Low power context adaptive variable length encoder in H.264

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Abstract

The adoption of digital TV, DVD video and Internet streaming led to the development of Video compression. H.264/AVC is the industry standard delivering highly efficient and reliable video compression. In this Video compression standard, H.264/AVC one of the technical developments adopted is the Context adaptive entropy coding schemes.

This thesis developed a complete VHDL behavioral model of a variable length encoder. A synthesizable hardware description is then developed for components of the variable length encoder using Synopsys tools. Many implementations were focused on density and speed to reduce the hardware cost and improve quality but with higher power consumption. Low power consumption of an IC leads to lower heat dissipation and thereby reduces the need for bigger heat sinking devices. Reducing the need for heat sinking devices can provide lot of advantages to the manufacturers in terms of cost and size of the end product. Focus towards smaller area with higher power consumption may not be appropriate for some end products that need thinner mechanical enclosures because even if the design has smaller area it needs a bigger heat sink thereby making the enclosures bigger. This thesis therefore aimed at low power consumption without compromising much on the area. The designed architecture enables real-time processing for QCIF and CIF frames with 60-fps using 100MHz clock. The resultant hardware power is 1.4mW at 100MHz using 65nm technology. The total logic gate count is 32K gates.
# Table of Contents

1 Overview.................................................................................................................. 1
  1.1 Video Coding Overview .................................................................................. 1
  1.2 HW/SW CAVLC Design ................................................................................ 4
2 Background Theory ................................................................................................. 5
  2.1 Video Compression ....................................................................................... 5
    2.1.1 Encoder ............................................................................................... 7
    2.1.2 Decoder ............................................................................................. 8
  2.2 H.264 ............................................................................................................. 10
    2.2.1 Prediction Block ............................................................................... 11
    2.2.2 Transform and Quantization block .................................................... 16
    2.2.3 Encoding ......................................................................................... 20
3 Context Adaptive Variable Length Coding (CAVLC) ........................................... 23
  3.1 Coefficient token ............................................................................................ 24
  3.2 T1 sign .......................................................................................................... 24
  3.3 Level .............................................................................................................. 24
  3.4 Total zeros ..................................................................................................... 25
  3.5 Run before .................................................................................................... 25
4 CAVLC ARCHITECTURE ....................................................................................... 26
  4.1 Zigzag Scan Block ........................................................................................ 27
  4.2 Ngen block .................................................................................................... 28
  4.3 Coeff_token block ....................................................................................... 28
  4.4 Total Zeros block ....................................................................................... 29
  4.5 Level block .................................................................................................. 30
  4.6 Run before block ........................................................................................ 31
  4.7 Bitstream generator ..................................................................................... 32
5 Simulation and Synthesis Results .......................................................................... 33
  5.1 Zigzag Scan Block Simulation ..................................................................... 33
  5.2 Ngen block Simulation ............................................................................... 33
  5.3 Coeff_token block Simulation ................................................................... 35
  5.4 Total Zeros block Simulation ....................................................................... 35
  5.5 Level block Simulation ............................................................................... 37
  5.6 Run before block Simulation ....................................................................... 37
  5.7 Bitstream generator block Simulation .......................................................... 38
  5.8 Results .......................................................................................................... 43
6 Conclusion ............................................................................................................ 45
  6.1 Future Work .................................................................................................. 46
List of Figures

Figure 1: H.264 Baseline Profile Encoder[1] ................................................................. 4
Figure 2: Video Compression[1] ....................................................................................... 6
Figure 3: Baseline Profile Decoder ................................................................................... 9
Figure 4: Encoder and Decoder ....................................................................................... 10
Figure 5: Macroblock ........................................................................................................ 12
Figure 6: 4x4 Intra Prediction Patterns (sub-block) ........................................................... 14
Figure 7: 16x16 Intra Prediction Patterns[3] ..................................................................... 14
Figure 8: Tree Structured Macroblock Partitions ............................................................... 16
Figure 9: 16x16 Macroblock Block Ordering[5] ................................................................. 21
Figure 10: Zig-Zag Scan Order ......................................................................................... 22
Figure 11: Proposed CAVLC Architecture ..................................................................... 26
Figure 12: Zigzag simulation ............................................................................................ 34
Figure 13: Ngen simulation .............................................................................................. 34
Figure 14: Coeftoken simulation ...................................................................................... 34
Figure 15: Totalzeros simulation ..................................................................................... 34
Figure 16: Level simulation .............................................................................................. 35
Figure 17: Run before simulation .................................................................................... 36
Figure 18: Bitstream simulation ....................................................................................... 37
Figure 19: CAVLC synthesized core ................................................................................. 38
Figure 20: Clock Gating .................................................................................................... 42
Figure 21: Power comparison ........................................................................................... 42
List of Tables

Table 1: Video Formats and Macroblocks.......................................................... 11
Table 2: PF Look-up Table .............................................................................. 18
Table 3: Q_{step} Look-up Table .................................................................... 17
Table 4: coeff_token Table Look-up Table .................................................... 25
Table 5: Coefftoken VLC table................................................................. 29
Table 6: Pseudo code for total zeros............................................................ 30
Table 7: Pseudo code for Run before........................................................... 31
Table 8: Area, power and Latency comparison............................................. 42
Glossary

CABAC – Context-Adaptive Binary Coding - An efficient coding algorithm geared towards streams with a fixed table of transmitted data.

CAVLC – Context-Adaptive Variable Length Code – An encoding scheme used by AVC to encode data at the bit-level.

DCT – Discrete Cosine Transform – A matrix transform common in image and video compression standard that converts data from the spatial domain into a frequency domain.

IP – Intellectual Property – Within the scope of this paper IP refers to modules design by Xilinx that attach to a soft-processor bus.

ITU – International Telecommunications Union – An organization that shares the goal in standardizing video media.

MPEG – Motion Picture Experts Group – An organization that shares the goal in standardizing video media.

SAE – Sum of Absolute Errors – Method of calculation to measure the error of a given prediction.

VHDL – VHSIC (Very High Speed Integrated Circuit) Hardware Description Language – Language used to model and design hardware from the gate level to algorithm level.
1 Overview

1.1 Video Coding Overview

When digital video is being widely adopted in various devices and mediums, there was a need for standardization and two standardization groups took on the field of video compression, the International Telecommunications Union (ITU) and Motion Picture Experts Group (MPEG). The ITU came up with H.26x series publications while the MPEG’s claim to fame has been the MPEG-x series video standards [2]. In 1997 the ITU and MPEG groups combined efforts to put together the next generation video compression standard [2]. In 2003 they came up with the standard known as H.264 which was also known as MPEG-4 Part 10 [2]. It was also called Advanced Video Code (AVC), standard. This standard offers several improvements to its predecessors (H.261, H.262/MPEG-2, and H.263) [2] such as:

- Variable block-sizes ranging from 16x16 to 4x4
- ¼ pixel resolution for motion prediction
- Multiple reference frames for temporal residual calculation
- Introduction of an integer form of the Discrete Cosine Transform

High Efficiency Video Coding (HEVC) is a new Standard under development by the ISO and ITU-T. The Moving Picture Experts Group (MPEG) and Video Coding Experts Group (VCEG) have set up a Joint Collaborative Team on Video Coding (JCT-VC) with the aim of getting the new standard ready for publication in 2012/2013[13]. The expectation is that it is likely to be published jointly as a new MPEG standard and a new
ITU-T standard, possibly H.265 following the JCT-VC and MPEG meeting in October 2010. The Test Model defines two broad categories of video coding tools, for (a) High Efficiency and (b) Low Complexity applications. The test model according to [13] consists of:

- Coding unit: Block sizes from 8x8 to 64x64 in tree structure
- Intra prediction: Up to 34 intra prediction directions
- Interpolation: 6- or 12-tap interpolation filter, down to 1/4-sample
- Motion prediction: Advanced motion vector prediction
- Entropy coding: CABAC or Low Complexity Entropy Coding (LCEC)
- Loop filter: Deblocking filter or Adaptive Loop Filter (ALF)
- Precision: Extended precision options

Many coding tools have been scheduled for further investigation and may be incorporated into the Test Model if they offer suitable compression gains [13]. Current indications are that the new standard could provide 2x better video compression performance (i.e. around half the bitrate for a similar quality level) at the expense of significantly higher computational complexity, compared with H.264/AVC [13]. The HEVC standard is still uncomplete and is expected to complete the draft by February 2012 and it is speculated to be ready to be ratified as a standard by January 2013 [13]. The scope of this document concentrates on the encoding side of the H.264.
It is the responsibility of the encoder to compress the data into bitstream. A block diagram of an H.264 encoder may be found in Figure 1. The encoder forms a prediction of the macroblock based on previously coded data. The encoder subtracts the prediction from the current macroblock to form a residual. The residual samples are transformed using a 4x4 or 8x8 integer transform. The output of the transform is a set of coefficients. Each of the coefficients is a weighting value for a standard basis pattern. The block of transform dividing each coefficient by quantization parameter then quantizes coefficients. After quantization the result is a block in which most or all of the coefficients are zero, with a few non-zero coefficients. These quantized transform coefficients are encoded to form compressed bit stream. Converting the values and parameters into binary codes using variable length encoding or arithmetic coding does this encoding. The encoded stream can then be transmitted or stored in a storage device.

The H.264 standard defines three profiles of operation, Baseline, Main, and Extended, and two types of entropy coding, Context adaptive variable length coding (CAVLC) and Context-Based Adaptive Binary Arithmetic Coding (CABAC). Each profile adds a level of flexibility to the standard. The CAVLC is used for two out of three profiles and this is covered in this thesis.
1.2 HW/SW CAVLC Design

The CAVLC design is a combined software hardware solution. Development of a complete VHDL behavioral model of a context adaptive variable length encoder is done and verified using the Modelsim simulation tools. A synthesizable hardware description is then developed for components of the variable length encoder using Synopsys tools. The relative hardware cost and speed of the context adaptive variable length encoder are obtained. It also obtained the power and developed low power intellectual property design using power compiler Synopsys tools. The CAVLC takes a frame of 4x4 quantized coefficient matrices and N values for N generation block as input and outputs encoded bitstream.
2 Background Theory

2.1 Video Compression

The digital video has very high bitrates that make their transmission and storage very difficult. Even if the high bandwidth technologies like fiber optic cables are available for transmission and more storage space like Blu-Ray disk are available, it is still not feasible to transmit and store those large amounts of data and also the hardware at the receiver end to process such large amounts of data would be very expensive. It is only possible with the reduction of the amount of data that needs to be transmitted, stored, and processed which is achieved with the Video compression.

Video compression not only makes it possible to transmit and store digital video but also it enables more efficient use of bandwidth and storage resources. Video compression shown in fig2 involves encoding and decoding. The encoder converts the source video into a compressed form prior to transmission or storage and the decoder converts the compressed form back into a representation of the original video data.
The two kinds of compression techniques are lossless compression and lossy compression. In lossless compression the statistically redundant information in the signal is eliminated and the perfect signal is reconstructed at the receiving end. In lossy compression the subjectively redundant information in the signal is eliminated without significantly affecting the viewer’s perception. The decoded signal is not perfectly identical to the encoded signal. Most practical video compression techniques use lossy compression to achieve greater compression and compression algorithms to minimize the distortion in the decoded signal. To facilitate interworking and competition between different manufacturers and provide increased choice to customers, standard methods of compression encoding and decoding were developed. The International Standards for image and video compression are the JPEG, MPEG and H.26× series.
2.1.1 Encoder

The encoder shown in fig 1 forms a prediction of the macroblock (16x16 displayed pixels) based on previously coded data, either from the current frame that is known as intra prediction or from other frames that have already been coded and transmitted inter prediction. The encoder subtracts the prediction from the current macroblock to form a residual. The residual samples are transformed using a 4x4 or 8x8 integer transform that is an approximate form of the Discrete Cosine Transform. The output of the transform is a set of coefficients. Each of the coefficients is a weighting value for a standard basis pattern. When the coefficients are combined the weighted basis patterns re-create the block of residual samples. The block of transform coefficients are then quantized by dividing each coefficient by an integer value i.e. quantization parameter. After quantization the result is a block in which most or all of the coefficients are zero, with a few non-zero coefficients. If quantization parameter is set to a high value then more coefficients are set to zero resulting in high compression but poor decoded image quality. Setting quantization parameter to a low value means that more non-zero coefficients remain after quantization, resulting in better-decoded image quality but lower compression.

These quantized transform coefficients need to be encoded to form compressed bit stream. Along with the quantized transform coefficients, information for the decoder to recreate the predicted macroblock, the structure of the compressed data needs to be encoded. Also the information about the video sequence needs to be encoded. Converting the values and parameters into binary codes using variable length encoding or arithmetic
coding does this encoding. The encoded stream can then be transmitted or stored in a storage device.

2.1.2 Decoder

The decoder shown in Figure 4 receives the compressed bit stream and decodes values and parameters by extracting the quantized transform coefficients, prediction information and information about encoding. The quantized transform coefficients are re-scaled. Each coefficient is multiplied by an integer value to restore its original scale. An inverse transform combines the standard basis patterns, weighted by the re-scaled coefficients, to re-create each block of residual data. These blocks are combined together to form a residual macroblock. For each macroblock, the decoder forms an identical prediction to the one created by the encoder. The decoder adds the prediction to the decoded residual to reconstruct a decoded macroblock that can then be displayed as part of a video frame.
Figure 3: Baseline Profile Decoder
2.2 H.264

The H.264/AVC standard was first published in 2003. It builds on the concepts of its predecessors MPEG-2 and MPEG-4 Visual and offers better compression efficiency and greater flexibility in compressing, transmitting and storing video. The H.264/AVC standard is designed for a broad range of applications including broadcasting, Interactive or serial storage, conversational services, multimedia streaming services, multimedia messaging services. The bit rates supported by H.264/AVC are broad, ranging from very low bit rate, small resolution video for mobile and dial-up devices, to high quality standard-definition television services, HDTV, and beyond. This standard is a document published by the international standards bodies ITU-T and ISO/IEC.

H.264 encoder involves in the prediction, transform and encoding processes to produce a compressed bit stream. H.264 decoder involves in the complementary processes of decoding, inverse transform and reconstruction to produce a displayable video sequence as shown in Figure 4. This thesis concentrates on the encoding side.

![Figure 4: Encoder and Decoder](image-url)
2.2.1 Prediction Block

The H.264 standard defines 5 different types of slices P, SI, SP, B, and I. Macroblocks in the slice ‘I’ are encoded using intra prediction. Macroblocks in the slice ‘P’ are encoded using both inter and intra prediction. A Macroblock is a basic building block of a video image. The size of a static macroblock is 16 pixels by 16 pixels shown in Figure 5. There are different standard formats for digital video ranging from QCIF to High Definition. Each format has the number of horizontal and vertical pixels defined per frame as shown in Table 1. The table also shows the number of macroblocks that a frame can be divided into for each format.

The Intra prediction algorithms are employed to macroblocks to remove spatial redundancy whereas the Inter prediction algorithms are employed to macroblocks to remove temporal redundancy. Intra prediction algorithms use neighboring previously encoded macroblocks from the current frame. Inter prediction algorithms use macroblocks from previously encoded frames that have been filtered.
Figure 5: Macroblock

<table>
<thead>
<tr>
<th>Video format</th>
<th>Horizontal pixels per frame</th>
<th>Vertical pixels per frame</th>
<th>Number of Macroblocks (16x16 pixels) per frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCIF</td>
<td>176</td>
<td>144</td>
<td>$(176 \times 144)/(256)= 99$</td>
</tr>
<tr>
<td>CIF</td>
<td>352</td>
<td>288</td>
<td>$(352 \times 288)/(256)=396$</td>
</tr>
<tr>
<td>SD</td>
<td>720</td>
<td>480</td>
<td>$(720 \times 480)/(256)=1350$</td>
</tr>
<tr>
<td>HD 720p</td>
<td>1280</td>
<td>720</td>
<td>$(1280 \times 720)/(256)=3600$</td>
</tr>
<tr>
<td>HD 1080p</td>
<td>1920</td>
<td>1080</td>
<td>$(1920 \times 1080)/(256)=8100$</td>
</tr>
</tbody>
</table>

Table 1: Video formats and macroblocks
2.2.1.1 Intra Prediction

In intra prediction a current macroblock is obtained by using neighboring previously encoded macroblocks. There is a possibility of Intra prediction occurring at the luma and sub-block levels. The luma is (16x16) macroblock and sub-block is (4x4) block. The possible prediction patterns for a sub-block are nine and for macroblocks are four (Figure 5 and Figure 6 respectively). The Encoder is responsible in choosing the optimal intra prediction pattern. Measuring the Sum of Absolute Errors does this. The prediction pattern is chosen based on its Sum of absolute errors value. The smaller the value measured, the better the prediction pattern. The compression rate is also greater when the value is smaller\cite{3}. After the prediction pattern has been chosen, residual block is obtained by subtracting the prediction from the current macroblock. The residual blocks are then sent to the transform and quantization blocks.
Figure 6: 4x4 Intra Prediction Patterns (sub-block)

Figure 7: 16x16 Intra Prediction Patterns\[^3\]
2.2.1.2 Inter Prediction

In Inter prediction, prediction macroblock is obtained by using history of previously encoded frames. This history is stored in the reference frame buffer. The information about the reference frame is encoded in the bitstream along with the residual. This information will be used during decoding of the bitstream. The new feature in H.264 is the capability of storing multiple reference frames. Inter prediction uses a 16x16 macroblock that can be partitioned in multiples of 4x4 blocks. As shown in figure 7, the partitions are tree-structured partitions. The 16 x 16 macroblock can be partitioned into four 8x8 blocks, which can further be sub-partitioned into four 4x4 blocks. Whenever the macroblock is partitioned, an additional field is added to the bit-stream that specifies whether or not and how the sub-block is partitioned. The macroblock when partitioned also needs to have reference frame number and motion vector that is associated with it. The reference frame number is to identify which frame the prediction used to calculate the residual and the motion vector is to identify which sub-block it is. All the blocks within a partition use the same reference frame but the motion vectors will all be different. For a 16x16 macroblock partitioned into 4x4 sub-blocks, there will be 16 - 4x4 blocks, so the motion vectors will be 16.
The encoder has to optimally partition blocks to balance between the cost of transmitting/storing motion vectors and the savings of accurate motion prediction that results in low energy residuals.

### 2.2.2 Transform and Quantization block

Visual data contained within frame can be categorized as high and low frequency data. High frequency data is usually data located on the boundaries of the frame while low frequency data is located in smooth regions. When transmitting frames, removal of low
frequency data from the frame results in a different image while removal of high frequency data doesn’t cause much of a difference. Thus the low frequency data is very important for the frame and has higher priority while the high frequency data is not very important and has lower priority. This low priority high frequency data can be removed by using transformation from the spatial domain into frequency domain. H.264 uses quantization to remove the high frequency data.

The H.264 uses simple 16-bit integer transform. This transform is the integer version of the Direct Cosine Transform (DCT).

### 2.2.2.1 4x4 Core Transform and Quantization

H.264 standard uses inter and intra prediction to get prediction of the current macroblock and to remove temporal and spatial redundancies within a frame. It then subtracts the prediction obtained from the current macroblock to obtain the residual data. This residual is then transformed to frequency domain.

\[
Y = \mathbf{C}_i \mathbf{X} \mathbf{C}_i^T
\]

Eq. 1

\[
Y = \begin{bmatrix}
1 & 1 & 1 & 1 \\
2 & 1 & -1 & -2 \\
1 & -1 & -1 & 1 \\
1 & -2 & 2 & -1
\end{bmatrix}
\begin{bmatrix}
X_{11} & X_{12} & X_{13} & X_{14} \\
X_{21} & X_{22} & X_{23} & X_{24} \\
X_{31} & X_{32} & X_{33} & X_{34} \\
X_{41} & X_{42} & X_{43} & X_{44}
\end{bmatrix}
\begin{bmatrix}
1 & 2 & 1 & 1 \\
1 & 1 & -1 & -2 \\
1 & -1 & -1 & 2 \\
1 & -2 & 1 & -1
\end{bmatrix}
\]

This transformation is done using the core transform in Eq.1. The core transform is used on all 4x4 residual blocks. If the data comes from inverse quantization then Eq. 2 is used.

\[
X' = \mathbf{C}_i^T \mathbf{W} \mathbf{C}_i
\]

Eq. 2

\[
X' = \begin{bmatrix}
1 & 1 & 1 & 1/2 \\
1/2 & -1 & -1 & 1 \\
1 & -1/2 & -1 & 1 \\
1 & -1 & 1 & -1/2
\end{bmatrix}
\begin{bmatrix}
Z_{11} & Z_{12} & Z_{13} & Z_{14} \\
Z_{21} & Z_{22} & Z_{23} & Z_{24} \\
Z_{31} & Z_{32} & Z_{33} & Z_{34} \\
Z_{41} & Z_{42} & Z_{43} & Z_{44}
\end{bmatrix}
\begin{bmatrix}
1 & 1 & 1 & 1 \\
1/2 & -1/2 & -1 & -1 \\
1 & -1 & -1 & 1 \\
1/2 & -1 & 1 & -1/2
\end{bmatrix}
\]
to get inverse core. After applying the core transform the obtained result is passed to the quantization block, which applies Eq.3 for quantization. In Eq.3, $Y_{ij}$ is the value after applying core transform, PF is a post-scaling factor determined according to Table 2 where $a = \frac{1}{2}$ and $b = \sqrt{\frac{2}{5}}$, $Q_{\text{step}}$ is a table look-up factor from Table 3.

$$Z_{ij} = \text{round} \left( \frac{Y_{ij} \cdot PF}{Q_{\text{step}}} \right)$$

Eq. 3

<table>
<thead>
<tr>
<th>Position (i,j)</th>
<th>PF</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0,0), (2,0), (0,2), (2,2)</td>
<td>$a^2$</td>
</tr>
<tr>
<td>(1,1), (1,3), (3,1), (3,3)</td>
<td>$b^2/4$</td>
</tr>
<tr>
<td>else</td>
<td>$ab/2$</td>
</tr>
</tbody>
</table>

Table 2: PF Look-up Table

The look-up table, Table.3 facilitates sending the Quantization Parameter (QP) avoiding fractional numbers.

<table>
<thead>
<tr>
<th>QP</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q_{\text{step}}</td>
<td>0.625</td>
<td>0.6875</td>
<td>0.8125</td>
<td>0.875</td>
<td>1</td>
<td>1.125</td>
<td>1.25</td>
<td>1.375</td>
<td>1.625</td>
<td>1.75</td>
<td>2</td>
<td>2.25</td>
<td>2.5</td>
<td>...</td>
</tr>
<tr>
<td>QP</td>
<td>...</td>
<td>18</td>
<td>...</td>
<td>24</td>
<td>...</td>
<td>30</td>
<td>...</td>
<td>36</td>
<td>...</td>
<td>42</td>
<td>...</td>
<td>48</td>
<td>...</td>
<td>51</td>
</tr>
<tr>
<td>Q_{\text{step}}</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>80</td>
<td>160</td>
<td>224</td>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Q_{\text{step}} Look-up Table
2.2.2.2 4x4 and 2x2 Transform for 16x16 Intra Prediction Mode

When the encoder uses 16x16 intra prediction mode then it incorporates two additional transforms. The core transform is applied 16 times to transform a luma block and 4 times to transform a chroma block. Thus it applies core transform 24 times to transform a 16x16 macroblock. The core transform applied to luma block 16 times will result 16 DC luma coefficients ($Y_{11} - Y_{44}$ in Eq.4). Then Hadamard transform (Eq.5) is applied to the 16 DC luma coefficients and divided by 2.

$$W_D = \begin{bmatrix} 1 & 1 & 1 & 1 & Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ 1 & 1 & -1 & -1 & Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ 1 & -1 & -1 & 1 & Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ 1 & -1 & 1 & -1 & Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix}$$  \hspace{1cm} \text{Eq. 4}

$$X_D = \begin{bmatrix} 1 & 1 & 1 & 1 & Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ 1 & 1 & -1 & -1 & Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ 1 & -1 & -1 & 1 & Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ 1 & -1 & 1 & -1 & Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix}$$  \hspace{1cm} \text{Eq. 5}

The core transform applied 4 times to chroma block will result in 4-chroma DC coefficients (($Y_{11} - Y_{22}$ in Eq.6) and these are sent through Eq.6 and quantized using (Eq.3).
\[ \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \]

Eq. 6

### 2.2.3 Encoding

In the encoding path after passing transform and quantization block, the macroblock consists of 24 blocks of which 16 are 4x4 luma coefficient blocks and 8 are 4x4 chroma coefficient blocks as shown in Figure 9. In addition to these blocks, when 16 x 16 intra prediction is used there will be additional 4x4 and two 2x2 coefficient blocks. All the coefficients are scanned in a zigzag order as shown in Figure 10.
Figure 9: 16x16 Macroblock Block Ordering\(^6\)
2.2.3.1 Entropy Coding

H.264 standard defines entropy-coding techniques. They are Context based arithmetic coding (CABAC), context adaptive variable length coding (CAVLC) and exp-Golomb entropy coding. This thesis concentrates on the Context adaptive variable length coding technique and developed a low power VLSI architecture for this algorithm, which is discussed in the next section.
3 Context Adaptive Variable Length Coding (CAVLC)

This entropy coding technique encodes residual, zigzag ordered 4x4 blocks of transform coefficients. CAVLC takes advantage of quantized 4x4 blocks.

- After prediction, transformation and quantization blocks typically contain mostly zeros. CAVLC uses run-level coding to compactly represent strings of zeros.
- The highest non-zero coefficients after the zigzag scan are often sequences of +/-1. CAVLC signals the number of Trailing 1s in a compact way.
- The number of non-zero coefficients in neighboring blocks is correlated. The number of coefficients is encoded using a look-up table where the choice of look-up table depends on the number of non-zero coefficients in neighboring blocks.
- The level or magnitude of non-zero coefficients tends to be higher at the start of the reordered array and lower towards the higher frequencies. CAVLC takes advantage of this by adapting the choice of VLC look-up table for the level parameter depending on recently coded level magnitudes.

The context adaptive variable length encoder encodes coefficient token, T1 sign, Level, Total zeros and run before in order.
3.1 Coefficient token

The coefficient token encodes the total number of non-zero coefficients (TotalCoeffs) and the number of trailing ones (T1). TotalCoeffs can be anything from 0 to 16. T1 can be anything from 0 to 3. If there are more than 3 trailing ones, only the last 3 are treated as trailing ones and any others are coded as normal coefficients. There are 4 choices of look-up table to use for encoding coefficient token, 3 variable length code tables and a fixed-length code. The choice of a table depends on the number of non-zero coefficients in upper and left hand previously coded blocks NA and NB. Parameter, \( N = (\text{NA} + \text{NB})/2 \). If only upper block is available then \( N=\text{NA} \). If only left hand block is available then \( N=\text{NB} \). If neither is available then \( N=0 \).

3.2 T1 sign

The sign of each trailing one signaled by coefficient token is encoded in reverse order, starting with highest frequency T1. Bit zero is assigned for positive sign one and bit one for negative sign one.

3.3 Level

The level of each remaining non-zero coefficient in the block is encoded starting with the highest frequency to the lowest. One among the seven VLC tables is selected to encode each level. Each level is encoded depending on the magnitude of each successive coded level making it context adaptive.
3.4 Total zeros

Total zeros is the sum of all zeros preceding the last non-zero coefficient in the zigzag ordered array. This sum of all zeros is coded with a VLC.

3.5 Run before

Run before is the number of zeros preceding each non-zero coefficient and this is encoded in reverse zigzag order starting with the highest frequency non-zero coefficient.
4 PROPOSED CAVLC ARCHITECTURE

Figure 11: Proposed Architecture
Figure 11 shows the proposed CAVLC architecture. This architecture is built in software. It is then simulated to verify correct functionality, and then use Design Compiler to synthesize the end product. Since Design Compiler cannot synthesize file IO, a test bench (H264_test) is wrapped around the entire project to do the IO that proved the functionality. Inside the test bench H264_test, there is the Zigzag scan block, the Ngen block, Coeff_token, Totalzeros, Level, Run before and Bitstream generator blocks. Input data to the zigzag scan block is a quantized 4x4 block of coefficients and input to the Ngen block is the values of \( N_A \) and \( N_B \). The input data to the Zigzag is in the form of a 4x4 array of integers from 0 to 10. Each integer represents a very small image pattern.

### 4.1 Zigzag Scan Block

The Zigzag block receives the 4x4 arrays of integers. Here, 4 bits are used to store the integers. Figure 9 shows an example of input data, and how the Zigzag block turns it into output data. The array of integers is what the Zigzag block receives. The line is the path that the Zigzag block takes to send the data out. The reason for sending the data like this is that non-zero integers from the quantization block tend to come in groups. By performing the Zigzag on this array, more integers are grouped together, and zeroes are grouped together. After reordering the array the values of Totalcoeffs, T1, T1_sign, Level, Totalzeros, run before are extracted from the zigzag and reverse ordered array. All these values are stored in buffers to reduce the dynamic activity. Reduction in dynamic activity reduces switching thereby reducing power consumption.
4.2 Ngen block

There are 4 tables to choose from to encode the Coeff_token (Table 3). 3 tables are variable length code tables and 1 table is fixed length code table. The choice of the table depends on the value of N. \( N = \frac{N_A + N_B}{2} \) where \( N_A \) & \( N_B \) are the number of non-zero coefficients in upper and left hand previously coded blocks. If only upper block is available then \( N = N_A \). If only left hand block is available then \( N = N_B \). If neither is available then \( N = 0 \). The value of N is generated in this block. The variable length code tables are biased from small to large number of Totalcoeffs in a block so that smallest code word can be used for Coeff_token. The fixed length code table is fixed 6-bit code.

<table>
<thead>
<tr>
<th>N</th>
<th>Table for Coeff_token</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,1</td>
<td>Num-VLC0</td>
</tr>
<tr>
<td>2,3</td>
<td>Num-VLC1</td>
</tr>
<tr>
<td>4,5,6,7</td>
<td>Num-VLC2</td>
</tr>
<tr>
<td>8</td>
<td>FLC</td>
</tr>
</tbody>
</table>

Table 4: Coeff_token Look-up Table

4.3 Coeff_token block

The Coeff_token generates the code by reading the values of Totalcoeffs, T1 from the buffers and N value from the Ngen block. After taking the N value from the Ngen block, the Coeff_token block implemented an algorithm to represent the VLC tables and FLC instead of storing the VLC tables in memory. The VLC tables and FLC table has codes and lengths of the codes that are implemented by adding, subtracting or multiplexing the
number of trailing ones and the number of non zero coefficients. The flowchart representing the algorithm for VLC1 is shown in table5. The VLC tables are biased from small to large number of total nonzero coefficients in a block to facilitate the Coeff_token to be coded with smallest possible codeword. The output of the Coeff_token block is the length of the Coeff_token and the Coeff_token itself.

Table 5: Coeff_token VLC Table

4.4 Total Zeros block

Totalzeros block encodes the total number of zeros preceding the last nonzero coefficient in the zigzag array by reading the Totalcoeffs and Totalzeros from the buffers as input. Case by case code and length are stored in look up tables. Conditional statements are inserted in the code as shown in table 5 for the look up tables to facilitate clock gating for low power. Depending on the value of the Totalcoeffs and Totalzeros the code and length of the code are sent as outputs to the bitstream block. For example if the value of Totalcoeffs is 7, the value of Totalzeros can range from 0 to 9. So the code and length for each case i.e. Totalzeros=0 to Totalzeros=9 is stored and the output of the Totalzeros
block will be the code output and length depending on the value of the Totalzeros and Totalcoeffs obtained from the zigzag block.

```
begin
  if rising_edge(clk) and done_lut='0' and input_1
  if Totalcoeffs_in = 1 then
    case totalzeros_in is
      when 0 => outa <= outa(9 downto 1) & "1";
      when 1 => outa <= outa(9 downto 3) & "011";
      when 2 => outa <= outa(9 downto 3) & "010";
      when 3 => outa <= outa(9 downto 4) & "0011";
      when 4 => outa <= outa(9 downto 4) & "0010";
      when 5 => outa <= outa(9 downto 5) & "00011";
      when 6 => outa <= outa(9 downto 5) & "00010";
      when 7 => outa <= outa(9 downto 6) & "000011";
      when 8 => outa <= outa(9 downto 6) & "000010";
      when others => outa <= outa(9 downto totalzeros_in);
    end case;
end if;
```

**Table 6: Pseudo code for total zeros**

### 4.5 Level block

The level block encodes the nonzero coefficients. The inputs to the block are level and Totalcoeffs. Totalcoeffs gives the number of nonzero coefficients to be encoded and the level gives the level of each nonzero coefficient. The format of the level code is the level prefix followed by bit 1 and that followed by level suffix. Level prefix is the array of zeros that are in level code and level suffix is the array of bits. The level input is taken for each nonzero coefficient and this block generates the level prefix, length of level prefix, level suffix and length of level suffix based on the look up tables which are implemented using the conditional statements for power reduction. These are then sent to the bitstream generator.
4.6 Run before block

The run before block encodes the number of zeros preceding each nonzero coefficient in reverse zigzag order by taking the inputs run before, Totalcoeffs and Totalzeros. The block takes the run before input into an array and Totalzeros into another. It determines the number of zeros left by subtracting the run before from Totalzeros. Depending on the value of the zeros left and the run before, the code and the length of the code are determined from the look up table. The look up table is implemented using conditional statements to facilitate the clock gating insertion for power reduction. The pseudo code for the look up table implementation is shown in table 6. The code and length of the code for run before for each of the nonzero coefficients is sent to the bitstream generator.

```java
if zerosleft(p+1) = 4 then
    case rb(p) is
    when 0 => outa <= outa(2) & "11";
              length <= 2;
    when 1 => outa <= outa(2) & "10";
              length <= 2;
    when 2 => outa <= outa(2) & "01";
              length <= 2;
    when 3 => outa <= "001";
              length <= 3;
              runbefore_out <= outa;
              length_out <= length;
    when 4 => runbefore_out <= "000";
              length_out <= 3;
    when others => outa <= "111";
    end case;
```

Table 7: Pseudo code for run before
4.7 Bitstream generator

The bitstream generator block gets Totalcoeffs, T1’s and Sign inputs from the Zigzag block; Coefftoken and length of the token from the Coefftoken block; Totalzeros code and its length from the Totalzeros block; Level suffix, level prefix and their lengths from the level block; Run before code and its length for each nonzero coefficient from run before block. The Bitstream generator reads in the inputs and their lengths and appends all the code based on their lengths together in order to generate the encoded bitstream.
5 Simulation and Synthesis Results

The CAVLC architecture was designed and verified with simulations using the Mentor Graphics Modelsim tools. VHDL code was written to describe the architecture and each block was verified for functionality with simulations. After verifying the functionality of each block, all the blocks were wrapped around with the testbench and the test bench was verified with simulations. A .do file was generated with the clock input and run time for the simulation. The clock used was of period 10ns for the simulation of the testbench. The results of the simulation for each block are in the next sections.

5.1 Zigzag Scan Block Simulation

The inputs to the Zigzag block are 16 std_logic_vectors and clock with a 10ns period. The 16 vectors are then read into 4x4 array and reordered. After reordering the array, the values of Totalcoeffs, T1, T1_sign, Level, Totalzeros, run before are extracted from the zigzag and reverse ordered array. Figure 12 shows the simulation results.

5.2 Ngen block Simulation

The inputs to the Ngen block are the values of Na, Nb and NFlag depending on the algorithm; the value of the N is calculated. Figure 13 shows the simulation results for the Ngen block.
Figure 12: Zigzag simulation

Figure 13: Ngen simulation
5.3 Coeff_token block Simulation

The inputs to the Coeff_token block are the values of Totalcoeffs, T1 and N value. After taking these values as inputs, the Coeff_token block implements an algorithm [3] to represent the VLC tables instead of storing the VLC tables in memory. This block then outputs the length of the Coeff_token and the Coeff_token itself. Figure 14 shows the simulation result.

![Diagram of Coeff_token block simulation](image)

**Figure 14: Coeff_token simulation.**
5.4 Total Zeros block Simulation

The inputs to the Totalzeros block are the Totalcoeffs and Totalzeros. Totalzeros block encodes the total number of zeros preceding the last nonzero coefficient in the zigzag array by taking these inputs. Depending on the value of the Totalcoeffs and Totalzeros the code and length of the code outputs are generated. Figure 15 shows the simulation results.

![Figure 15: Totalzeros simulation.](image-url)
5.5 Level block Simulation

The inputs to the level block are level and Totalcoeffs. After taking level input for each nonzero coefficient, this block outputs the level prefix, length of level prefix, level suffix and length of level suffix. Figure 16 shows the simulation result.

![Figure 16: Level simulation.](image)

5.6 Run before block Simulation

The inputs to the run before block are run before, Totalcoeffs and Totalzeros. After taking these inputs, run before block encodes the number of zeros preceding each nonzero coefficient. Depending on the value of the zeros left and the run before, the code and the length of the code are determined from the look up table. The code and length of
the code for run before for each of the nonzero coefficients are the outputs of this block.

Figure 17 shows the simulation results for this block.

![Simulation Results](image)

**Figure 17: Run before simulation.**

### 5.7 Bitstream generator block Simulation

The inputs to the bitstream generator block are Totalcoeffs, T1’s, Sign inputs, Coeftoken, length of the token, Totalzeros code, length of Totalzeros code, Level suffix, length of level suffix, level prefix, length of level prefix, Run before code and its length. The Bitstream generator reads in the inputs and their lengths and appends all the code based on their lengths together to generate the encoded bitstream (bs_out) Figure 18 shows the results of the simulation.
Figure 18: Bitstream simulation.
Synopsys Design Compiler was used for the synthesis of the VHDL description of the CAVLC architecture. Design Compiler was provided with VHDL description of the functionally verified CAVLC architecture as input along with constraints to generate the gate level net list. In addition to inputs and design rule constraints, technology and symbol libraries are needed to generate the net list. The technology libraries specify the operating conditions and wire load models. The symbol libraries contain the definitions of the symbols that represent cells in the schematics. The technology library used for the synthesis of the CAVLC architecture was a 65nm technology library. The synthesized CAVLC core is shown in Figure 19.

Figure 19: CAVLC synthesized core
Initially Design compiler was used to carry out a preliminary synthesis to see if the design meets the basic goals. The design was modified until the desired goals were met and then Power compiler was used to get the low power design. Power Compiler is used to minimize power consumption at the RTL and gate level. Power Compiler and Design Compiler share the same GUI and it is integrated with Design Compiler’s design flow. There is multiple commonly used power reduction techniques like supply voltage reduction, clock gating, multi voltage design etc. The most suitable power reduction technique for this design seemed to be the clock gating technique.

Compiling a design with design compiler usually implements registers with a feedback loop and a multiplexor. Some of the registers have same value for multiple clock cycles using power unnecessarily. Clock gating saves power by eliminating the unnecessary switching on these registers. Clock gating removes the feedback loop and multiplexor and inserts gates in the clock net of the registers to prevent the clock from clocking the register. Figure 20 shows a sample schematic before and after clock gating. Significant improvements in Power were observed when clock gating was applied.
Before clock gating

After clock gating

Figure 20: Clock Gating
6 Results

The proposed architecture designed, simulated and synthesized using a 100MHz clock. The architecture could encode a 4x4 block in 1200 ns. The performance of the architecture can be calculated as:

- From Table 1 the number of macroblocks per CIF frame is 396.
- The number of 4x4 blocks per macroblock is 16 assuming the best case with skip mode.
- From above, the total number of 4x4 blocks per CIF frame is 396 x 16 = 6336.
- So the time taken to encode a CIF frame would be 6336 x 1200 ns = 7.6 ms.
- Therefore the time taken to encode 60 frames would be 60 x 7.6 ms = 456 ms.

The designed architecture therefore enables real-time processing for QCIF and CIF frames with 60-fps using 100MHz clock.

The resultant hardware implementation requires 32K number of logic gates. The resultant hardware power is 1.4mW. Reference [6] hardware is implemented in Verilog and synthesized using the Synopsys Design Compiler with TSMC Artisan 0.18μm cell library. The total power consumption is 3.7mW at 27MHz and 1.8V. The proposed architecture uses a 100MHz clock whereas the Reference [6] uses 27MHz. Instead of using a lower clock to decrease the switching activity, this architecture used buffers to store the symbols and then encoded by reading from the buffers instead of dynamically encoding the symbols. This helped to reduce the switching and thereby power. To achieve low power design, Synopsys Design Compiler was used for the synthesis of the
VHDL description of the CAVLC architecture initially and then power compiler’s clock gating technique was used for power reduction. Significant improvements in Power were observed when clock gating was applied by almost 30%. The tool applies clock gating by finding the conditional statements prior to the assignment statements. This architecture consists of lot of look up tables and all the look up tables are implemented based on conditional statements to take advantage of the clock gating. Table 5 shows a comparison between reference [6], reference [7] and proposed architecture in terms of area, latency, technology library and power.

<table>
<thead>
<tr>
<th>Design</th>
<th>Area</th>
<th>Latency</th>
<th>Technology library</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed</td>
<td>32K</td>
<td>QCIF and CIF @ 60fps</td>
<td>65nm</td>
<td>1.4mW</td>
</tr>
<tr>
<td>Reference [6]</td>
<td>27K</td>
<td>QCIF and CIF @ 30fps</td>
<td>0.18um</td>
<td>3.7mW</td>
</tr>
<tr>
<td>Reference [7]</td>
<td>23.6K</td>
<td>1920x1088 @30fps</td>
<td>0.18um</td>
<td>12mW</td>
</tr>
</tbody>
</table>

*Table 5: Area, Latency and Technology Comparison.*
7 Conclusion

The CAVLC architecture was designed and verified with simulations using the Mentor Graphics Modelsim tools. VHDL description of the architecture was verified for functionality with simulation. Synopsys Design Compiler was used for the synthesis of the VHDL description of the CAVLC architecture initially and then power compiler’s clock gating technique was used for power reduction. The technology library used for the synthesis of the CAVLC architecture was a 65nm technology library. Significant improvements in Power were observed when clock gating was applied by almost 30%. The designed architecture therefore enables real-time processing for QCIF and CIF frames with 60-fps using 100MHz clock. The resultant hardware implementation requires 32K number of logic gates. The resultant hardware power is 1.4mW.
8 Future Work

High Efficiency Video Coding (HEVC) standard is still under development by the ISO and ITU-T. The Moving Picture Experts Group (MPEG) and Video Coding Experts Group (VCEG) have set up a Joint Collaborative Team on Video Coding (JCT-VC) with the aim of getting the new standard ready for publication in 2012/2013 [13]. The expectation is that it is likely to be published jointly as a new MPEG standard and a new ITU-T standard, possibly H.265 following the JCT-VC and MPEG meeting in October 2010. According to [13] the new standard there are changes in the Prediction and transform block sizes and also there will be a Low complexity entropy coding scheme introduced in this standard which can be implemented in the same way as this proposed design after the standard is released and available.
Bibliography

[12] Hong, B., “Introduction to H.264”, Multimedia Communications Laboratory, University of Texas, Nov. 22,