Prediction based on Boolean filters for multiresolution lossless image compression

Doina Petrescu* Moncef Gabbouj

Signal Processing Laboratory
Tampere University of Technology
P.O. Box 553, FIN-33101, Finland

Abstract

In this paper Boolean filters and a variation of these, FIR-Boolean hybrid filters are proposed for realizing the prediction stages of a multiresolution lossless image compression structure. Optimal and adaptive Boolean filters are used for prediction in The proposed predictors performance is compared to the performance of other lossless multiresolution methods: the hierarchical interpolation scheme (HINT) [2] and the S+P transform [8].

1 Introduction

Lossless compression of images has recently received increasing attention being of major importance in applications such as medical and satellite image transmission and storage.

The majority of the lossless image compression methods are predictive methods encoding the pixels sequentially, in raster scan order. These methods are restricted by causal constraints to use only partially the two-dimensional spatial information. One way to surpass this disadvantage is to use *progressive-resolution*, or *pyramidal* methods where each level of the pyramid represents the entire image, at different spatial resolutions. The pixel values of the lowest resolution level are first encoded in a raster scan order; the prediction at higher resolutions is more accurate, owing to the use of 360 degree information available from the complete and perfect reconstruction of lower resolution levels.

One pyramidal lossless encoding method is the *hierarchical interpolation* (HINT) presented in [2] and improved in [1], where a subsampled version of the image is encoded at the lowest level of the pyramid and FIR filters are used for prediction at higher levels. The term interpolation is often used instead of prediction at higher levels, due to the apparent noncausality of the prediction mask. Interpolation techniques based on median filters and FIR median hybrid filters have been investigated in [7] and [10] and shown to achieve lower entropy for prediction errors than linear interpolation.

A lossless progressive image compression scheme based on the *sequential + prediction* transformation was presented in [8], and experimentally proven to achieve better compression performance than HINT.

In this paper we propose a progressive-resolution lossless image compression structure, where a subsampled version of the image is first encoded at the lowest resolution level, and the pixels at higher levels are predicted using optimal and adaptive Boolean and FIR Boolean-hybrid (FBH) filters from the lower resolution levels and the already available information of the current resolution level.

Boolean and stack filters have been recently used for lossless image coding in sequential predictive methods in [5] and [6]. The performance achieved in reducing the entropy of errors in addition to the simplicity of the design procedure and the very small load for transmitting filter parameters make the optimal Boolean predictors good candidates to replace fixed structures involving linear predictors. We extend here the applications and performance investigation of optimal Boolean filters used for prediction to the progressive-resolution methods.

2 Boolean and FIR–Boolean hybrid filters used for prediction

2.1 Boolean predictors

Consider an $n_r \times n_c$ greylevel image, with pixel values in $\{0,\ldots,M\}$ the current pixel being denoted $D(i,j)$. The values of N pixels in a neighborhood of the current pixel, $\mathcal{N}_{D(i,j)}$, enclosed in the input vector $\underline{X}(i,j)$ are used to calculate the predicted value $\hat{D}(i,j)$, as the output of a Boolean filter, as follows:

$$\hat{D}(i,j) = \sum_{m=1}^{M} f(T_m(\underline{X}(i,j))), \qquad (1)$$

where $(i,j) \in \{1\ldots n_r\} \times \{1\ldots n_c\}$, f denotes the Boolean function of the predictor, and T_m is the

*Now with Nokia Telecommunications, Espoo, Finland.

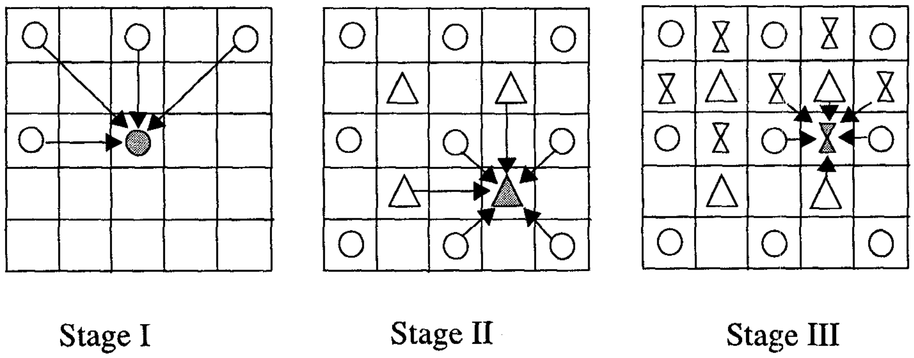

Figure 1: Predicting at different resolution levels

thresholding operator

$$T_m(D) = \begin{cases} 1, & \text{if } D \geq m \\ 0, & \text{else,} \end{cases} \quad (2)$$

applied to each component of the input vector $\underline{X}(i,j)$. An equivalent computation of the output is performed as in [9], using only N threshold values for the input vector, namely the values of its components, as follows:

$$\begin{aligned} \hat{D}(i,j) &= X_{(1)} f([1 \ \dots \ 1]) \\ &+ \sum_{m=1}^{N-1} (X_{(m+1)} - X_{(m)}) f(T_{X_{(m+1)}}(\underline{X}(i,j))) \\ &+ (M - X_{(N)}) f([0 \ \dots \ 0]), \end{aligned} \quad (3)$$

where $X_{(1)} \leq \dots \leq X_{(N)}$ denote the ordered elements of the input vector. FIR–Boolean hybrid filters used for prediction are Boolean filters processing input vectors which contain in addition to the values of the pixels in $\mathcal{N}_{D(i,j)}$ several fixed linear combinations of them: e.g. the average of the spatially nearest pixels is also added in the input vector [5].

2.2 Optimal Boolean and FIR–Boolean hybrid filters used for prediction

Optimal Boolean filters minimizing the sum of absolute prediction errors at all threshold levels are designed using the procedure proposed in [9]. In a first pass through the image to be encoded, a set of 2^N statistics are computed using comparisons and accumulations, and then the Boolean function values are decided based on the sign of these statistics. The Boolean function, in the form of a 2^N length binary vector is the side information for encoding the optimal predictor. For the FIR–Boolean hybrid filters, only the Boolean filter is optimally designed, the linear combinations are kept fixed. For an optimal FIR–Boolean hybrid filter processing a N-pixel mask, and including P linear combinations of the input values, denoted $FBH(N,Q)$, with $Q = N + P$, the vector representing the optimal Boolean function has 2^Q bits.

2.3 Adaptive Boolean filters for prediction

Usually, prediction schemes have high errors near the edges (high local greylevel variations). The amplitude and direction of edges , can be used to adaptively design different predictors for different types of edges. We proposed in [4] an encoding/decoding method where Boolean predictors are modified during the procedure according to the information about the presence and orientation of greylevel discontinuities inside the prediction mask. At each stage of the progressive resolution structure, an overall optimal Boolean predictor is designed. The predictor is used for flat regions (with small greylevel variations) and also for the edges in the beginning of the adaptive procedure, (when no adaptation has been already performed). During the encoding/decoding process, the presence of an edge is detected when the difference between the local maximum and the local minimum within the processing mask is higher than a threshold. If the presence of an edge is detected, the Boolean predictor is switched between several predictors, whose parameters are adaptively modified during the encoding/decoding process. The switching scheme is based on the positions of maximum and minimum values inside the prediction mask, making the predictor sensitive to the orientation of greylevel discontinuity.

3 Multiresolution prediction structure

A progressive resolution structure combining three different prediction stages presented in Figure 1 is used for the lossless compression. In this figure the image is subsampled horizontally and vertically by a factor of 2. The first stage corresponds to sequentially transmitting the subsampled version of the original image. In the second and third stages the prediction mask may contain any combination of pixels (not restricted by causality) from the image transmitted in the previous stages and the pixels already transmitted in the current stage. The prediction accuracy is significantly increased at these stages. The principle is

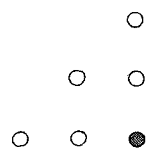

Figure 2: Prediction mask used in Stage I of the multiresolution structure

similar when starting with lower resolution images for the first stage, corresponding to higher subsampling factors. The image is first subsampled horizontally and vertically with the factor 2^L and encoded as in the first stage of Figure 1. Than a loop containing the second and third stages is performed L times until all pixels are encoded. In the proposed structure different Boolean filters are used at each stage, at every resolution level.

4 Experimental results

The performance of optimal and adaptive Boolean and FIR Boolean predictors in multiresolution prediction structures for a set of eight 576×720 greylevel images encoded with 8 bits/pixel from the JPEG test set is investigated.

In our experiments we used 6-pixels prediction masks at all stages. The masks for the second and third stages are presented in Figure 1. For the first stage, corresponding to sequential prediction, the mask is presented in Figure 2. In the case of FIR–Boolean hybrid filters FBH(6,8) the average values of 2 pixels inside the prediction mask selected from those which are spatially nearest from the predicted one are added to the input vector at each stage.

To evaluate the performance of the predictors we calculated in each case entropy of prediction errors as weighted mean of the entropies of errors at each stage of the prediction structure, as in [8].

In the first experiment we investigated the performance of the proposed structure when optimal Boolean and FIR–Boolean hybrid filters are used for prediction and different resolutions are used for the first stage. In Figure 3 the average over the image set of the entropy is plotted for different numbers of resolution levels involved in the prediction structure. For L resolution levels the image is first subsampled horizontally and vertically with the factor 2^L. The value $L = 0$ corresponds to sequential prediction in raster scan order. The figure illustrates that multiresolution prediction using optimal Boolean and FIR–Boolean hybrid filters achieves lower entropy for prediction errors than non-multiresolution methods, but only for a reduced number of resolution levels (3 or 4). For more levels, the entropy of prediction errors does not reduce. This can be explained by the fact that for highly subsampled images no more correlation exists between adjacent pixels which prediction could exploit.

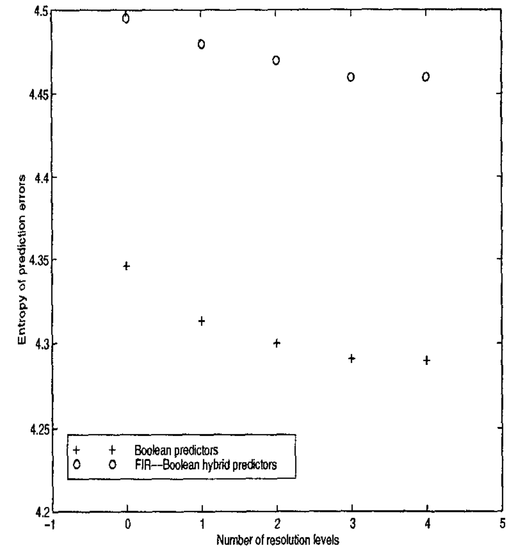

Figure 3: Entropy of prediction errors for different numbers of resolution levels for optimal Boolean and FIR–Boolean hibrid predictors for 6-pixels prediction masks when different numbers of resolution levels are used in the lossless compression structure.

The side information needed to encode predictors parameters at each stage is 64 bits for the optimal Boolean predictors and 256 bits for the optimal FIR–Boolean hybrid predictors and it may be considered negligible for $L \leq 4$.

In the second experiment we compared the performance of different optimal and adaptive Boolean predictors and optimal FIR–Boolean hybrid predictors for 6-pixels prediction masks. The entropy of prediction errors for the set of test images is presented in Table 1. We started the procedure with the image subsampled horizontally and vertically with a factor of 16. Adaptive Boolean predictors whose parameters change according to local information about the presence and orientation of the local gradient outperform the optimal Boolean predictors without any increase in the side information. The optimal FIR–Boolean hybrid filters achieve the lowest entropy for prediction errors for the 6-pixel prediction mask among the proposed predictors.

For comparison, we included in the table the performance of lossless JPEG and other multiresolution lossless image compression methods: HINT [2] and S+P [8]. For JPEG the linear predictor achieving the lowest average entropy of errors for all images among the 7 linear JPEG predictors is selected. For the S+P method the free access codec provided by A. Said and W.A. Pearlman obtained via anonymous ftp from ipl.rpi.edu/pub/EW_Code was used, and the