Scalable-to-Lossless Transform Domain Distributed Video Coding

Xin Huang #, Anna Ukhanova #, Anton Veselov *, Søren Forchhammer #, Marat Gilmudtinov *

# DTU Fotonik, Technical University of Denmark, Building 343, Lyngby 2800, Denmark
* Saint-Petersburg University of Aerospace Instrumentation, 67, Bolshaya Morskaya str., Saint-Petersburg, Russia

Abstract—Distributed video coding (DVC) is a novel approach providing new features as low complexity encoding by mainly exploiting the source statistics at the decoder based on the availability of decoder side information. In this paper, scalable-to-lossless DVC is presented based on extending a lossy Transform Domain Wyner-Ziv (TDWZ) distributed video codec with feedback. The lossless coding is obtained by using a reversible integer DCT. Experimental results show that the performance of the proposed scalable-to-lossless TDWZ video codec can outperform alternatives based on the JPEG 2000 standard. The TDWZ codec provides frame by frame encoding. Comparing the lossless coding efficiency, the proposed scalable-to-lossless TDWZ video codec can save up to 5%-13% bits compared to JPEG LS and H.264 Intra frame lossless coding and do so as a scalable-to-lossless coding.

I. INTRODUCTION

Distributed Video Coding (DVC) [1] is a new video coding paradigm, which mainly exploits the source statistics at the decoder instead of at the encoder as in motion-compensated video encoding. Thereby computational power requirements are shifted from encoder to decoder. According to the Slepian-Wolf theorem [2], it is possible to achieve the same rate by independently decoding but jointly decoding two statistically dependent signals as for typical joint encoding and decoding (with a vanishing error probability). The Wyner-Ziv theorem [3] extends the Slepian-Wolf theorem to the lossy case. This work laid the basis for distributed source coding and it forms the key theoretical basis for DVC. The source is lossy coded based on the knowledge that a correlated source is available at the decoder, which utilizes this so-called side information. There are various approaches to DVC, e.g. PRISM [4], Pixel Domain Wyner-Ziv (PDWZ), and feedback channel based Transform Domain Wyner-Ziv (TDWZ) [5] have been applied for lossy coding. However, the lossless distributed source, image and video coding has also been devised, [6]-[9]. One application considered is for hyperspectral images [7]-[9], but lossless distributed source coding may also find relevant applications in other scientific and medical applications. A good example of the need for lossless coding could be scanned image sequences for 3D reconstructions. There could be several approaches for providing lossless DVC. For example, a wavelet based DSC approach for lossy-to-lossless compression of hyperspectral images is proposed in [9] but inter-band

processing is utilized at the encoder. In [6] a novel lossless compression technique is presented based on exploiting the temporal correlation under the distributed source coding paradigm. This technique operates in the pixel-domain to avoid any lossy transform and relies on syndrome decoding of trellis codes by encoding the final state of the trellis. The lattice based approach was also applied to lossless video coding, but here applying motion compensation also at the encoder side, which we want to avoid. These techniques were presented for lossless coding. In this work, instead a scalable-to-lossless distributed video codec based on Discrete Cosine Transform (DCT) is proposed based on TDWZ. This may be used for high-quality applications, where lossless is desired, but the system can not (efficiently) guarantee the resources for lossless coding. Furthermore, the coding scheme is also modified to a backward adaptive video coding system, which is evaluated to indicate the potential room for improvement in (scalable-to-lossless TDWZ) DVC.

This paper is organized as follows: Section II introduces a reversible integer DCT. The lossy TDWZ video codec is reviewed in Section III [13]. In Section IV, the TDWZ codec is modified to achieve scalable-to-lossless coding. In Section V, backward adaptive video coding is described. Finally, test conditions, results and analysis are presented in Section VI.

II. REVERSIBLE INTEGER DCT

In H.264/(MPEG4 part 10) Advanced Video Coding, a $4 \times 4$ transform is used. It is an integer transform, but not designed for reversible transformation. A $4 \times 4$ transform is also a part of TDWZ coding scheme. The transforms are derived from DCT. For this transform the basic functions are cosines, and therefore the transform values and transform results are not integer. We shall apply a separable two-dimensional transform defined by one-dimensional (1-D) transforms. The initial one-dimensional transform with kernel

$$K_{DCT} = \begin{pmatrix} 0.5000 & 0.5000 & 0.5000 & 0.5000 \\ 0.6533 & 0.2706 & -0.2706 & -0.6533 \\ 0.5000 & -0.5000 & -0.5000 & 0.5000 \\ 0.2706 & -0.6533 & 0.6533 & -0.2706 \end{pmatrix}$$

can be implemented in a reversible version using fixed point arithmetic, but this solution leads to additional bit depth (and thereby biplanes), which will negatively influence lossless compression. The main features of reversible integer transforms proposed and analyzed in [10] and [11] are 1)
reversibility, 2) a good approximation preserving the main transform properties and 3) limiting the number of required bitplanes.

The reversibility is achieved by using results of general matrix factorization theory. In [10] triangular elementary reversible matrix (TERM) and single-row elementary reversible matrix (SERM) are used for DCT kernel factorization. The reversible transform used in this paper is obtained by DCT kernel $K_{DCT}$ factorization via the PLUS method [11]:

$$K_{DCT} = P \ast L \ast U \ast S$$ (1)


It is important to maintain the order of operations in order to preserve reversibility properties. Input vector $\bar{x}$ should be multiplied by matrix-by-matrix with rounding for each intermediate coefficient:

$$\bar{y} = P \ast \text{round}(L \ast \text{round}(U \ast \text{round}(S \ast \bar{x})))$$ (2)

Here operation of rounding is denoted by $\text{round}(.)$. So far as separation property is preserved for reversible transform, 2D transform can be obtained by independent applying Eq. 2 to each row and column of $4 \times 4$ input matrix $X$. The operation is denoted as:

$$\hat{Y} = [(PLUS \ast X] \ast (PLUS)^T]$$ (3)

To verify that this approximation leads to a transform preserving the main properties of the DCT, the variance of the differences between the DCT output and the results of the reversible integer transform were estimated. Variances were calculated for the Y component of the first 50 frames of the Foreman (CIF) sequence as follows. Each frame was divided in $4 \times 4$ non-overlapped blocks. The original (float point) DCT with the $K_{DCT}$ kernel and the reversible integer transform were applied to the $4 \times 4$ blocks $B$, thereafter the differences were calculated for each position of the transform.

$$d_B(i,j) = y^B(i,j) - \hat{y}^B(i,j),$$

where $i, j \in \{0, ..., 4\}$ are the index row and column, $y^B(i,j)$ is the element of float point matrix of DCT coefficients, obtained by:

$$Y = K_{DCT} \ast X \ast (K_{DCT})^T.$$  

After that all differences corresponding to each position $(i,j)$ were calculated over all blocks $B$ and the variance value for each position was calculated:

$$VAR_D = \begin{pmatrix} 0.3887 & 0.3079 & 0.3276 & 0.3967 \\ 0.3164 & 0.2352 & 0.2776 & 0.3984 \\ 0.3403 & 0.2591 & 0.2975 & 0.4235 \\ 0.4248 & 0.3333 & 0.3595 & 0.4989 \end{pmatrix}.$$  

Here the coefficient at position $(i,j)$ contains the variance value of the sequence corresponding to this position. Standard deviation for the worst case (lower right corner) is less than one. It means that energy redistribution for reversible transform case is not significant.

To examine the last feature, the ranges of one-dimensional DCT with kernel $K_{DCT}$ and its reversible approximation used in the proposed TDWZ scheme are determined. Minimal and maximal values of each DCT coefficient can be easily found from the scalar product of input vector and corresponding basis vector:

$$y(i) = \sum_{j=0}^{3} x(j) \ast k_{DCT}(i,j), i = 0, ..., 3,$$

where $x(j)$ are input vector values, $k_{DCT}(i,j)$ are coefficients of $K_{DCT}$. Minimal and maximal values are given in Table I. For the reversible integer transform $\bar{y}(i)$ values are calculated by Eq. 2. In the 2D case, the number of bitplanes given by the full range for each transform coefficient is therefore 10.

| TABLE I  |
| VALUE RANGES FOR DCT4 AND REVERSIBLE TRANSFORM (1D CASE, 8-BIT INPUT) |

<table>
<thead>
<tr>
<th>Output Value</th>
<th>DCT</th>
<th>Reversible Integer Transform</th>
</tr>
</thead>
<tbody>
<tr>
<td>y(0)</td>
<td>0</td>
<td>510</td>
</tr>
<tr>
<td>y(1)</td>
<td>-235.59</td>
<td>235.59</td>
</tr>
<tr>
<td>y(2)</td>
<td>-255</td>
<td>255</td>
</tr>
<tr>
<td>y(3)</td>
<td>-235.59</td>
<td>235.59</td>
</tr>
</tbody>
</table>

III. TRANSFORM DOMAIN WYNER-ZIV VIDEO CODING

The architecture of the TDWZ video codec with feedback channel [13], which we shall base the new lossless version on is depicted in Fig. 1. It follows the same architecture as the one developed by Stanford group [1] and later further developed by the DISCOVER project [5]. However, an advanced Overlapped Block Motion Compensation (OBMC) based side information generation method [12] and an improved adaptive noise model [13] are adopted in the TDWZ video codec. These improvements lead to state-of-the-art TDWZ performance. A fixed Group of Pictures (GOP=N) is utilized with periodically designating one frame out of $N$ in the video sequence as a key frame and utilizing these for coding the intermediate frames as Wyner-Ziv frames. The key frames are intra coded by using a conventional video coding solution with low complexity such as H.264/AVC Intra, while the Wyner-Ziv frames in between are coded using a Wyner-Ziv approach. At the encoder, Wyner-Ziv frames are partitioned into non-overlapped $4 \times 4$ blocks and applying a transform to each block. The transform coefficients within a given band $b_k, k \in \{0...15\}$, are grouped together and then quantized. DC coefficients and AC coefficients are uniformly scalar quantized and deadzone quantized, respectively. Within each coefficient band $b_k$, eight pre-defined quantization levels ($2^{M_{b_k}}$) are used, as in [5], depending on the target quality of the Wyner-Ziv frame. The quantized coefficients are then decomposed into bitplanes with bit depth $M_{b_k}$. Each bitplane is fed to a rate-compatible Low-Density-Parity-Check Accumulate (LDPCA) encoder [14] starting from the most significant bitplane. For each encoded bitplane, the corresponding accumulated syndrome is stored in a buffer together with an 8-bit Cyclic Redundancy Check (CRC). The amount of bits to be transmitted depends on the requests made by the decoder through a feedback channel as shown in Fig. 1.

At the decoder, a side information frame $Y$ is interpolated and an estimated noise residue $R$ is generated by using two
Fig. 1. Architecture of feedback channel based Transform Domain Wyner-Ziv video codec

previously decoded frames [12]. The noise residue $R$ and side information $Y$ undergoes the same $4 \times 4$ transform to obtain the transformed coefficients $C_Y$ and $C_R$, respectively. $C_R$ is used to estimate the noise distribution between the corresponding bands of the side information frame and the original Wyner-Ziv frame. Using a modeled noise distribution [13] (with estimated Laplacian parameter $\alpha$), the coefficient values of the side information frame $C_Y$ and the previous successfully decoded bitplanes, soft-input information (conditional bit probabilities $P_{\text{cond}}$) for each bitplane is estimated. With this soft-input information, $P_{\text{cond}}$, the LDPCA decoder starts to process the various bitplanes to correct the bit estimation errors. Convergence is tested by an 8-bit CRC sum and the Hamming distance between the received syndrome and the one obtained from the decoded bitplane [15]. If both the Hamming distance and CRC sum are satisfied, convergence is declared. If not, more syndrome bits are requested and decoding and testing is run again. After a bitplane is successfully decoded, a quantization interval can be obtained. It indicates the range of the original Wyner-Ziv coefficient $C_X$. Together with side information coefficients $C_Y$, noise distribution parameter $\alpha$ and the interval information, decoded coefficients within band $b_k$ of the Wyner-Ziv frame are reconstructed as in [16]. Finally, the inverse transform is performed to obtain the reconstructed Wyner-Ziv frame $X'$. 

IV. SCALABLE-TO-LOSSLESS TDWZ

In order to achieve scalable-to-lossless TDWZ video coding, some aspects of a basic lossy TDWZ video codec are required to be updated and modified. At the encoder side, the modifications are mainly on key frame coding, the transform and not applying quantization besides the quantization implicit in coding bitplanes. The key frames are lossless encoded. Obviously any lossless encoder may be applied, we chose JPEG-LS. The main modification is to apply the $4 \times 4$ reversible integer transform presented in Section II to the Wyner-Ziv frames to obtain the integer transform coefficients. We shall refer to a lossy TDWZ scheme using the reversible integer DCT by rTDWZ. The coefficients are coded in a slightly modified sign-magnitude representation (where the 0 interval is associated with the positive values). Instead of pre-defined quantization matrices as in [5], the maximum absolute magnitude of transformed coefficients, $m_k$ in each band $b_k$ is calculated at the encoder. The smallest value of $M_{b_k}$, such that $2^{M_{b_k}}$ can cover the range of values, is chosen to decompose the transformed coefficient into bitplanes with the image and band dependent, minimum required bit depth $M_{b_k}$ for lossless coding. For 8 bit pixel values, $M_{b_k}$ will not exceed 10 bits, as shown in Sec. II. The deadzone quantization of the TDWZ has to be dealt with for lossless coding. No dead-zone is applied in defining the bitplanes. Actually deadzone quantization could be applied for lossy coding and then resolved by sending additional bits in the scalable-to-lossless refinement. Starting from the most significant bitplane, each bitplane is fed to a LDPCA encoder together with the CRC. The encoded bitplane is saved in a buffer and the amount of transmitted bits depends on the requests from decoder. Since all the encoded bitplanes are available at the encoder buffer, by controlling the number of transmitted bitplanes, the quality of transmitted and decoded Wyner-Ziv frames can be vary and be scalable-to-lossless. The Rate-Distortion (RD) performance of this scalable-to-lossless TDWZ video coding can be influenced and optimized by selective ordering of the different bitplanes and frequency bands. However, the RD optimization is not considered in the scalable-to-lossless TDWZ codec described in this paper. The decoding order is starting from the most significant bitplane to the least significant bitplane and from the low frequency band to high frequency band.

Besides employing a reversible integer transform, the modification of the decoder is mainly in the reconstruction module (Fig. 1). The rest of the decoding of Wyner-Ziv frames is the same as in the TDWZ decoder. For a given coefficient band $b_k$, if the current bitplane $M_i$ is not the final bitplane providing the required bit depth, $M_{b_k}$, i.e. $M_i < M_{b_k}$, reconstruction by the method in [16] is employed to guarantee that the reconstructed coefficients are located in the correct interval. If the current bitplane $M_i$ is the final bitplane providing the required bit depth $M_{b_k}$, all the available bitplanes generated at the encoder have been received and thus the decoded coefficient provides the lossless reconstructed transformed coefficients. After all the transform coefficients are obtained, inverse reversible integer transform is performed to reconstruct the Wyner-Ziv frame.

V. SCALABLE-TO-LOSSLESS BACKWARD ADAPTIVE CODING

Fig. 2. Architecture of backward adaptive video coding

Interpreting the Wyner-Ziv theorem in terms of a practical Wyner-Ziv video codec as outlined above, it should be possible to achieve a RD performance similar to that of a conventional video codec under certain conditions [3]. However, based on
previous results e.g. in [12][13], there is still a gap between the performance of practical TDWZ video codec and conventional hybrid video codec (e.g. H.264/AVC Inter coding). This gap depends on the video characteristics and it may be substantial. This loss of performance of practical TDWZ video codecs may be introduced by the low quality of side information frame, an inaccurate noise model and loss of performance in the LDPCA codec etc. In order to evaluate the performance of the LDPCA codec [14] in a practical TDWZ video codec, a backward adaptive prediction coding scheme is described in this section.

Deviating from the distributed encoding, the LDPCA decoder may be replaced by an arithmetic decoder using the same conditional probabilities, \( P_{\text{cond}} \), as input. Now the encoder performs the same processing achieving the same conditional probabilities, \( P_{\text{cond}} \), and uses these as input to the arithmetic encoder. As shown in Fig. 2, the general architecture of backward adaptive decoding scheme is the same as in the scalable-to-lossless TDWZ video codec. However, backward frame prediction (here in B-frames) is allowed to calculate the same conditional probabilities, \( P_{\text{cond}} \), at encoder side. This is based on employing both the side information generation method [12] and the noise modeling module [13] also at the encoder side, hence the estimated soft input \( P_{\text{cond}} \) otherwise fed into the LDPCA decoder in Wyner-Ziv coding is now available both at the encoder and the decoder and used to drive the arithmetic encoding and decoding, respectively. What we have is more like a conventional coding scheme, but now with backward adaptive motion compensation without explicit encoding of motion vectors. For ease of calculation in the experiments, we estimate the code length of the arithmetic encoder by calculating an Ideal Code Length (ICL) based on soft input \( P_{\text{cond}} \), which the TDWZ utilizes in the LDPCA decoder.

For one bitplane \( x \), the ICL is given by

\[
L(x) = \sum_{j=0}^{n} - \log P_{\text{cond}}(x_j)
\]

(4)

where \( x_j \in \{0,1\} \) and \( P_{\text{cond}}(x_j) \) represents the estimated conditional probability of \( x_j \), i.e. the symbol with index \( j \). The decoder is able to losslessly decode each bitplane with the same side information generation method [12], noise model [13] and the received coding bits. It is well known that context adaptive arithmetic coding can provide code lengths very close to the ICL. For both context adaptive coding and distributed source coding the ICL can take the place of an (upper bound of) the conditional entropy \( H(X|Y) \), which is theoretically achievable asymptotically. The backward adaptive coding scheme is utilized to indicate the potential room for improvement of the TDWZ video codec if an ideal Slepian-Wolf codec is employed. But it may also serve as a codec in itself and evaluate the performance of modifying a DCT based video coding as H.264 to a scalable-to-lossless DCT based video codec.

VI. EXPERIMENTAL RESULTS

Performance of scalable-to-lossless TDWZ video coding is evaluated in this section. Furthermore, the performance of backward adaptive coding with ICL is also reported to illustrate potential for improvement of scalable-to-lossless TDWZ. The test sequences are Coastguard, Hall Monitor and Foreman, at QCIF, 15 frames per second (fps). Hall Monitor is dominated by a static background and thus simple capture cross-frame correlation. Coastguard is also characterized by in some sense simple apparent motion, due to a panning camera, while the motion of the water is not so simple. Foreman is a typical video telephony scene including some complex motion and scene change. Commonly used GOP size \( N \) equal to 2 is chosen.

Initially, the influence of introducing a reversible integer DCT is examined. The RD performance of lossy TDWZ video codec with reversible integer DCT (denoted as rTDWZ) is evaluated in Figs. 3 and 4. The performance is evaluated based on the luminance components of all the frames of a sequence. Key frames are encoded with H.264/AVC Intra [17] with the same Quantization Parameters (QP) as in [15]. For comparison, the performance of the lossy TDWZ video codec (Sec. III) and the benchmark codecs with relevant low encoding complexity, i.e. not using motion estimation at the encoder, are also reported (Figs. 3 and 4). These are H.264/AVC Intra codec, H.264/AVC No Motion codec and DISCOVER video codec. It may be noted that lossy TDWZ video coding gives better RD performance than H.264/AVC Intra codec and DISCOVER video codec on both sequences. With the reversible integer DCT, minor (acceptable) performance loss is introduced in rTDWZ, but the performance is still better than that of the DISCOVER codec.

![Fig. 3. Rate-Distortion performance comparison on Hall Monitor for all frames](image_url)

Thereafter, the RD performance of scalable-to-lossless TDWZ video coding described in Section IV is compared with scalable-to-lossless solutions based on the JPEG 2000 codec in Figs. 5 and 6. For GOP size 2, the performance is evaluated on the luminance component of even/WZ frames only, since key frames are lossless coded. As we focus on high-quality and scalable-to-lossless, the distortion is here expressed...
by \( \log(1 + \text{MSE}) \), where MSE is the standard mean square error. (It may be noted that values of 1 and 6 corresponds to a PSNR of 48.1 dB and 30.1 dB, respectively.) For fair comparison, both Intra frame lossless coding scheme and a low complexity Inter frame coding scheme (i.e. JPEG 2000 Diff) are included. JPEG 2000 Diff denotes compression of difference frames with JPEG 2000 coding. The difference frame \( D \) is obtained by directly calculating the difference between the current frame \( X_i \) and the previous key frame \( X_{i-1} \).

\[
D = (X_i - X_{i-1} + 128) \mod 256 \quad (5)
\]

As shown in Figs. 5 and 6, the performance of the proposed scalable-to-lossless TDWZ video codec is better than JPEG 2000 Intra frame coding. Compared with low-complexity Inter frame coding schemes, the performance of scalable-to-lossless TDWZ video codec is better than JPEG 2000 Inter frame coding for the sequence Coastguard and it gives a comparable performance in the mostly static sequence Hall Monitor. Among all the RD curves, the backward adaptive coding measured by ICL always gives the best results. This indicates that the side information and noise modeling are indeed efficient, but there is still room for improvement of the scalable-to-lossless TDWZ video coding and it further shows that good performance may be achieved by video codecs using a reversible integer DCT.

Finally, the performance of different lossless coding schemes are listed and compared in Table. II and the RD performance of the scalable-to-lossless TDWZ video codec is compared with non-scalable video codecs in Figs. 7 and 8. The DCT based H.264 does not provide lossless encoding, using the JM H.264 reference software [17] but achieving high PSNR values is possible. For lossless mode using predictive coding another available H.264 codec (x.264[18]) was used. It can be seen that the lossless TDWZ video coding can save around 5% bit rate compared to JPEG LS and compared to JPEG 2000 and lossless H.264 Intra frame coding the reduction is 8%-13% for sequences with low motion. For the sequence with intensive motion, e.g. Foreman, the performance of lossless TDWZ video coding is competitive as well.

Compared with low complexity Inter frame coding schemes (i.e. JPEG-LS Diff and JPEG 2000 Diff), lossless TDWZ coding gives better performance in Coastguard and comparable result in Foreman but not as good results in the almost static sequence Hall Monitor. Compared with lossless backward adaptive coding with ICL, there is a penalty about 13%-18% introduced by the practical lossless TDWZ video coding. This suggests improving the performance of the LDPCA codec employed, a topic we leave as an area for future research. Very good performance is achieved by the x.264 lossless inter, but this applies motion estimation at the encoder. Furthermore, it can be seen from the Table II that the lossless coding performance of backward adaptive coding using arithmetic coding (but here evaluated by ICL) can match conventional predictive video coding (i.e. x.264 Inter frame coding) in most cases, while providing scalable-to-lossless at the same time.

As shown in Figs. 7 and 8, the RD performance of the scalable-to-lossless TDWZ video codec is compared with non-scalable H.264/AVC (JM H.264 [17]) and JPEG LS near lossless coding. It shows that scalable-to-lossless TDWZ video can outperform H.264/AVC Intra coding and JPEG LS near lossless Intra frame coding. Compared with H.264/AVC no motion (key frames are near lossless coded with PSNR value around 80 dB) and JPEG LS near lossless Inter frame coding (key frames are lossless coded), the performance of scalable-to-lossless TDWZ video codec is better for the sequence.
Coastguard but not as good results (especially at high quality) in the almost static sequence Hall Monitor. It may be noted from Fig. 7 that RD performance of JPEG LS near lossless Inter frame coding is better than scalable-to-lossless TDWZ only above 43 dB. H.264/AVC No Motion Inter frame coding is better but only gives the maximum PSNR around 65 dB.

### Lossless Compression. Comparison of Average bpp of Even/WZ Frames (GOP 2)

<table>
<thead>
<tr>
<th></th>
<th>Hall Monitor</th>
<th>Coastguard</th>
<th>Foreman</th>
</tr>
</thead>
<tbody>
<tr>
<td>JPEG-LS</td>
<td>3.8987 bpp</td>
<td>5.0067 bpp</td>
<td>4.3499 bpp</td>
</tr>
<tr>
<td>JPEG-LS Diff</td>
<td>3.0684 bpp</td>
<td>5.4030 bpp</td>
<td>4.3652 bpp</td>
</tr>
<tr>
<td>JPEG 2000</td>
<td>4.2798 bpp</td>
<td>5.2126 bpp</td>
<td>4.5991 bpp</td>
</tr>
<tr>
<td>JPEG 2000 Diff</td>
<td>3.2852 bpp</td>
<td>5.4588 bpp</td>
<td>4.5454 bpp</td>
</tr>
<tr>
<td>x.264 Lossless Intra</td>
<td>4.1446 bpp</td>
<td>5.1815 bpp</td>
<td>4.6621 bpp</td>
</tr>
<tr>
<td>x.264 Lossless Inter</td>
<td>3.1162 bpp</td>
<td>4.1545 bpp</td>
<td>3.3324 bpp</td>
</tr>
<tr>
<td>Lossless TDWZ</td>
<td>3.7080 bpp</td>
<td>4.7463 bpp</td>
<td>4.5850 bpp</td>
</tr>
<tr>
<td>Lossless ICL</td>
<td>3.1545 bpp</td>
<td>4.1880 bpp</td>
<td>4.0793 bpp</td>
</tr>
</tbody>
</table>

Fig. 7. Non-scalable video codecs compared with scalable-to-lossless TDWZ on Hall Monitor for even/WZ frames only

Fig. 8. Non-scalable video codecs compared with scalable-to-lossless TDWZ on Coastguard for even/WZ frames only

### VII. Conclusion

Scalable-to-lossless DVC was introduced based on using a reversible integer DCT as the transform in a TDWZ scheme. Experimental results show that the proposed scalable-to-lossless TDWZ video codec achieves good performance at high quality and competitive lossless performance on the test images. The codec outperformed lossless coding based on the standardized JPEG 2000. For lossless coding efficiency, the proposed scalable-to-lossless TDWZ video codec can save up to 5%-13% bits compared to lossless coding by JPEG LS, JPEG 2000 and H.264 Intra frame coding. Compared with low complexity Inter frame lossless coding schemes (i.e. JPEG-LS Diff and JPEG 2000 Diff), the proposed scalable-to-lossless TDWZ video codec gives better performance for Coastguard, comparable result in Foreman but worse results for the mostly static Hall Monitor sequence. Furthermore, a system based on backward adaptive coding is also introduced and tested. The results illustrate that there are still room for improvement of the scalable-to-lossless TDWZ video codec. It also showed that efficient scalable-to-lossless coding using a reversible integer DCT is feasible.

### REFERENCES


