This paper proposes an RD optimized adaptive recursive extrapolation filter for intra coding based on 2-D non-separable Markov model with four taps, which:

- Predicts from all standard directions
- Is designed to account for the overall rate-distortion cost in conjunction with the codec decisions
- Adapts the filter coefficients to relevant local information

Filter Design

Filter coefficients are determined through off-line training.

Minimizing Prediction Error - “K-modes” iterative clustering

Iteratively repartition the training data into subsets corresponding to the modes, and re-optimize the prediction filter for each mode.

- Initialize the clustering according to the distribution of original modes.
- Initialize the cluster coefficients according to open-loop linear estimation theory based on the Markov model

\[
\begin{bmatrix}
R_{VV} & R_{VU} & R_{VD} & R_{VH} \\
R_{VU} & R_{UU} & R_{UD} & R_{UH} \\
R_{VD} & R_{UD} & R_{DD} & R_{DH} \\
R_{VH} & R_{UH} & R_{DH} & R_{HH}
\end{bmatrix}
\]

- Repartition: Assign each block to the mode whose filter minimizes the prediction error
- Re-optimization: Employ gradient descent method to minimize the mean-squared prediction error for recursive prediction:
  - Since pixels are predicted from previously predicted pixels recursively in a block, the open-loop formula is not applicable
  - The gradient is analytically calculated recursively following the recursive prediction formula

Related Work

- 2D Non-separable Markov Model
- Three-tap recursive extrapolation filter
  - Cannot capture all direction
- Four-tap recursive extrapolation filter designed to minimize the mean-squared prediction error
  - Design is mismatched with the ultimate RD cost that coders optimize
  - Except adaptation to block size, no adaptation to other important local signal statistics

Conventional Spatial Prediction

- Copies reconstructed boundary pixels in a given direction
- Problem - Information Under-utilization
- Assumes a separable Markov mode - incompatible with real data
- Assumes correlation is stationary - however in real data correlation decays with distance from the boundary

Motivation

Experimental Results

The proposed approach was implemented in VP9 and HEVC.

- VP9: 10 filter modes were added in addition to the original 10 intra prediction modes; Overhead of filter adaptation to bit rate: 3 bits/frame.
- HEVC: 9 least used intra modes were replaced by filter modes, which can be disabled selectively by a frame level flag; no adaptation to target bit rate.
- Average reduction in BD-rate for the proposed method over standard VP9 and HEVC coders under intra-only settings.

<table>
<thead>
<tr>
<th>Resolution</th>
<th>VP9 Bit Savings (%)</th>
<th>HEVC Bit Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIF</td>
<td>2.90</td>
<td>0.20</td>
</tr>
<tr>
<td>720p</td>
<td>3.55</td>
<td>0.71</td>
</tr>
<tr>
<td>1080p</td>
<td>2.89</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Comparison of filters designed to minimize prediction error and filters designed to minimize RD cost in VP9 codec under intra-only settings.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Prediction error optimized filters</th>
<th>RD optimized filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSNR (in dB)</td>
<td>Bit savings (%)</td>
<td>Bit savings (%)</td>
</tr>
<tr>
<td>bus(CIF)</td>
<td>0.78</td>
<td>0.93</td>
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<tr>
<td>stockholm(720p)</td>
<td>0.78</td>
<td>2.25</td>
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<tr>
<td>ducks take off (720p)</td>
<td>0.80</td>
<td>1.10</td>
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<tr>
<td>crowd_run(1080p)</td>
<td>1.18</td>
<td>1.44</td>
</tr>
</tbody>
</table>

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