Lossless Image Compression Scheme with Binary Layers Scanning

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***Abstract*—In this work a novel lossless coding approach for color images is considered. It is based on local-adaptive combination of inter- and intra-component prediction. New context modeling method based on decomposition to binary layers is used for prediction errors. Compression performance of proposed algorithm is proved by experimental results obtained for popular public benchmarks.**

I. Introduction

In the modern world many applications, e.g. medical and astronomy imaging, are critical to visual artifacts. Most popular image compression standards e.g. JPEG-LS [1] and JPEG-2000 [2] have lossless mode, but they do not consider some image properties like correlation between color image components.

A common approach for lossless image compression is based on differential pulse-code modulation (DPCM) idea. Typical lossless image compression scheme is depicted in Fig. 1.

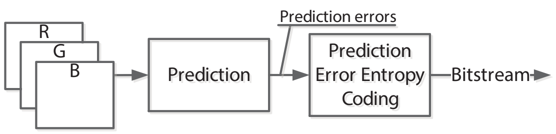

Fig. 1. Typical lossless image compression scheme

The main objective of prediction procedure is the reduction of adjacent pixels correlation. In case of color images both spatial (intra-component) and inter-component redundancy should be considered.

Entropy coding procedure is applied to the prediction errors for compression. The common structure widely used in image and video compression consists of two main blocks:

- *Context modeling*: the main objective of context modeling is the improvement of compression performance by considering *residual* correlation between prediction errors at neighboring positions;
- *Universal coding*: This procedure usually consists of probability estimation for symbols of the source with unknown statistic and also code construction based on obtained estimates.

In this paper a new lossless compression scheme for color images is proposed. Local adaptive of inter- and intra-component predictions is used in the proposed scheme. A new approach to scanning order based on decomposition by binary layers is considered in entropy coding part.

The paper is organized as follows. The essence of the proposed scheme is presented in section II. In section III we provide a formal description of the developed compression scheme. The evaluation results of the proposed scheme and comparison with state-of-the-art compression algorithms and standards are presented in section IV.

II. Background

In this section we provide a short description of prior art and ideas underlying the proposed compression scheme.

A. Prediction

The three channel RGB-based images are considered in this paper. In order to achieve good compression ratio, intra- and inter-component redundancy should be removed.

Various inter-component decorrelation transforms are widely used in compression standards to convert RGB color space to YCbCr [3] or its modifications. The main disadvantage of YCbCr-based transforms is the irreversibility due to rounding after float-point calculations. These color transforms also do not take into account the local characteristics of the image components. Thus for regions with low inter-components correlation the transform might increase the variance of prediction errors. The assumption of expectation values matching for different components is usually not valid for photorealistic images.

Let us denote prediction between components as *inter* prediction and spatial prediction as *intra* prediction. Median edge detection (MED) [1] and gradient adjusted prediction (GAP) [4] are state-of-the-art intra prediction methods. Some codecs, e.g. JPEG-LS part 2 [5], use a combination of intra and inter predictions. According to JPEG-LS part 2 standard inter prediction is followed by the intra one. The main feature of this scheme is simplicity. However, errors variance obtained by prediction method from [5] has usually the same order with errors variance of MED prediction (intra only) applied to original components separately. This fact can be explained by the low performance of the previous inter-component decorrelation transform, especially when the components' expectations are different.

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Proposed prediction scheme is a *combination* (weighted sum) of intra and inter prediction. The main advantage of proposed scheme is local-adaptation which allows the problem of different correlation in local image regions to be avoided. This approach allows to the best prediction value for each pixel be selected. We will refer to the proposed method as LCP (Local-adaptive Combined Prediction method). In tables II, III of section IV demonstrates efficiency of LCP scheme.

B. Prediction Errors Entropy Coding

The input values of entropy coding block are prediction errors. They are non-binary values which can also be negative. It was suggested to represent each prediction error as a pair of sign and absolute value (abs). In practice, compression performance increases with the growth of encoded data amount due to coder adaptation to unknown source statistics. Therefore joint processing of values with similar statistics is preferable. Sign and absolute value representation is similar to modulo reduction and error mapping methods from JPEG-LS standard [1].

Binary arithmetic coding [6] is used for sign and absolute values compression in proposed scheme. Arithmetic coding is a state-of-the-art compression approach, which is especially efficient for single-pass universal encoding. Most popular image and video compression standards [2], [7] use various versions of adaptive *binary* arithmetic codecs [8], [9] due to their implementation simplicity. To map the output of non-binary source to binary presentation several codes are used, e.g. uniform and unary codes. It is easy to show that usage of unary code for such "binarization" does not increase entropy of original non-binary source. Mapping by unary code forms a set of independent binary sources $X^{(i)}$ $(i = 1 \dots N$, where N is alphabet of original non-binary source $X)$ as shown in Fig. 2. Entropy of X can be written as:

$$H(X) = \sum_i \omega_i H(X^{(i)}), \tag{1}$$

where $\omega_i = Pr\{i - th$ binary stream is used $\}$. Therefore, usage of unary code allows to make a transition from non-binary source to set of binary sources without loss in compression performance.

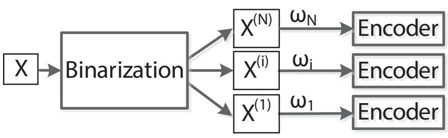

Fig. 2. Representation of non-binary source X as a set of binary sources $X^{(i)}$. Value ω_i represents portion values from i-th binary source

The combined result of absolute values binarization by unary code resembles a *surface relief* (see Fig. 3.a). Binarized vectors are arranged vertically. The scanning order of encoded bits is similar to bit-plane style of JPEG-2000 standard [10]. We will call this structure as *binary layers* or *bin-layers*. The example of bin-layer decomposition is depicted in Fig. 3.b. It should be noted that binarization vectors have different lengths so the bin-layers may have empty positions (difference JPEG-2000 standard). Bits in such positions should be not encoded during layer encoding. In Fig. 3.b this empty positions are filled in gray. Unlike bit-planes coding in JPEG-2000 standard proposed approach takes into account inter-layers correlation. So this fact allows to use bits from already processed bin-layers in context modeling. Most popular method for context selection is using a combination of four nearest already processed neighbors pixels at positions A, B, C and D (see Fig. 4). Proposed bin-layer scanning order allows to additional neighbors from previous layer at positions E, F, G and H be used. On the other hand, usage of additional neighbors leads to increasing of context models number. To prevent statistics dilution a simple context modeling scheme based on number of *non-zero known* neighbors of encoded bit position was suggested. Proposed heuristic can be proved by statistical dependence of non-zero prediction errors. For sign context modeling a common method based on 4 neighbors is used in the developed algorithm.

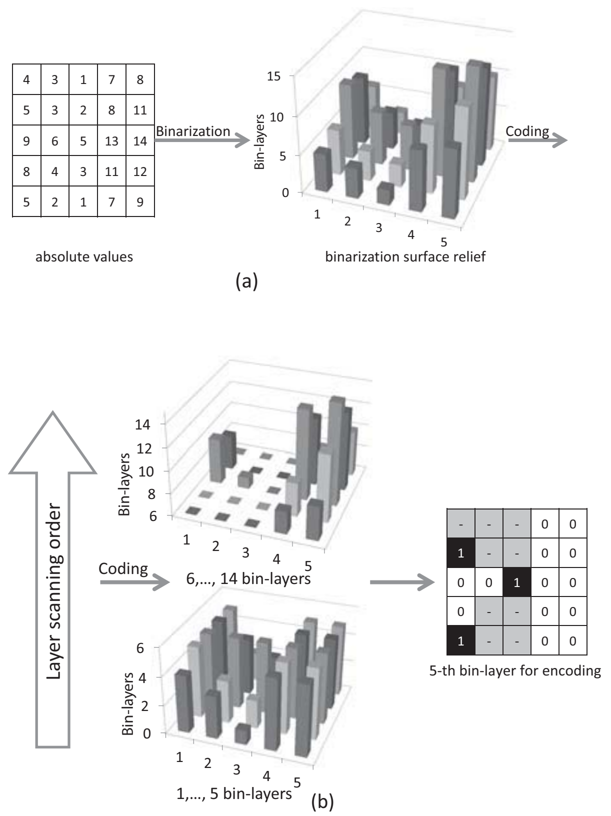

Fig. 3. (a) - presentation ot the binarization procedure result as a surface relief - a set of bin-layers. (b) - example of bin-layer processing.

Finally current bit is coded using probability estimation corresponding to the selected context model. A common approach is to use counters of encoding symbols for probability estimation. Many compression algorithms use Krichevsky-Trofimov estimation [11]. Usage of this procedure always allows to obtain non-zero probability for encoded symbol which is necessary for arithmetic coder implementation. In proposed compression scheme all counters are initialized by one to obtain non-zero estimates.

The statistical characteristics of the obtained binary data streams vary in time. To adapt probability estimation the method similar to JPEG-LS [1] standard is used.

Context model statistics are divided in half when the number of considered model selection achieves threshold value. This adaptation method is similar to exponential decaying memory estimation described in [12]. It is used to reduce the impact of old symbols on probability estimation procedure:

$$n_{x,t} = \frac{\frac{e_{x,1}+\cdots+e_{x,Reset}}{2} + e_{x,Reset+1} + \cdots + e_{x,2*Reset}}{2} + \cdots + e_{x,t-1}, \quad (2)$$

where $n_{x,t}$ - counter of symbol x in time moment t, $e_{x,t}$ - increment of symbol x counter in time moment t and $Reset$ coefficient allows to control decay rate.

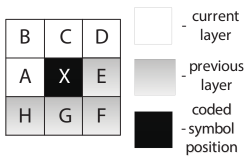

Fig. 4. Neighbor positions for context modeling

III. Codec scheme description

A. Proposed compression scheme

In this section proposed codec structure is shown in Fig. 5. Predictor and entropy encoder are connected via multiplexer MUX. Multiplexer *MUX* is used to decompose each prediction error by pair of values:

$$\begin{cases} Sign_{i,j} = \text{sign}(e_{i,j}), \\ |e|_{i,j} = |e_{i,j}|. \end{cases} \quad (3)$$

where $e_{i,j}$ - prediction error at position i, j. $|e|_{i,j}$ - absolute value of error and sign(.) is the following indicator function:

$$\text{sign}(e_{i,j}) = \begin{cases} -1 \text{ if } e_{i,j} < 0, \\ 0 \text{ if } e_{i,j} = 0, \\ 1 \text{ if } e_{i,j} > 0. \end{cases} \quad (4)$$

Absolute values are processed at first. This encoding order allows to skip sign coding for zero error values.

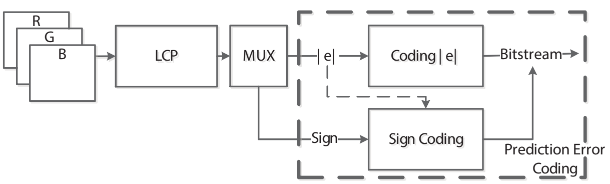

Fig. 5. Proposed compression scheme

B. Local-adaptive Combined Prediction

The term "combined" means that both intra and inter predictions are used. Proposed LCP method is single-pass. Inter-component part is similar to SICLIC codec [13] proposed by Feder et al., while intra-component part is MED from JPEG-LS standard [1]. The prediction flow-chart is depicted in Fig. 6.

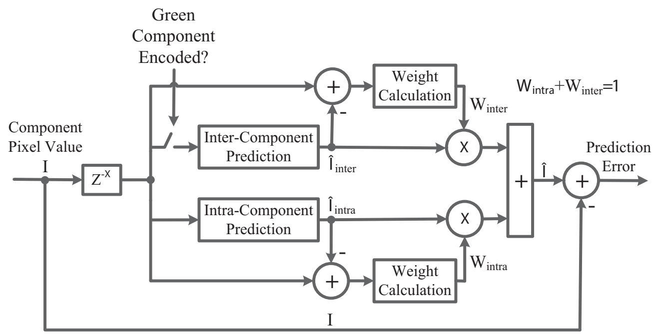

Fig. 6. LCP predictor scheme

Our experiments show that green component has the better correlation with other components in the RGB color model, so green component is predicted first using MED [1] prediction only. Remaining components are predicted using weighted sum of SICLIC-based and MED predictors. The weights are calculated according to history of each type of prediction errors. History with smaler prediction error is preferable in weight calculation procedure. The last component is predicted using two previously processed components.

C. Coding absolute values of prediction errors

The flow-chart of coding absolute values of prediction errors is depicted in Fig. 7. It consists of the following steps:

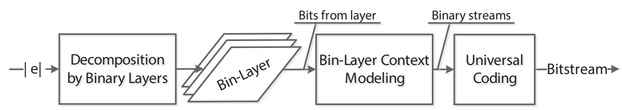

Fig. 7. Absolute values coding scheme

1) Decomposition by binary layers: Decomposition by bin-layers starts from *binarization* procedure. Unary binarization procedure is applied for absolute value $|e|_{i,j}$ in each pixel position independently. Unary binarization maps non-negative value x to binary vector $\bar{b}$ of length $x+1$:

$$U(x) = (b^{(0)}b^{(1)}, \ldots, b^{(x)}) \quad (5)$$

where $b^{(i)}$ is a following indicator function:

$$b^{(i)} = \begin{cases} 0 \text{ if } i < x, \\ 1 \text{ if } i = x. \end{cases} \quad (6)$$

Further the decomposition to $N = \max\limits_{i,j} |e|_{(i,j)}$ binary layers is applied. The value at the position (i, j) in layer k is determined by the following rule:

$$l_{i,j}^{(k)} = \begin{cases} 0 \text{ if } |e|_{i,j} > k, \\ 1 \text{ if } |e|_{i,j} = k. \\ - \text{ if } |e|_{i,j} < k. \end{cases} \quad (7)$$

where the symbol '-' means that the bit at this position is not coded. The encoding procedure starts from the 0 bin-layer and continues until N-th layer.

2) Layer Context Modeling: Context model selection procedure depends on number of non-zero neighboring error values at this position. These non-zero errors are presented by zero bins in current layer. So the context model index (Idx) for pixel position (i, j) is calculated by the following equation:

$$Idx_{i,j} = \sum_{n,m \in \mathcal{N}_{i,j}} I(i+n, j+m), \quad (8)$$

where $\mathcal{N}_{i,j}$ is a set of (i, j) neighbor positions in relative coordinates (see Fig. 4) and $I(.,.)$ is indication function:

$$I(i+n, j+m) = \begin{cases} 1 \text{ if } l_{i,j}^{(k)} = 0, \\ 0 \text{ otherwise } . \end{cases} \quad (9)$$

As far as neighbor values $l_{i+n,j+m}^{(k)}$ at the positions F, G, E and H (see Fig. 4) are unknown the values $l_{i,j}^{(k-1)}$ are used at this positions are used.

Context model index takes following values $Idx \in [0, 8]$ and therefore there is 9 different context models for absolute values.

3) Universal Coding: Binary arithmetic coder [6], [8] is used for $l_{i,j}^{(k)}$ compression. For probability estimation of symbol $l_{i,j}^{(k)}$ the following equation is used:

$$\hat{P}_x = \frac{n_x}{n_0 + n_1}, \quad (10)$$

where n_x - is counter for symbol 'x' (zero and one) in already encoded sequence. All counters are initialized by with '1' value.

To update counters for varying statistics exponential decaying memory method is applied:

$$\begin{cases} n_x = n_x + 1, \\ n_0 = n_0/2, \text{if } n_0 + n_1 = Reset, \\ n_1 = n_1/2, \text{if } n_0 + n_1 = Reset, \end{cases} \quad (11)$$

where x is currently encoding symbol.

D. Sign coding procedure

Sign value coding procedure is similar to coding of absolute values of prediction errors excepts context modeling. Sign model selection is defined by combination of the four already processed sign values at positions A, B, C and D (see Fig. 4). Sign takes one of the following values: {-1,0,1}, so $3^4 = 81$ different context models are used.

IV. Experimental results

Several experiments were conducted for evaluation of suggested compression scheme coding performance using 24 bit per pixel RGB color image sets. Table I presents basic properties of the following benchmarks:

- Lossless Photo Compression Benchmark (LPCB) [14] - contains large set of high definition images. This set consists of 3 image types: natural images, orbital pictures of Earth surface and pictures of space objects;
- Squeeze Chart (SC) [15] Benchmark - contains small set of high definition universal images;
- Kodak [16] corpus - state-of-the-art test set of natural images;
- Rawzor corpus - image test set presented by Rawzor Inc.

We also use state-of-the-art images, e. g. lena, baboon and airplane for evaluation.

Tables II, III contain values of prediction errors variances and estimates of compression performance for different prediction methods: MED prediction from JPEG-LS standard [1], MED with inter-component color transform (CT) from JPEG-LS part 2 specification [5] and proposed LCP method. It can be seen that LCP method outperforms other considered methods.

Results of the proposed compression scheme with LCP prediction were compared with performance estimates for state-of-the-art compression schemes. It is necessary to mention that some effective multipass compression scheme [17] is not considered in the comparison because the suggested scheme is single-pass.

Table IV depicts performance estimates for the suggested and state-of-the-art lossless compression schemes and standards: GraLIC [18], ZPAQ [19], JPEG-2K [2] in lossless mode, JPEG-LS with CT. Coding rate on image set and place in benchmark efficiency rating are considered as performance estimates for each compression schemes. Value in brackets represents the place of scheme in benchmark efficiency rating excluding repeated results (sieving) for different implementation versions or parameters of the same compression algorithm. Only best version of each codec stays in the rating.

Proposed compression scheme outperforms JPEG-LS and JPEG-2K standards in all benchmarks. It loses to high-complexity algorithms as GraLIC and ZPAQ. But the average speed of the proposed codec implementation is lower than fastest PAQ version by two orders. It is possible to improve scheme compression performance at the expense of increasing complexity of context modeling procedure. This is the subject for future research.

TABLE I. Public benchmarks description

Corpus name:	Files number:	Size, bytes	Codecs in benchmark (filtered number)
LPCB	107	3 456 571 880	83 (45)
SC	7	242 932 451	100 (65)
Kodak	24	28 311 912	5
Rawzor	14	470 611 702	5

TABLE II. VALUES OF VARIANCES OF PREDICTION ERRORS

File name	Corpus name	SICLIC	MED	MED+CT	LCP
STA13844	LPCB	45.13	42.23	141.42	**36.43**
cathedral	Rawzor	15.54	23.80	16.60	**15.19**
IMG0003	Kodak	19.25	48.33	65.76	**19.18**
sigma24	SC	9.16	22.03	12.88	**9.11**
lena	State-of-the-art	59.75	67.92	196.82	**50.39**
airplane	State-of-the-art	32.17	45.55	56.24	**29.54**
baboon	State-of-the-art	579.82	664.23	862.55	**489.17**

TABLE III. COMPARISON OF PREDICTION METHODS (BITS/PEL)

Corpus name:	MED	MED+CT	LCP
LPCB	8.85	8.3	**7.98**
SC	12.25	10.38	**10.3**
Kodak	13.19	**8.49**	8.69
Rawzor	10.57	10.25	**10.01**

V. CONCLUSION

This paper presents a novel lossless image compression scheme based on the decomposition by binary layers (bin-layers). Detail description for two main blocks of the suggested scheme were given: LCP prediction method and prediction errors coding procedure.

Experimental results show that proposed prediction method has higher performance then prediction methods used in image compression standards.

According to the obtained results, the suggested scheme outperforms image compression standards with similar complexity in different benchmarks.

TABLE IV. COMPARISON WITH STATE-OF-THE-ART SCHEMES

Codec name:	Place in benchmark efficiency rating (afther sieving)	Compression performance (bits/pel)
LPCB		
GraLIC	1	6.74
Proposed scheme	13 (9)	7.98
JPEG-2K (LuraWave)	25 (19)	8.64
JPEG-LS+CT	33 (27)	8.97
SC		
ZPAQ	1	8.88
Proposed scheme	21 (13)	10.3
JPEG-LS+CT	24 (16)	10.38
JPEG-2K (Kakadu 7.2.2)	28 (19)	10.52
Kodak		
Proposed scheme	1	8.69
JPEG-2K	2	9.52
JPEG-LS	4	9.72
Rawzor		
Proposed scheme	1	10.01
JPEG-2K	3	10.62
JPEG-LS	4	10.64

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