# Efficient Lossless Coding of Highpass Bands from Block-based Motion Compensated Wavelet Lifting Using JPEG 2000

Wolfgang Schnurrer, Tobias Tröger, Thomas Richter, Jürgen Seiler, and André Kaup

*Multimedia Communications and Signal Processing*
*Friedrich-Alexander Universität Erlangen-Nürnberg (FAU), Cauerstr. 7, 91058 Erlangen, Germany*

Email: { schnurrer, troeger, richter, seiler, kaup } @lnt.de

***Abstract*—Lossless image coding is a crucial task especially in the medical area, e.g., for volumes from Computed Tomography or Magnetic Resonance Tomography. Besides lossless coding, compensated wavelet lifting offers a scalable representation of such huge volumes. While compensation methods increase the details in the lowpass band, they also vary the characteristics of the wavelet coefficients, so an adaption of the coefficient coder should be considered. We propose a simple invertible extension for JPEG 2000 that can reduce the filesize for lossless coding of the highpass band by 0.8% on average with peak rate saving of 1.1%.**

***Index Terms*—Computed Tomography, Wavelet Lifting, Signal Analysis, Adaptive Coding, Lossless Image Coding**

## I. Introduction

Multi-dimensional data volumes, like 3-D or 3-D+t image data from Computed Tomography (CT) or Magnetic Resonance Tomography, can become unhandy large very fast. Storing, transmitting, processing and even displaying such huge volumes becomes a challenging task. A scalable representation is desired, where a coarse representation can be used for previewing or fast browsing, while interesting areas can be reconstructed lossless [1]. The latter is very important, e.g., for diagnosis in telemedical applications.

For a multi-dimensional wavelet transform (WT), the 1-D WT is applied successively along the different dimensions, shown in Fig. 1. The lowpass band of a WT can be considered as downscaled version of the original signal. In contrast to a subsampling when every other frame is taken, the lowpass band contains information from the complete original signal. To obtain a more detailed lowpass band, the WT in temporal or $z$-direction can be extended by compensation methods [2], [3], [4]. Fig. 1 shows occurring structures in the highpass band caused by block-based compensation. Deformable motion models [4], [5], [6] can avoid these structures. Since these models usually use a complex iterative estimation process, this paper focuses on block-based compensation. However, the characteristics of the WT coefficients are varied significantly by the block-based compensation, as also shown in [7]. Several methods exist for coding wavelet coefficients. They all exploit characteristics of the coefficients of a traditional WT, i.e., without a compensation method incorporated. Extensions like a variable blocksize [8] can be used but the shown structures can still occur. We observed that the lossless coding efficiency can be improved when the coding method is adapted to the variation of the coefficients in compensated lifting.

In [7], this problem is addressed by adapting the wavelet basis to the characteristics of the signal. The highpass band of compensated

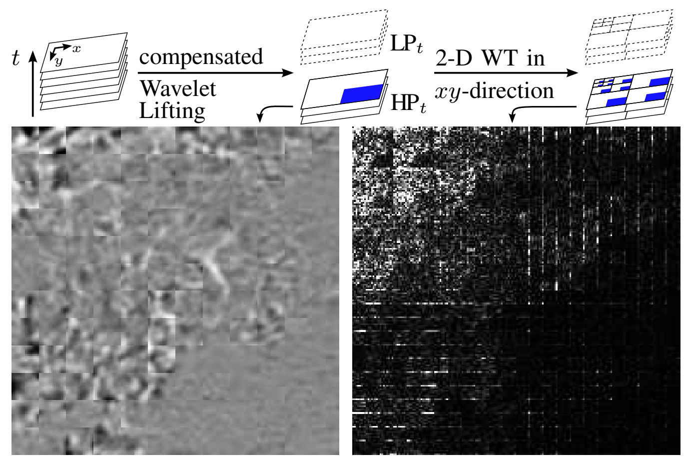


Figure 1. Visualization of the occurring structures in the highpass. The marked details from the block-diagram are shown below. Left: detail of the highpass band from wavelet lifting with block-based compensation (gray=0), Right: corresponding further decomposition in $xy$-direction (absolute values)

wavelet lifting can be considered as prediction residual as well. Instead of modifying the wavelet basis, we present a different approach that just adapts the order of the coefficients prior to the entropy coder. Our goal is to keep the coding method unchanged, so specialized hardware coders can still be used.

We propose a method to improve the efficiency for lossless coding of highpass coefficients of a WT with block-based compensation using JPEG 2000 [9], [10], [11]. JPEG 2000 is a wavelet-based image coding method that is also part of the DICOM standard [12]. We present a re-sorting of the compensated highpass coefficients that can also be implemented as a preprocessing step of a standard JPEG 2000 coder. This paper focuses on the computation and the processing of the highpass band. An efficient processing of the lowpass band has already been proposed in [13].

In Section II, we briefly review compensated wavelet lifting and sketch the coding chain of JPEG 2000. In Section III we introduce our coefficient re-sorting approach into the coding framework together with an optimum as well as a low complexity decision approach. Simulation results and discussion follow in Section IV. Section V concludes this paper.

## II. Compensated Wavelet Lifting

Wavelet lifting is an efficient implementation of a wavelet transform (WT) [14]. A WT can be applied in temporal direction to obtain temporal scalability. To reduce the motion artifacts and ghosting artifacts in the lowpass band for a better quality, motion compen-

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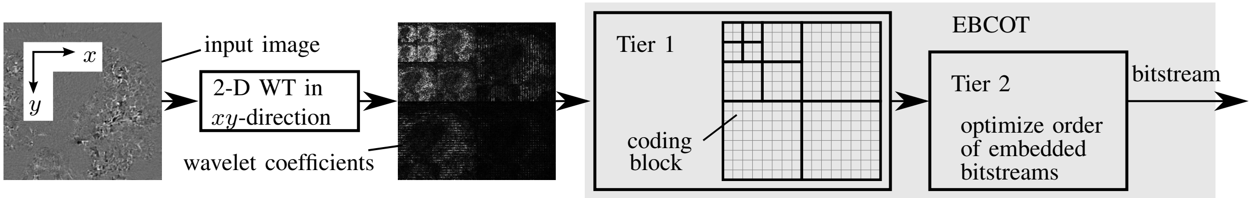


Figure 2. Simplified processing chain of JPEG 2000, according to [9], [10], [11]

sation methods can be implemented directly into the transform [2]. Therefore, the compensated frames $p_{2t-1}$ and $p_{2t+1}$ are subtracted from the current frame $f_{2t}$ to compute the highpass frame $\mathrm{HP}_t$ with index $t$ as shown in (1) for the LeGall 5/3 wavelet.

$$\mathrm{HP}_t = f_{2t} - \left\lfloor \frac{1}{2} \left( p_{2t-1} + p_{2t+1} \right) \right\rfloor \tag{1}$$

This further leads to a reduction of the energy in the highpass band and thus a better decorrelation of the signal and higher transform gain [3].

The resulting subbands from the compensated transform are coded frame by frame with JPEG 2000. JPEG 2000 is a wavelet-based image coder and fits seamless into a wavelet-based framework. Fig. 2 shows a simplified processing chain of JPEG 2000. An input image is decomposed using a 2-D WT. The coefficients are then coded using Embedded Block Coding with Optimized Truncation (EBCOT) [11]. Therefore, the subbands are subdivided into coding blocks. EBCOT consists of two tiers. In Tier 1, the coefficients of each coding block are traversed in a specific scan order and arithmetically coded into an embedded bitstream. Tier 2 operates on the results of Tier 1 and determines the optimum order of the embedded bitstreams, i.e., the coding blocks, in the resulting final bitstream for optimum scalability. For a more detailed description, please refer to [9], [10], [11].

To summarize, all subbands are processed independently by JPEG 2000. After Tier 1, the rate needed for each subband can be computed by summing up the lengths of all embedded bitstreams. The next section describes our proposed method making use of these coder properties for adapting the characteristics of compensated highpass frames to increase the coding efficiency of JPEG 2000.

## III. Proposed Coefficient Re-sorting

Block-based compensation methods can lead to a predictor containing block structures, especially when the translatory motion model does not exactly fit the occurring motion. The highpass band can be regarded as prediction error signal when a compensated transform is considered. The block structures in the highpass band also have to be coded. This can increase the amount of bits needed for coding [7].

Neighboring pixels in the highpass band are still correlated, so a further decomposition in $xy$-direction is reasonable. We observed that the decomposition of a highpass frame with block structures leads to characteristic structures that are dependent on the block-size of the block-based compensation. These structures are shown in Fig. 1 on the right.

The first wavelet decomposition yields four subbands, namely $\mathrm{LL}_1$, $\mathrm{HL}_1$, $\mathrm{LH}_1$, and $\mathrm{HH}_1$. Fig. 3 shows a dyadic decomposition with four steps, where a further decomposition of the lowpass band $\mathrm{LL}_i$ leads to the subbands $\mathrm{LL}_{i+1}$, $\mathrm{HL}_{i+1}$, $\mathrm{LH}_{i+1}$ and $\mathrm{HH}_{i+1}$. For lossless coding, the fully reversible integer LeGall 5/3 wavelet [1] is used for the decomposition in the $xy$-direction [9].

The coefficients in the LH bands correspond to horizontal edges, i.e., high frequencies in vertical direction and coefficients in the HL bands correspond to vertical edges, i.e., high frequencies in horizontal direction. The horizontal respectively vertical edges from block boundaries change the characteristic of the coefficients significantly. The entropy coder of JPEG 2000 is not able to exploit the occurring structures because only a small local neighborhood of coefficients is used for prediction [11].

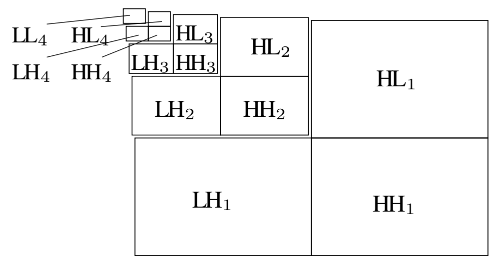


Figure 3. Notation of the subbands of a dyadic 2-D wavelet decomposition with four decompositions

Fig. 4 shows our proposed re-sorting algorithm and our two decision approaches. The occurring structures are represented by gray color in the top center resulting from the further decomposition of the compensated highpass band, shown on the left. To exploit these structures, we propose a re-sorting of the coefficients. In the subbands of the first decomposition in $xy$-direction, namely $\mathrm{HL}_1$, $\mathrm{LH}_1$, and $\mathrm{HH}_1$, the distance between the structures is one half of the blocksize $bs$ of the compensation method. For the second decomposition the distance is $\frac{1}{4}bs$, as shown in Fig. 4. For a blocksize $bs$ of $16 \times 16$ pixels, the distance is 8 in $\mathrm{HL}_1$, $\mathrm{LH}_1$, and $\mathrm{HH}_1$, 4 in $\mathrm{HL}_2$, $\mathrm{LH}_2$, and $\mathrm{HH}_2$ and 2 in $\mathrm{HL}_3$, $\mathrm{LH}_3$, and $\mathrm{HH}_3$. In the fourth decomposition, the structures are next to each other and thus within the reach of the internal predictor of EBCOT [11]. The maximum number of decompositions $d_m$ for re-sorting to be evaluated computes to

$$d_m = \log_2 (bs) - 1. \tag{2}$$

The re-sorting works as follows: for the LH bands, all rows of coefficients corresponding to block boundaries are moved to the top, as illustrated on the top right in Fig. 4. For the HL bands, all respective columns are moved to the left. For the HH bands, both operations are applied. The result is shown in Fig. 4 on the top right. Please note that the coefficients are re-sorted and the order of the code-blocks is not modified, i.e., the two tiers remain unchanged.

On the right side of Fig. 4, the algorithm for obtaining the optimum decision is shown. The coefficients per subband can be modified and it can be checked whether the rate decreases. For each subband, the rate needed for traditional coding, i.e., standard JPEG 2000 without re-sorting, as well as the rate needed for coding the re-sorted coefficients is determined by executing the Tier 1 coding pass. Next, for each subband, the smaller rate corresponds to the optimum decision.

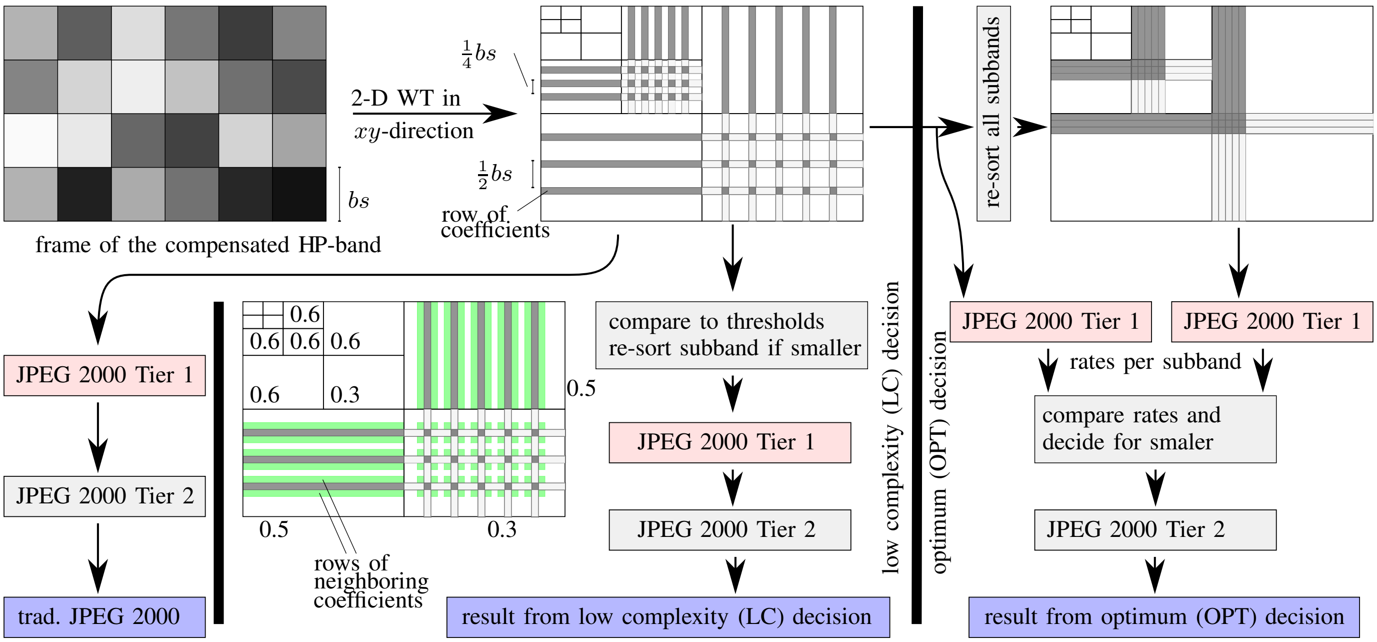


Figure 4. Block diagram showing our proposed coefficient re-sorting algorithm with optimum (OPT) decision approach on the right and low complexity (LC) decision approach in the center. For comparison, traditional JPEG 2000 is shown on the left.

Due to arithmetic coding, Tier 1 is a quite complex part of JPEG 2000. Executing Tier 1 twice increases the computational complexity a lot. To avoid this, a simple decision method was developed, shown in the bottom center of Fig. 4. After the wavelet decomposition, a quotient is computed for every subband. Therefore, for every subband, the sum of the absolute values of the coefficients corresponding to block boundaries (gray color) is computed in a first step. Next, the sum of the absolute values of the coefficients corresponding to the neighboring coefficients (green color) is computed. Then, the quotient of the previously computed two values is compared to a threshold. When the quotient is small enough, i.e., the difference between the block boundary coefficients and their neighbors is big enough, the coefficients of the subband are re-sorted. For the HL bands, the neighbors (green) left and right of each gray column are summed up. So the values of the gray columns are multiplied by 2 to compensate for the twice as many neighbors. This is done analogue for the respective rows of the LH bands. For the HH bands, the absolute values of the four diagonal neighbors of each dark gray coefficient are summed up and the absolute sum of the dark gray coefficients is multiplied by 4 respectively. As shown in Fig. 4, the decision is made before Tier 1 for this low complexity approach, so Tier 1 is executed only once.

The traditional JPEG 2000 processing chain is again shown on the left side for comparison as well as to show all cases of our simulation setup in Fig. 4.

For signaling the decision to the decoder, one additional bit for each subband is needed. One more bit per frame indicates whether re-sorting is used at all. If the re-sorting is not used, the overall filesize will increase only by one bit per frame. The operations are all reversible so the property of lossless coding is not harmed.

The re-sorting can be implemented as a preprocessing step before JPEG 2000-encoding and a postprocessing step after JPEG 2000-decoding, so a standard JPEG 2000 coder can be used. For the post-processing, the wavelet decomposition has to be computed after JPEG 2000 decoding, followed by the inverse coefficient re-sorting and an inverse WT.

## IV. SIMULATION RESULTS

For evaluating our method, we used different CT data sets. One 3-D+t CT *heart* data set[1] was used where the transform is applied in slice-direction (*heart spat*) and in time-direction (*heart time*). Further, we tested four 3-D CT *head* data sets and four 3-D CT *thorax* data sets[2].

We applied a compensated LeGall 5/3 wavelet in temporal, respectively slice-direction and evaluated the lossless coding of the highpass coefficients. The block-based compensation was used with a blocksize of $16 \times 16$ with a full-search within a search range of 15. The resulting highpass bands were coded frame by frame using the JPEG 2000 implementation [15] with 7 wavelet decompositions. The re-sorting was evaluated for the subbands from the first 3 decompositions in $xy$-direction, as computed by (2).

Table I shows the lossless coding results for the compensated highpass coefficients using the three cases shown in Fig. 4, namely traditional, i.e., standard JPEG 2000, and the proposed re-sorting method with optimum (OPT) and low complexity (LC) decision. The thresholds for the LC approach are given in Fig. 4. The overhead information for signaling the re-sorting is included.

The absolute savings in bytes are given for the two re-sorting approaches against traditional JPEG 2000. Negative values indicate that more data has to be stored using our proposed method due to signaling overhead, e.g., for *head2*, 36 HP frames result in an overhead of $\lceil \log_2 36 \rceil = 5$ bytes. For medical CT volumes, the proposed re-sorting can reduce the number of bits for lossless coding by 0.8% on average with peak rate saving of 1.1%. This is notable since in general, even small gains are hard to achieve in lossless coding. Compared to the achievable gains, the loss due to the signaling information is negligible. The column on the right compares the results from the two decision approaches showing that the LC decision performs mostly close to the OPT decision. Although the

[1]The CT volume data set was kindly provided by Siemens Healthcare.

[2]The CT volume data sets were kindly provided by Prof. Dr. med. Dr. rer. nat. Reinhard Loose from the Klinikum Nürnberg Nord.

| sequence | filesize in bytes | | | savings | | |
|---|---|---|---|---|---|---|
| | trad. JPEG 2000 | re-sort OPT | re-sort LC | abs OPT | abs LC | rel LC/OPT in % |
| *heart spat* | 98880861 | **97776086** | **97776578** | 1104775 | 1104283 | -0.045 |
| *heart time* | 92972210 | **92122327** | **92122485** | 849883 | 849725 | -0.019 |
| *head* | **3751832** | 3751834 | 3751834 | -2 | -2 | 0 |
| *head 2* | **7318102** | 7318107 | 7318107 | -5 | -5 | 0 |
| *head 3* | 1502434 | **1492997** | **1493900** | 9437 | 8534 | -9.569 |
| *head 4* | 1814188 | **1809398** | **1811464** | 4790 | 2724 | -43.132 |
| *thorax 1* | 7661846 | **7651164** | **7651651** | 10682 | 10195 | -4.559 |
| *thorax 2* | **5979688** | 5979693 | 5979693 | -5 | -5 | 0 |
| *thorax 3* | **7850487** | 7850492 | 7850492 | -5 | -5 | 0 |
| *thorax 4* | 9164221 | **9163155** | **9163335** | 1066 | 886 | -16.886 |
| average | | $-0.836\%$ | $-0.834\%$ | | | |

Table I
CODING RESULTS FOR TRADITIONAL JPEG 2000 AND OUR PROPOSED RE-SORTING ALGORITHM WITH OPTIMUM (OPT) DECISION APPROACH AND LOW COMPLEXITY (LC) DECISION APPROACH

gains are a little smaller, the LC approach achieves gains where OPT performs better then traditional JPEG 2000.

The achievable gain strongly depends on the content of the sequence. The re-sorting can be applied to video sequences as well resulting in smaller gains. The medical sequences show less high frequency content compared to the video sequences. We observed, that if the absolute values of the coefficients corresponding to the block boundaries are significantly larger than the surrounding neighboring coefficients it is advantageous to re-sort the coefficients to achieve a higher compression.

As shown in Fig. 4, the optimum decision needs to run the Tier 1 part two times, which then leads to the optimum results. Our low complexity decision approach shows that this increase of the encoder complexity can be avoided by a decision method, that determines more efficiently whether it is advantageous to apply the re-sorting for a subband. Furthermore, the decoder complexity is only changed marginally as only a simple re-ordering of the coefficients is necessary.

## V. CONCLUSION

In this paper we propose an efficient method that can improve lossless compression of highpass bands from block-based compensated wavelet lifting of medical CT data sets using JPEG 2000. We showed that an adaption of the compensated coefficients to the coder can improve the coding efficiency. The proposed reversible method can be implemented as preprocessing before encoding and postprocessing after decoding, so a standard JPEG 2000 encoder and decoder can be used. Within our simulation data set, the filesize of the lossless coded highpass band was reduced by 0.8% on average with peak rate saving of 1.1%. The optimum decision performs best but has a high computational complexity. Our proposed low complexity decision approach comparing sums of coefficients performs close to the optimum decision.

The proposed re-sorting method is not limited to highpass bands from compensated wavelet lifting but can be applied to wavelet-based coding of residuals from block-based motion compensation as well. Further work aims at an evaluation of the lossy-to-lossless scalability as well as a detailed complexity analysis.


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