6	60.3
Average	94.3	65.1

we obtained up to 96% energy reduction for SR DPCM. In addition, our proposed DPCM PM achieved approximately up to 46 and 96% energy reduction for the luminance and the chrominance components, respectively. As shown in the table, the improved performance for the chrominance components seemed to be more significant because the chrominance predictor of the H.264/AVC was not as good as the luminance intra predictor. Although redundancy between consecutive pixels was not negligible even after the H.264/AVC spatial intra prediction, our proposed algorithm removed the redundancy effectively for the luminance and the chrominance components. Note that lossless coding gain highly depends on reduction of entropy rather than MSE of the prediction residual. However, when the MSE of prediction error is smaller, we can find statistically more zero and small residual values. Because the residual from prediction for video coding commonly has zero-mean Laplacian distribution, small MSE of the source statistically could reduce entropy of symbols for coding the residual signals.

To evaluate a performance of the proposed methods, we used the existing H.264/AVC FRExt lossless coding, lossless intra 4:4:4 coding proposed by Lee [6,7], Takamura's method [8], JPEG-2000 in lossless mode [20], and JPEG LS (LOCO-I) algorithm [21]. The lossless intra 4:4:4 coding was recently proposed and it is well-known as the best lossless

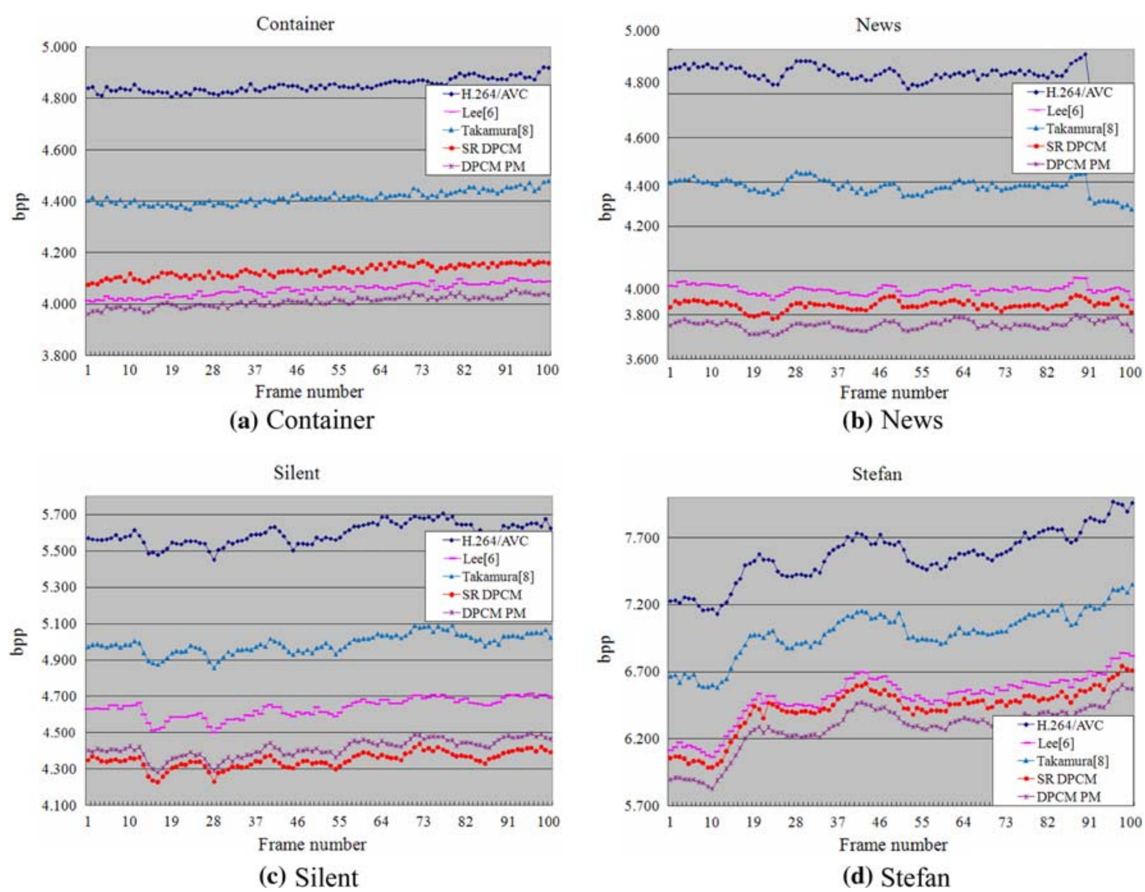


Fig. 6 Bits per pixel (*bpp*) produced by the proposed algorithm, H.264/AVC FRExt, Lee's, and Takamura's methods for each sequence, in terms of frame number. **a** 'Container' sequence, **b** 'News' sequence, **c** 'Silent' sequence, and **d** 'Stefan' sequence

Table 3 Compression ratios of the proposed methods and conventional algorithms (*QCIF, +CIF)

Test sequence	H.264/ AVC FRExt	JPEG-2000 in lossless mode	Lossless intra 4:4:4 [6]	Takamura [8]	JPEG LS LOCO-I	SR DPCM	DPCM PM
Container*	1.649	1.787	1.973	1.812	1.865	1.938	1.996
Silent*	1.430	1.728	1.726	1.603	1.796	1.840	1.813
News*	1.638	1.831	2.044	1.827	2.021	2.082	2.132
Stefan*	1.058	1.470	1.229	1.145	1.536	1.246	1.274
Coastguard+	1.396	1.692	1.678	1.633	1.665	1.693	1.714
Foreman+	2.019	1.917	2.264	2.157	2.009	2.261	2.271
Silent+	1.627	1.791	1.874	1.765	1.842	1.907	1.925
Paris+	1.379	1.633	1.715	1.518	1.758	1.695	1.744
Mobile+	0.982	1.402	1.146	1.051	1.459	1.143	1.170
Average	1.464	1.695	1.739	1.612	1.772	1.756	1.782

video coding method. In 2006, it was also adopted as International Standard in the JVT for the advanced intra 4:4:4 profile. We also compare coding efficiency of the proposed methods with that of prominent still-image compression methods, JPEG-2000 in lossless mode and JPEG LS.

Table 2 shows the selection ratio that our proposed DPCM modes were chosen as best modes. The SR DPCM option was selected as the best mode of approximately 94.3% and our proposed DPCM PM was selected as the best mode around 65.1%. We found that the DPCM PM was selected less frequently than the SR DPCM but the DPCM PM yields higher compression efficiency.

Figure 6 shows bits per pixel (bpp) in terms of the number of frames for the four QCIF test sequences. As shown in the figures, the DPCM PM was significantly better than the H.264/AVC FRExt and other methods. In particular, the conventional intra prediction yields the worst prediction performance for "Stefan" sequence, because its intra prediction has poor performance due to high spatial texture complexity. We found that the maximum coding gain was achieved by removing inter pixel-redundancy for the sequence.

Table 3 shows average compression ratios of the proposed methods and conventional algorithms for 100 frames of each sequence. The SR DPCM and DPCM PM methods are comparable to JPEG LS in compression efficiency. The proposed algorithms are better than the other methods. Compression ratio of the SR DPCM is 20% better than the H.264/AVC FRExt. Table 4 shows the percentage gain of the proposed algorithm again the H.264/AVC FRExt, lossless intra 4:4:4, and Takamura methods for the test sequences. Compression ratio of the DPCM PM is average 22.0% more efficient than the conventional H.264/AVC FRExt algorithm, as shown in the table. The DPCM PM offered coding gain of 2.6 and 10.7% against the lossless intra 4:4:4 coding and Takamura's methods, respectively. While pixel-wise prediction of the lossless intra 4:4:4 coding is performed along the horizontal or vertical direction according to a selected intra

Table 4 Coding gain of the proposed DPCM PM versus conventional methods (*QCIF, +CIF)

Test sequence	Coding gain of DPCM PM (%)		
	vs. H.264/AVC FRExt	vs. Lossless intra 4:4:4 [6]	vs. Takamura [8]
Container*	21.0	1.2	10.2
Silent*	26.8	5.0	13.1
News*	730.2	4.3	16.7
Stefan*	20.4	3.7	11.3
Coastguard+	22.8	2.1	5.0
Foreman+	12.5	0.3	5.3
Silent+	18.3	2.7	9.1
Paris+	26.5	1.7	14.9
Mobile+	19.1	2.1	11.3
Average	22.0	2.6	10.7

prediction mode, the proposed DPCM PM adaptively makes use of neighboring pixels. Furthermore, the proposed algorithm removes inter pixel redundancy not only inside 4 × 4 block but also across block boundaries. While the SR DPCM is conducted on residual domain obtained by the conventional intra prediction, the DPCM PM is considered as an additional inter-pixel prediction on image domain. That is the reason why the proposed DPCM PM is superior to the SR DPCM by around 2%.

5 Conclusions

In this paper, we proposed a lossless intra coding method by applying the selective residual DPCM (SR DPCM) and DPCM prediction mode (DPCM PM). The proposed algorithms contribute to reducing spatial redundancy of remaining residual signal even after the H.264/AVC intra prediction. The coding efficiency of the proposed lossless coding method was shown to be significantly improved through full codec implementation. In our further work, we will focus on applying the pixel-wise prediction to inter-frame coding. We will investigate the possibility of extending this idea to lossy video coding.

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References

1. ISO/IEC JTC 1, ISO/IEC JTC1/SC29/WG11 Coding of Moving Picture and Audio, Draft of version 4 of ISO/IEC 14496-10(E) MPEG/N7081, April (2005)
2. Sullivan, G.J., Topiwala, P., Luthra, A.: The H.264/AVC advanced video coding standard: overview and introduction to the fidelity range extensions. In: SPIE conference on application of digital image processing XXVII, vol. 5588, pp. 454–474. Denver, Canada (2004)
3. ITU-T and ISO/IEC JTC 1, Draft text of H.264/AVC fidelity range extensions amendment, JVT of ITU-T VCEG & ISO/IEC MPEG L-047 (2004)
4. Wiegand, T., Sullivan, G.J., Bjontegaard, G., Luthra, A.: Overview of the H.264/AVC video coding standard. IEEE Trans. Circuits Syst. Video Technol. **13**(7), 560–576 (2003)
5. Tamhankar, A., Rao, K.R.: An overview of H.264/MPEG-4 part 10. In: Fourth EURASIP conference on video/image processing and multimedia communications, vol. 1, pp. 1–51. Zagreb, Croatia (2003)
6. Lee, Y.L., Han, K.H., Lim, S.C.: Lossless intra coding for improved 4:4:4 coding in H.264/MPEG-4 AVC. JVT of ITU-T VCEG & ISO/IEC MPEG P-016 (2005)
7. Lee, Y.L., Han, K.H., Sullivan, G.J.: Improved lossless intra coding for H.264/MPEG-4 AVC. IEEE Trans. Image Process. **15**(9), 2610–2615 (2006)
8. Takamura, S., Yashima, Y.: H.264-based lossless video coding using adaptive transforms. In: IEEE International Conference Acoustics, Speech and Signal processing (*ICASSP '05),* vol. 2, pp. 301–304. Philadelphia, USA (2005)
9. Carotti, E.S.G., De Martin, J.C., Meo, A.R.: Backward-adaptive lossless compression of video sequences. In: IEEE International Conference Acoustics, Speech and Signal processing (ICASSP'02), vol. 4, pp. 3417–3420. Orlando, USA (2002)
10. Carotti, E.S.G., De Martin, J.C.: Lossless video coding using multiframe motion compensation. In: 13th EURASIP European Signal Processing Conference (EUSIPCO 2005), Antalya, Turkey (2005)
11. Brunello, D., Calvagno, G., Mian, G.A., Rinaldo, R.: Lossless compression of video using temporal information. IEEE Trans. Image Process. **12**(2), 132–139 (2003)
12. Fang, Y.C., Lee, C.Y., Wang, Y.M., Chiang, T.: Low complexity lossless video compression. In: IEEE International Conference on Image Processing (ICIP 2004), vol. 4, pp. 2519–2522, Singapore (2004)
13. ISO/IEC JTC 1: Coding of audio-visual object—part 2: Visual, MPEG-4 14496–2 Visual version 1 (1999)
14. ITU-T and ISO/IEC JTC 1: Text description of joint model reference encoding methods and decoding concealment methods, JVT of ITU-T VCEG & ISO/IEC MPEG N-046 (2005)
15. Sun, S.: New results of lossless coding. JVT of ITU-T VCEG & ISO/IEC MPEG D-028 (2002)
16. Iain E. G. Richardson: Video Codec Design, pp. 30–31. Wiley, New York (2002)
17. Chen, K., Ramabadran, T.V.: Near-lossless compression of medical images through entropy-coded DPCM. IEEE Trans. Med. Imaging **13**(3), 538–548 (1994)
18. Weinberger, M.J., Seroussi, G., Sapiro, G.: The LOCO-I lossless image compression algorithm: principles and standardization into JPEG-LS. IEEE Trans. Image Process. **9**(8), 1309–1324 (2000)
19. JVT Model reference software from ftp://ftp3.itu.ch/jvt-site/reference_software/jm98.zip.
20. Kakadu software (JPEG-2000) WIN32 executable from http://www.kakadusoftware.com.
21. LOCO-I/JPEG-LS software executable from http://www.hpl.hp.com/loco/