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Boundary Handling Mechanism for Lifting Based Spatial Adaptation of Filter Banks

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ABSTRACT

Time/space varying filter banks (FBs) are proved to be useful in building signal adaptive transforms. Lifting factorization of FBs allows to spatially adapt between arbitrary FBs, avoiding the need to design border FBs to complete perfect reconstruction (PR) during the transition. However, lifting based switching between arbitrarily designed FBs induces spurious transients into the resulting subbands during the transition. In this paper we propose a boundary handling mechanism that maintains good frequency response and eliminates the transients during the transition. We successfully show spatial adaptation between JPEG2000 9/7 and 5/3 FBs to reduce the ringing artifacts in images.

Keywords: W avelets, Lifting, Time varying filter banks, Adaptive transforms.

1. INTRODUCTION

Adaptive wavelet transforms that adapt to the non-stationary behavior of images (or signals in general) have received lot of attention. Time/space varying FBs are proved to be useful in building such signal adaptive transforms. Switching between two (or more) independently designed PR FBs generally results in significant amount of reconstruction distortion in the transition region. Forcing the completion of PR during the region of overlap demands designing the two (or more) FBs together along with a set of transition FBs (generally known as boundary FBs). Design of such time varying FBs have been studied in,[1,2] and in many more.

The structural PR property of lifting factorization of FBs[3] allows to spatially adapt between arbitrary FBs, avoiding the need to design border FBs to complete PR and has led to the development of efficient adaptive transforms. In[4,5] and in many more, either the filter coefficients or the filter direction is automatically (without any side information) adapted to signal local behavior. However, these constructions are limited to only 2 step lifting structure. In,[6,7] the direction of the lifting steps of a 1D FB are seamlessly adapted to the local image directionality and was shown to be successful in image coding application compared to the separable DWT.

If the lifting based adaptive transforms adapt the direction of a FB keeping the FB coefficients fixed, they don't induce any transition discontinuities. However, the lifting structure having the ability to seamlessly switch between arbitrarily designed FBs without any issues in the transition region would give more flexibility. Though lifting based spatial adaptation of FBs solves PR problem, it induces spurious transients in the resulting subbands around the point of adaptation, which is not desirable in many applications. In this paper we study the transients during the transition of FBs and propose a boundary handling mechanism to switch between any given FBs.

Rest of the paper is outlined as follows. In section II the transients are analyzed during the switching between 9/7 and 5/3 FBs of JPEG2000.[8] The proposed boundary handling mechanism is discussed in Section III. In section IV we show the construction of an adaptive transform by switching between 9/7 and 5/3 FBs using the proposed method and show its effectiveness in reducing the ringing artifacts in image coding. Finally, Section V concludes the paper.

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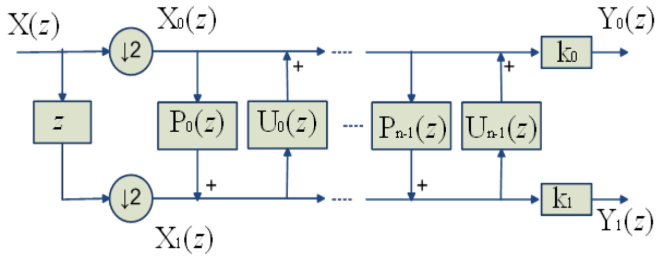


Figure 1. Analysis stage of a lifting based 2 channel FB

2. LIFTING BASED SPATIAL ADAPTATION OF FBS

Lifting structure[3] for 1D 2-channel FBs is shown in Fig.1. Essentially it consists of splitting the signal into 2 polyphase components (even and odd), then applying a series of alternate predict (lifting) and update (dual lifting) steps followed by scaling. The polyphase matrix of a 2 channel PR FB in terms of lifting factorization, such as in Fig.1, is given by

$$\mathbb{E}(z) = \begin{bmatrix} k_0 & 0 \\ 0 & k_1 \end{bmatrix} \prod_{i=1}^{n} \begin{bmatrix} 1 & U_{n-i}(z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ P_{n-i}(z) & 1 \end{bmatrix} \tag{1}$$

As long as each lifting step can be exactly inverted at synthesis, PR is achieved even around the point of adaptation, thus avoiding the need of transition FBs.

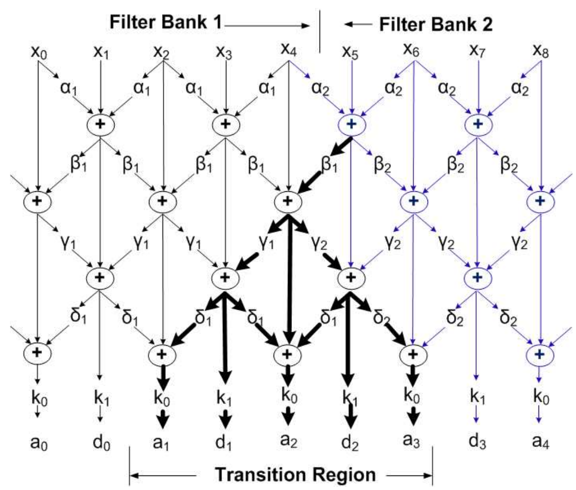


Figure 2. Signal flow diagram of a 4 step lifting process with a swicth between FB1 and FB2.

Consider the lifting factorization of linear phase 9/7 family FBs with lifting steps $P_{0i} = \alpha_i(1+z), U_{0i} = \beta_i(1+z^{-1}), P_{1i} = \gamma_i(1+z), U_{1i} = \delta_i(1+z^{-1})$ and scaling coefficients k_{0i}, k_{1i} for i = 1,2 (FB1 and FB2). Fig.2 shows the signal flow diagram of the lifting process when FB1 is applied for the signal upto the sample x_4 followed by FB2 from x_5. Thin lines show the lifting process of FB1 and FB2. Thick lines show how the intermediate values of one FB is accessed by the lifting steps of the other FB and also shows the subsequent lifting steps that are getting affected. The low pass coefficients a_1 to a_3 and the high pass coefficients d_1 to d_2 are the ones affected. Tracking backwards through the flow diagram, the filter coefficients effectively used in generating each of these coefficients in the transition region can be obtained.

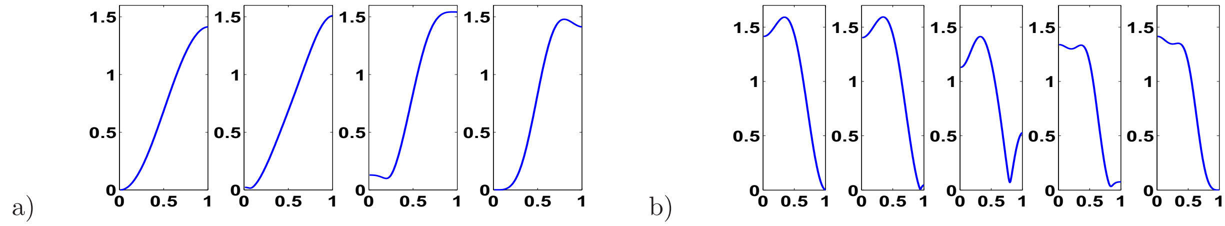


Figure 3. Without any boundary handling mechanism in switching from 5/3 to 9/7 FB: a) Frequency responses of the resulting high pass filters for the high pass coefficients d_0 to d_3. b) Frequency responses of the resulting low pass filters for the low pass coefficients a_0 to a_4.

Consider switching between the 5/3 and 9/7 FBs used in JPEG2000.[8] 9/7 FB has 4 lifting steps. For the 5/3 FB we also consider 4 lifting steps with the last 2 steps equal to the lifting steps of 5/3 FB and the first two being zero. Fig.3 shows the resulting filters responses for the high pass coefficients d_0 to d_3 and for the low pass coefficients a_0 to a_4 when switching from 5/3 to 9/7 (switching from 9/7 to 5/3 can be shown similarly). The high pass filters have “DC leakage” and the low pass filters have “High frequency leakage”. Essentially the zero response at alias frequencies (at $z = -1$ in low pass filters, at $z = 1$ in high pass filter) is lost during the transition. These energy leakages induce transients into the resulting subbands. For a constant input of length 128 we switch between 9/7 and 5/3 FBs for every block of length 32. Fig.4 shows the resulting low pass and high pass subbands with such adaptation. Spurious transients can be seen at the block boundaries. Similarly, transients can be shown for a high frequency input.

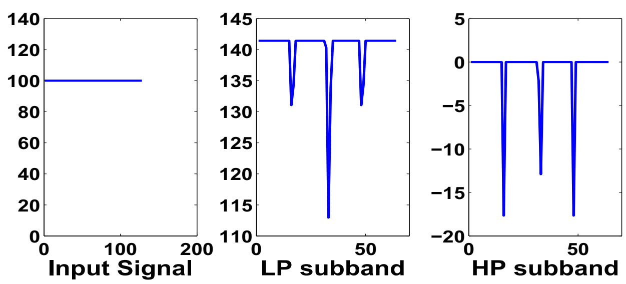


Figure 4. Low pass and high pass subbands with switching between 9/7 and 5/3 FBs for a constant input.

3. PROPOSED BOUNDARY HANDLING MECHANISM

The proposed boundary handling mechanism consists of 3 modifications to handle “DC leakage”, “High frequency leakage” and “Gain normalization” in the transition region, and they can be summarized as follows.

1. *No DC leakage*: To avoid DC leakage, at the input of every lifting step scale the values from the neighboring block such that they have same DC level as that of the values in the current block. For example if the i^{th} lifting step in FB1 is accessing values from FB2 then the intermediate values from the FB2 should be scaled by the constant N_{12} which is given by

$$N_{12} = H_{1i}(1)/H_{2i}(1), \tag{2}$$

where $H_{1i}(1)$ and $H_{2i}(1)$ are the DC responses of the filter responses $H_{1i}(z)$ and $H_{2i}(z)$ at the input of i^{th} lifting step in FB1 and FB2 respectively. Table.I shows the DC levels at the input of every lifting step in the 9/7 FBs. If any of the above DC responses are zero then for the convenience of implementation we replace them with 1 to indicate no effect. As can be seen the above proposed modification imposes a zero at $z = 1$ in the high pass filters in the transition region as long as the high pass filters in the given FBs have atleast a zero at $z = 1$. Also

Table 1. DC levels at the input of every lifting step in the 9/7 FBs

Lifting step	DC level in 9/7 FB
P_0	1
U_0	$1 + P_0(1)$
P_1	$1 + U_0(1)(1 + P_0(1))$
U_1	$(1 + P_0(1)) + P_1(1)(1 + U_0(1)(1 + P_0(1)))$

if the given FBs are symmetric then a second order zero at $z = 1$ is imposed. This is because in a symmetric filter, say $H(z)$, the second order zero is a scaled version of the first order zero i.e, $H^1(1) = kH(1)$ for some constant k.

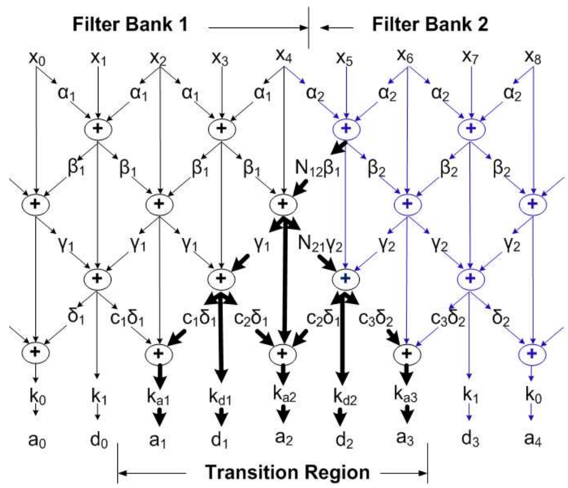


Figure 5. Modified signal flow diagram of a 4 step lifting process with a swicth between FB1 and FB2 using the proposed boundary handling mechanism.

2. *No high frequency leakage*: No high frequency leakage into low pass channel means that for an input signal with highest frequency ($f = \pi$) the low pass coefficients after final update step are zero. From the signal flow diagram in Fig.2, the frequency response of the low pass filter after the final update step can be written as

$$H^{LP}_{m4}(z) = H^{LP}_{m3}(z) + H^{HP}_{m3}(z)U_1(z) \tag{3}$$

where $H^{LP}_{m4}(z)$ (or $H^{HP}_{m3}(z)$) is the effective low (or high) pass filter after 4^{th} (or 3^{rd}) lifting step at time step m and $U_1(z)$ is the final update step. Note that m runs at the down sampled rate. At $z = -1$ we want $H^{LP}_{m4}(z) = 0$. Toward achieving this, at the final update step we introduce constants c_m such that

$$H^{LP}_{m4}(-1) = H^{LP}_{m3}(-1) + c_m H^{HP}_{m3}(-1)U_1(-1) = 0. \tag{4}$$

As can be seen the constants c_m ensure that in the transition region a zero at $z = -1$ is imposed in the low pass channel irrespective of the nature of the given FBs.

3. *Gain normalization*: For the coefficients a_m and d_m in the transition region scaling coefficients (denote them as K_{a_m}, K_{d_m} respectively) are calculated based on the effective filters used in generating them and are given by

$$K_{a_m} = \sqrt{2}/H_{a_m}(1), \text{ and } K_{d_m} = \sqrt{2}/H_{d_m}(-1), \tag{5}$$

where $H_{a_m}(z)$, $H_{d_m}(z)$ are the filter responses of the resulting filters in generating a_m and d_m respectively. To implement the above 3 modifications we need to be able to find the DC and Nyquist response of the filters of partial (or full) lifting steps. Towards this we use the recursive calculation of DC and Nyquist responses in terms of only the DC response of the lifting steps reported in.[9] With these modifications in the transition region the resulting signal flow diagram is shown in Fig.5. With the above modifications, Fig.6 shows the resulting filters responses for the high pass coefficients d_0 to d_3 and for the low pass coefficients a_0 to a_4 when switching from 5/3 to 9/7. As can be seen zero frequency response at alias frequencies is successfully maintained through out the transition region, thus resulting in a smooth transition from the frequency response of one FB to the other. Fig.7 shows the resulting subbands for a constant input with the proposed boundary handling mechanism where the transients are completely eliminated.

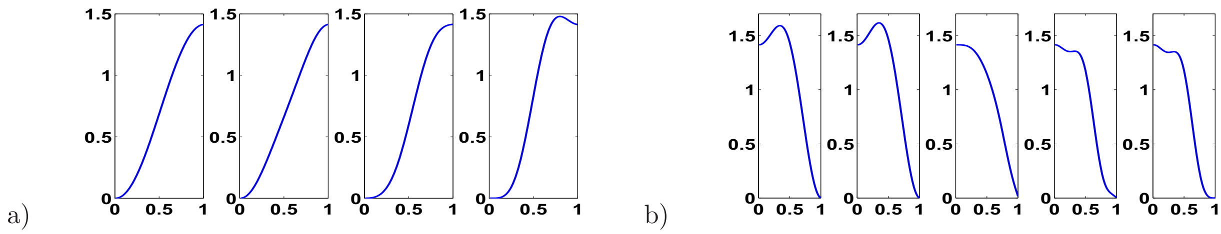


Figure 6. With the proposed boundary handling mechanism in switching from 5/3 to 9/7 FB: a) Frequency responses of the resulting high pass filters for the high pass coefficients d_0 to d_3. b) Frequency responses of the resulting low pass filters for the low pass coefficients a_0 to a_4.

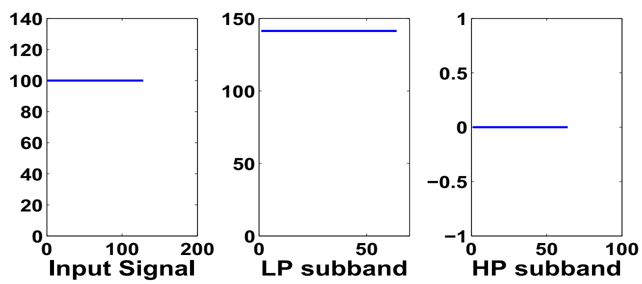


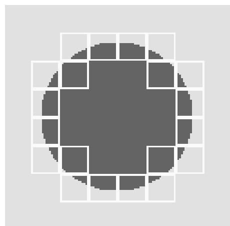
Figure 7. Low pass and high pass subbands with switching between 9/7 and 5/3 FBs for a constant input with proposed boundary handling mechanism.

4. APPLICATION: REDUCTION OF RINGING ARTIFACTS

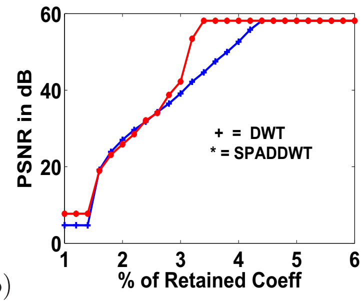
Ringing artifacts are some of predominant artifacts in wavelet based image transforms caused mainly by applying long length filters across the edges. With the proposed boundary handling mechanism we switch between the JPEG2000 9/7 and 5/3 FB's such that for the regions with edges we use 5/3 FB and for the smooth regions we use 9/7 FB. Fig.8(a) shows a synthetic image highlighted with the detected "edge blocks". Call this transform as Spatial Adaptive DWT (SPADDWT). We use the directional variance defined in[10] to classify the blocks. We generate the edge block decision map only at the finer level and the same edge map is used to derive edge block decision map in the subsequent levels, hence the over head bits to represent edge block decision map is very nominal (within 1% of total budget at 0.3bpp).

A 3-level decomposition using DWT and SPADDWT is applied on a synthetic image with circular edge. Fig.8(b) shows the PSNR results with non-linear approximation. SPADDWT recovers the edge regions faster than DWT and is reflected in the superior non-linear approximation. Fig.8(c) shows the reconstructed image with only 2% of retained coefficients. Reduction of ringing artifacts by SPADDWT can be clearly seen.

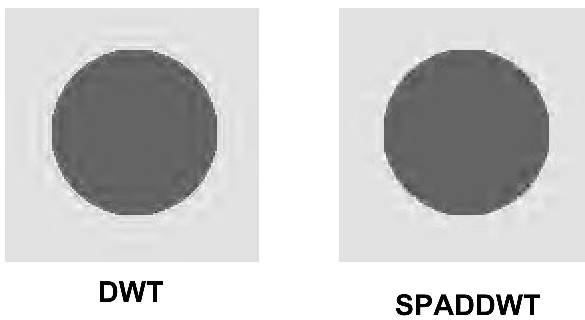
A 4-level decomposition using DWT and SPADDWT is applied on Cameraman image. Fig.9(a) shows the detected edge blocks. Fig.9(b) shows the rate-distortion (RD) performance of DWT and SPADDWT using SPIHT encoder.[11] SPADDWT shows slight improvements in PSNR below 0.25 bpp and subjectively SPADDWT showed reduced ringing artifacts upto 0.6 bpp, beyond that the reconstructed images were perceptually indifferent. Similar results are observed for other images as well. From left to right, Fig.9(c) shows the reconstructed images at 0.3bpp using DWT and SPADDWT respectively. Fig.9(d) shows the enlarged versions of the images reconstructed using DWT (top row) and using SPADDWT (bottom row). Reduction of ringing artifacts by SPADDWT can be clearly seen.



a)



b)



c)

Figure 8. a) Synthetic image with edge block highlighted. b) PSNR results with non-linear approximation using 3-level decomposition. c) Reconstructed images with only 2% of retained coefficients.

5. CONCLUSION

We have studied the transients during the lifting based switching between arbitrarily designed FBs by analyzing the frequency response in the transition region. We have proposed a boundary handling mechanism that maintains good frequency response and eliminates the transients during the transition. Using the proposed boundary handling mechanism we have developed an adaptive transform by switching between the JPEG2000 9/7 and 5/3 FBs and shown that it reduces the ringing artifacts in images significantly. With this we conclude that the proposed method adds more flexibility to the lifting based adaptation and can motivate the development of more elegant adaptive transforms for image processing.

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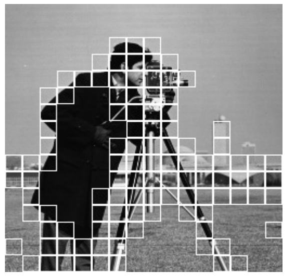
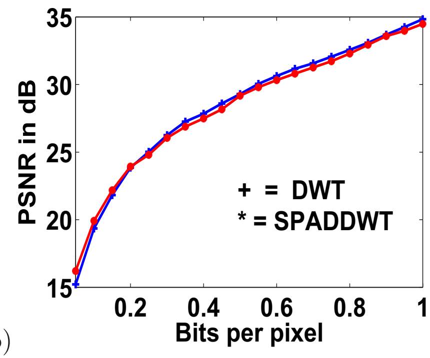


a)



b)

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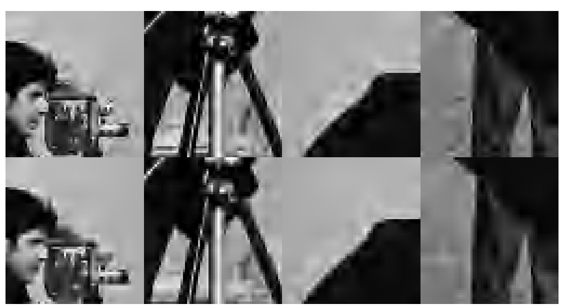

d)

Figure 9. a) Cameraman image with edge blocks highlighted. b) Rate-Distortion performance with SPIHT encoder using 4-level decomposition. c) Reconstructed images at 0.3bpp; Left image: using DWT, Right image: using SPADDWT. d) Enlarged parts of reconstructed image; Top row: using DWT, Bottom row: using SPADDWT.

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