Abstract—This paper presents a new approach for improving the visual quality of the lowpass band of a compensated wavelet transform. A high quality of the lowpass band is very important as it can then be used as a downscaled version of the original signal. To adapt the transform to the signal, compensation methods can be implemented directly into the transform. We propose an improved inversion of the block-based motion compensation by processing unconnected pixels by a reconstruction method. We obtain a better subjective visual quality while furthermore saving up to 2.6% of bits for lossless coding.

INTRODUCTION

In many video applications a scalable representation of the video sequences is very desirable especially when originally huge data has to be transmitted. A smaller resolution, e.g., in temporal direction, can be used for previewing or displaying on mobile devices. Thereby, a high quality of a downscaled representation is very important. The wavelet transform can lead to such a scalable representation but has the drawback of a blurry lowpass band. The lowpass band can further contain ghosting artifacts due to motion in the video sequences.

To improve the quality of the lowpass band, compensation methods can be incorporated directly into the transform. This technique is well known as Motion Compensated Temporal Filtering (MCTF) for video sequences [1].

The compensation method has to be inverted in the update step of the wavelet transform [2]. When using a block-based compensation method, blocking artifacts can occur in the lowpass band due to the inversion procedure.

In this paper, we will improve the visual quality of the lowpass band by avoiding annoying block artifacts caused by unconnected pixels. Further we can reduce the filesize for lossless coding compared to the traditional block-based motion compensated wavelet lifting.

The following sections briefly review MCTF and block-based compensation and introduce our proposed scheme for improving the compensated lifting. The simulation results are discussed in Section IV.

I. COMPENSATED WAVELET LIFTING

The lifting structure is a factorized representation of the wavelet transform [3]. Fig. 1 shows a schematic of the compensated lifting structure [1] of the Haar wavelet that has been extended by the Frequency Selective Extrapolation (FSE). The highpass coefficients \( \text{HP}_t \) are computed in the prediction step and the lowpass coefficients \( \text{LP}_t \) are computed in the update step by using the already computed highpass coefficients.

As illustrated in Fig. 1, a motion compensated transform is achieved by subtracting a motion compensated (MC) predictor \( p_{2t} \) instead of the original reference frame \( f_{2t-1} \) from the current frame \( f_{2t} \).

\[
\text{HP}_t = f_{2t} - \lfloor p_{2t} \rfloor .\tag{1}
\]

To obtain an equivalent wavelet transform, the compensation has to be inverted (IMC). So in the update step, the inverse compensated highpass coefficients \( u_{2t} \) are added to the reference frame. The lowpass coefficients \( \text{LP}_t \) are computed to

\[
\text{LP}_t = f_{2t-1} + \lfloor a_k \cdot u_{2t} \rfloor .\tag{2}
\]

by using the later discussed weighting factors \( a_k \). By further introducing floor operators in the lifting structure, rounding errors are avoided and the original sequence can be perfectly reconstructed from the transform coefficients without loss [4]. This makes the transform very feasible for high fidelity video applications as well as for medical image data.

II. BLOCK-BASED COMPENSATION AND ITS INVERSION

Compensation methods are incorporated in the wavelet transform to obtain a high quality lowpass band without ghosting artifacts. As in hybrid video coding, usually block-based
compensation methods are used. There are other methods like mesh-based approaches that show similar or even superior performance to block-based methods but may have the drawback of a blurred predictor. In this paper we concentrate on block-based compensation methods.

A block-based predictor $p_{2t}$ for the current frame $f_{2t}$ is computed by searching for every block in the current frame for a best fitting block in the reference frame $f_{2t-1}$ in a specific search window. As cost function we minimize the sum of squared differences (SSD).

The inversion of a block-based compensation leads to pixels that are one-connected, multiple-connected or unconnected [2], [5]. The colored blocks in Fig. 1 are for illustrating the occurrence of the three different cases of connectivity. In the inverse compensated highpass band $u_{2t}$, the areas of overlapped blocks show multiple-connected pixels while the white areas show unconnected pixels. The remaining pixels are one-connected. Several methods have been proposed for treating these cases.

In [6], the first candidate block is used for the update of multiple-connected pixels while [7] proposes to use the candidate block with the smallest sum of absolute differences which increases the similarity of the lowpass band and the corresponding original frames. An optimum inversion regarding the reconstruction error is proposed in [8] and [9] by analytically calculating the weights $a_k$ for multiple-connected pixels.

For unconnected pixels, there is no information available. Up to now, they are just copied from the reference frame without an update, as proposed in [2]. We observed that blocking artifacts occur at the boundaries of the unconnected areas which makes a processing of these areas necessary. In [10], interpolation methods on the motion vector field are proposed to incorporate the physical properties in addition to the reconstruction error.

For the inversion that is necessary for the update step, the blocks are moved back to their original position. Thereby, we use the weights from [8] for the one-connected and the multiple connected pixels for averaging. In general, $k$-connected pixels are weighted by $a_k = \frac{1}{k^t}$ before they are added to the reference frame.

Fig. 2 shows the intermediate results for a detail from the sequence crew for demonstrating the reason of the occurring artifacts. Fig. 2 (a) shows the reference frame and Fig. 2 (b) shows the current frame. There is a change in the illumination between these frames due to a flash light. The predictor that is computed for the current frame is shown in Fig. 2 (c). The resulting highpass band is computed by applying (1) and is shown in Fig. 2 (d). The inverse compensated highpass frame for the update $u_{2t}$ according to (2) is shown in Fig. 2 (e). The white areas in the middle correspond to unconnected pixels. This update is added to the reference frame so the resulting lowpass frame, shown in Fig. 2 (f), shows block artifacts in the areas of the unconnected pixels.

### III. Reconstruction of Unconnected Pixels

The unconnected pixels can be regarded as holes in the update frame $u_{2t}$ as shown by white areas in Fig. 2 (e). These pixels usually occur in areas of dis-occlusion and occlusion. It is hard to make any assumption about the actual motion in these areas. So in opposite to the mentioned methods that try to interpolate the motion vectors, we propose a different approach based on a signal reconstruction method.

For this we use the Frequency Selective Extrapolation (FSE) [11] which can be used for reconstructing lost areas in image and video data. It was shown in [12], that the FSE can also be used for processing high frequency images. FSE is an iterative method that generates a model

$$g[m, n] = \sum_{k \in K} \hat{c}_k \varphi_k[m, n]$$

for the unknown pixels based on the available pixels in $u_{2t}$. For this, a weighted superposition of 2-D Fourier basis functions $\varphi_k$ is generated where in every iteration the influence $\hat{c}_k$ of the basis function that reduces the approximation error the most is increased. For detailed description of FSE together with pseudo code, please refer to [11].

The finally reconstructed pixels are illustrated by the dark areas of $\hat{u}_{2t}$ in Fig. 1 and the result of the reconstructed update frame $\hat{u}_{2t}$ is shown in Fig. 2 (g). The resulting lowpass frame
of our proposed scheme is shown in Fig. 2 (h) where the block artifacts are suppressed. Hence, in our proposed scheme, (1) is left unchanged but (2) is modified to
\[ \text{LP}_2 = f_{2t-1} + \lfloor \bar{u}_{2t} \rfloor \] (3)
where the reconstructed update \( \bar{u}_{2t} \) is used for computing the lowpass frame instead of the traditional update \( u_{2t} \).

### IV. Simulation Results

We evaluated our proposed method with several video sequences, namely crew, foreman, orient, vimto, and the HEVC test sequences ClassA:People and ClassA:Traffic. The compensated transform can also be used for medical Computed Tomography (CT) volumes [13], [14] where adjacent slices are taken as sequence. We evaluated our method using several medical CT datasets, one head and two thorax 3-D CT data sets\(^1\) as well as a 4-D cardiac volume\(^2\). The slices of the CT data sets have a resolution of 512x512 with 32 slices (head), 80 slices (thorax1), 66 slices (thorax2), and 130 slices at 10 timesteps (cardiac). For the video sequences, we took the luminance component that has a bit depth of 8 bit per pixel. The CT data sets have an intensity component only that has a bit depth of 12 bit per voxel. The intensity values describe the attenuation of the material at each voxel position.

In our simulation, we perform one compensated Haar wavelet decomposition step in slice respectively temporal direction and analyze the performance of the proposed method for inverting the block-based compensation. We use a block-size of 16x16 and perform a full search for each block within a search window of 15 pixels. For the FSE we use the parameters according to [11] except the maximum number of iterations that was set to 1000. The resulting wavelet coefficients are then coded frame by frame with JPEG 2000.

The first group of rows in Table I shows the results for the video sequences and the second group of rows shows the results for the CT data sets. The first two rows of the second group show the results for the 4-D CT volume cardiac, where the first row shows the results for a transform in temporal direction (time) while the second row shows the results for a transform in slice direction (slice).

The first group of columns of Table I headed by ‘overall filesize’ lists the filesize in MB needed for coding the whole sequences listed in the first column in lossless mode. The numbers in the columns headed by ‘block’ respectively ‘block+FSE’ include the bits needed for motion vectors, as well. The reduction in the filesize is obtained by avoiding the sharp edges of the block artifacts. In the sequences foreman and orient, these sharp edges do not occur very often.

The second group of columns of Table I headed by ‘lowpass band only’ lists the filesize for the lowpass image in MB. The column ‘% diff’ lists the relative difference between the methods ‘block’ and ‘block+FSE’. Negative values indicate that ‘block+FSE’ reduces the filesize. For most cases ‘block+FSE’ can reduce the filesize compared to the traditional block-based method.

The third group of columns of Table I headed by ‘PSNR’ lists the PSNR of the lowpass band compared to the corresponding original frames for evaluating the quality. It is not surprising that the obtained PSNR values are a little bit lower for our proposed FSE-based method. Traditionally, the PSNR between the frames in the lowpass band and the corresponding original frames is one of the criteria for optimization. Fig. 1 shows that the corresponding frame to the lowpass frame \( f_{2t-1} \) is the reference frame \( f_{2t} \). Assuming an optimum case with a perfect prediction of the current frame, the highpass band (1) will become exactly zero. In this case, the lowpass band (2) will be identically the same as the reference slice \( f_{2t} \), consequently resulting in an PSNR value of infinity. This is exactly the case for unconnected areas as there is no update at all. So, traditionally for unconnected pixels, no error is added in the update step. No matter how good the processing of unconnected pixels works, as soon as we add an update for the unconnected pixels, the PSNR will decrease because the metric aims at an update equal to zero. But this is not desirable as the result is then a truncated wavelet transform, i.e., without an update step, and the lowpass frame contains no information about the current frame in these areas.

Nevertheless, we observed that artifacts can occur at the boundaries of unconnected pixels as shown in Fig. 2 (f). As Fig. 2 (h) shows, we can improve the visual quality by suppressing these artifacts although the PSNR will decrease. A perfect metric should evaluate how well the lowpass frame represents all the frames in the reach of the wavelet filter and

|                | overall filesize in MB | filesize for the lowpass band only in MB | mean PSNR in dB of the lowpass band |
|----------------|------------------------|----------------------------------------|------------------------------------|
|                | block | block+FSE | block | block+FSE | block | block+FSE | block | block+FSE |
| crew           | 26.35 | 26.29     | 13.13 | 13.07     | -0.43 | 38.60     | 38.57 |
|                | 20.89 | 20.89     | 10.66 | 10.67     | -0.05 | 37.70     | 37.70 |
|                | 22.61 | 22.62     | 10.90 | 10.91     | 0.10  | 40.20     | 40.10 |
|                | 24.09 | 24.04     | 11.40 | 11.35     | 0.45  | 36.30     | 36.10 |
|                  | 260.25| 259.91    | 126.84 | 126.55 | -0.23 | 35.40     | 35.30 |
|                  | 233.30| 232.22    | 122.32 | 122.23 | -0.03 | 41.90     | 41.80 |
|                  | 194.66| 192.24    | 95.00  | 92.88     | -2.16 | 47.90     | 47.70 |
|                  | 192.54| 190.41    | 94.89  | 92.56     | -2.30 | 46.80     | 46.60 |
|                  | 14.70 | 14.63     | 6.97   | 6.91      | -0.94 | 44.50     | 44.50 |
|                  | 11.72 | 11.70     | 5.67   | 5.65      | -0.33 | 45.90     | 45.60 |
|                  | 7.33  | 7.32      | 3.56   | 3.55      | -0.28 | 38.10     | 38.10 |

\( ^1 \)The CT volume data sets were kindly provided by Prof. Dr. med. Dr. rer. nat. Reinhard Loose from the Klinikum Nürnberg Nord.

\( ^2 \)The CT volume data set was kindly provided by Siemens Healthcare.

**TABLE I**

**QUALITY AND OVERALL FILESIZE FOR DIFFERENT METHODS, BLOCK AND BLOCK+FSE INCLUDE THE RATE NEEDED FOR THE MOTION VECTORS**
not how well it fits to only one of them.

Fig. 3 shows more examples of occurring block artifacts (marked by red arrows) in the images denoted by 'lowpass block' as well as the results of the reconstructed update frame denoted by 'lowpass block+FSE'.

Further we can reduce the filesize for the lossless case compared to the traditional compensated transform by avoiding the sharp edges occurring at the boundaries of unconnected pixels. However, for the medical CT volumes, the filesize increases when a compensation method is used. This is caused by the correlated noise contained in these data sets. Without a compensation method, the wavelet transform processes adjacent pixels together. A compensated transform is applied according to the structural information.

V. CONCLUSION

To obtain a high quality lowpass band without ghosting artifacts, compensation methods have to be incorporated into the wavelet transform. The block-based compensation method is a feasible compensation method but the unconnected pixels have to be updated as well. Otherwise annoying block artifacts can occur in the lowpass band and render it unusable as downscaled version of the original sequence.

We showed that the Frequency Selective Extrapolation can be used for creating an appropriate update for the unconnected pixels and improves the visual quality of the lowpass band considerably. By avoiding block artifacts in the lowpass band we can further reduce the filesize for the lossless case compared to the traditional compensated transform for video sequences and medical CT volumes.

Further work aims at the development of an appropriate metric for evaluating the quality of the lowpass band.

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