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Reduction of transients during lifting based spatial switching of two-channel filter banks

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ABSTRACT

Time/space varying filter banks (FBs) are useful for non-stationary images. Lifting factorization of FBs results in structural perfect reconstruction even during the transition from one FB to other. This allows spatial switching between arbitrary FBs, avoiding the need to design border FBs. However, we show that lifting based switching between arbitrarily designed FBs induces spurious transients in the subbands during the transition. In this paper, we study the transients in lifting based switching of two-channel FBs. We propose two solutions to overcome the transients. One solution consists of a boundary handling mechanism to switch between any arbitrarily designed FBs, while the other solution proposes to design the FBs with a set of conditions applied on lifting steps. Both solutions maintain good frequency response during the transition and eliminate the transients. Using the proposed methods, we develop a spatial adaptive transform by switching between the long length FBs (either the JPEG2000 9/7 FB or the newly designed 13/11 FB) and the short length FBs (JPEG2000 5/3 FB) for lossy image compression. This adaptive transform shows PSNR improvement for images over JPEG2000 9/7 FB in low bit rate region (up to 0.2 bpp) and subjective improvements with reduced ringing up to medium bit rates (up to 0.6 bpp).

1. Introduction

Time-varying filter banks (TVFBs) are useful to accommodate non-stationary behavior of signals like images. The advantages of TVFBs have been demonstrated in the application of subband coding of image [1–4], in the application of medical image analysis [5], etc. TVFBs were introduced in [6]. There are different ways that a filter bank can be time-varying. One simple yet very useful way is when the analysis and synthesis FBs are switched among a set of FBs while keeping the number of subbands unchanged. In general, though the given set of FBs individually gives perfect reconstruction (PR), switching among them does not result in PR. Allowing instantaneous switching between different analysis FBs, the authors in [7] formulated a time-domain PR condition that results in quite a number of transition synthesis FBs. Also, for a given set of analysis FBs, existence of such synthesis FBs is not always guaranteed. Hence, the analysis FBs must be redesigned simultaneously [8]. One alternate solution is to allow smooth transition between different analysis/synthesis FBs using a few set of intermediate FBs to achieve PR [9–11]. Usually, it is not easy to control the characteristics of these transition filters and these are not well behaved. In all of the above approaches, TVFBs need to explicitly design transition filters for switching between each pair of FBs. In another approach, instead of transition filters the authors in [8,12] studied the design of a post filter such that the overall cascaded system achieves near PR. In [13], the authors introduce a new delay operator to study the basic principles of linear TVFBs such as invertibility, losslessness, bi-orthogonality, etc.

Lifting factorization of FBs [14] gives structural PR and is complete in the sense that every 1-D 2-channel PR FB can be factorized into lifting steps. Lifting based FIR FBs allow the lifting coefficients to be time-varying, yet giving PR without the need of any explicit transition FBs. The lattice based FIR FBs [15,10] also give structural PR with time-varying coefficients. However, one important advantage of lifting over lattice factorization is that at every lifting step only one of the channels gets modified, while the rest act as reference. This particular property of lifting makes it very attractive over lattice factorization for constructing TVFBs. Different variations of adaptive transforms for images are recently developed based on lifting structure. In one class of adaptive transforms, as in [1–4] and many more, either the filter coefficients or the filter direction is seamlessly (without any side information) adapted at pixel level to the image local behavior. However, these constructions are limited only to 2 step lifting structure. In another class of adaptive image transforms, as in [16,17], the direction of the lifting steps of a 1-D FB is adapted at block level to the local

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0923-5965/

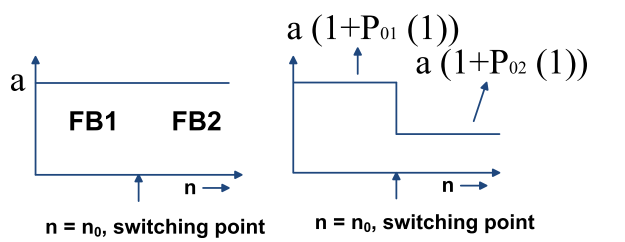

Fig. 1. (Left) *DC* input and switching from FB1 to FB2 at $n = n_0$, (Right) response in the high pass subband after first lifting step. The difference in the DC frequency response of the lifting filters $P_{01}(z)$ and $P_{02}(z)$ induces discontinuity at $n = n_0$ even though the input signal is zero at $n = n_0$.

image directionality. Similarly in [18], the direction of the lifting parameters of a DCT based generalized lapped orthogonal transform is adapted across the small blocks of an image.

Though lifting based switching between arbitrary FBs solves PR problem, it induces spurious transients in the resulting subbands around the point of switching. Transients come from the interaction of the lifting steps of the given FBs. This transient is seen as a discontinuity or glitch around the point of switching irrespective of the nature of the signal at that point and it is not desirable in many applications.

Before we analyze the transients thoroughly, here we give an intuitive reason behind them. Consider an example in 1-D where we want to decompose a constant signal with magnitude a into 2 channels by applying FB1 for $n < n_0$ and FB2 for $n \geq n_0$, as shown in the left side plot of Fig. 1. Let $P_{01}(z)$ and $P_{02}(z)$ be the first lifting steps in FB1 and FB2, respectively. After the first lifting step, the resulting high pass channel (or channel 2 in general) for the constant input is shown in the right side plot of Fig. 1, and is given by

$$y(n) = a(1 + P_{01}(1)) \text{ for } n < n_0 \text{ and } y(n) = a(1 + P_{02}(1)) \text{ for } n \geq n_0.$$

As shown in the right side plot of Fig. 1, such switching between the lifting steps $P_{01}(z)$ and $P_{02}(z)$ induces a discontinuity at $n = n_0$ even though the input signal is a constant at $n = n_0$. The strength of the discontinuity depends on the difference in the DC frequency response of the lifting filters $P_{01}(z)$ and $P_{02}(z)$. As this signal passes through the next lifting steps, the discontinuity will induce more such unwanted transients into both the channels around $n = n_0$. This is because the lifting steps of both the FBs access the region around $n = n_0$. If not at the first lifting step, such a discontinuity can be induced at some other lifting step and can cause transients in the resulting subbands at the end of final lifting steps (Later, Fig. 5 shows the transients for a constant signal at the end of final lifting steps during switching between two FBs).

The ability to seamlessly switch between arbitrarily designed FBs with arbitrary number of lifting steps without any transient is beneficial to the development of adaptive transforms. In this paper, we study the transients during the lifting based switching between FBs with the help of time-varying formulation of lifting factorization similar to the one in [19], and propose two solutions to overcome the transients. One solution consists of a boundary handling mechanism to switch between any arbitrarily designed FBs, while the other solution proposes to design the FBs with a set of conditions applied on lifting steps. Both methods eliminate any transient during the transition region, and at the same time maintain good frequency characteristics in the transition region.

The rest of the paper is outlined as follows. In Section 2, we discuss the formulation of the time-varying lifting factorization of two-channel FBs and then analyze the transients during the switching of FBs. In Sections 3 and 4, we discuss the proposed solutions, and then in Section 5 we discuss their scope in two-dimensions. In Section 6, we develop a spatial adaptive transform by switching between the long length FBs (either the JPEG2000 9/7 FB or the newly designed 13/11 FB) and the short length FBs (JPEG2000 5/3 FB). We conclude the paper in Section 7.

2. Transients in lifting based spatial adaptation of FBs

We consider direct switching between 2-channel FBs using lifting factorization. At the point of switching, all the lifting filters are switched from that of one FB to the other. Around the point of switching, the output pixels are generated by the combination of the lifting steps of both the FBs. We call this region as transition region or region of overlap. We study the time-varying nature of the resulting FB characteristics during the transition region using the time-varying formulation of lifting factorization.

2.1. Time-varying lifting factorization

Lifting structure for 1-D 2-channel FBs is shown in Fig. 2. Essentially, the signal is split into 2 polyphase components (even and odd), and then a series of alternate predict (lifting) and update (dual lifting) steps are applied followed by scaling. Here, we allow the lifting filters to vary with the time index m which runs at the sub-sampled rate. Therefore, the lifting filters can be changed for every 2 input samples in a 2-channel FB. As mentioned earlier, it is noteworthy to observe that at each lifting (or dual lifting) step only one of the polyphase components is modified and the other one is used as a reference signal. This particular nature of lifting factorization maintains invertibility of lifting steps even if they are time-varying. With the time-varying lifting steps, the analysis polyphase matrix of a 2-channel PR FB is given by

$$\mathbf{E}(z, m) = K(m) \prod_{i=1}^{n} L_{n-i}(z, m) \tag{1}$$

where $K(m) = diag(k_0(m), k_1(m))$, and the lifting step $L_i(z, m)$ can be either a predict step or an update step, represented respectively by a lower triangle matrix or an upper triangle matrix given by

$$\begin{bmatrix} 1 & 0 \\ P_{\lfloor i/2 \rfloor}(z, m) & 1 \end{bmatrix} \text{ or } \begin{bmatrix} 1 & U_{\lfloor i/2 \rfloor}(z, m) \\ 0 & 1 \end{bmatrix}.$$

Similarly, the synthesis polyphase matrix is given by

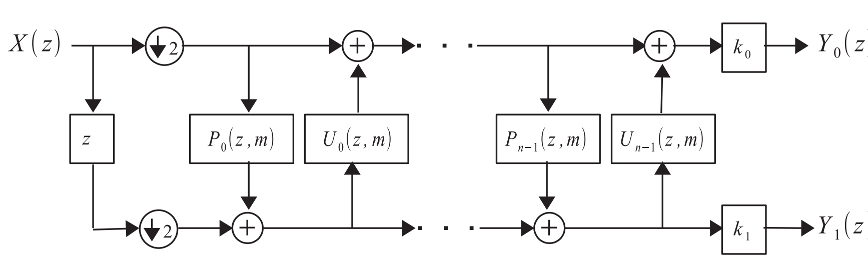

Fig. 2. Analysis stage of a lifting based 2 channel FB.