COE3DQ5 Project Description 2021
Hardware Implementation of an Image Decompressor

1 Introduction

1.1 Objective

In this project, students will gain experience in digital system design by implementing the custom McMaster Image Compression revision 15 (.mic15) image compression specification in hardware. Compressed data for a 320 x 240 pixel image will be delivered to the Altera DE2-115 board via the universal asynchronous receiver/transmitter (UART) interface from a personal computer (PC) and stored in the external static random access memory (SRAM). The image decoding circuitry will read the compressed data, recover the image using a custom digital circuit designed by you and store it back to the SRAM, from where the video graphics array (VGA) controller will read it and display it to the monitor. The decoder must meet the constraints summarized in Appendix A.

1.2 Preparation

- Revise the first five labs, especially finite state machines, VGA, SRAM and UART interfaces
- Read this document and get familiarized with the C source code for reference software model

1.3 Organization of this Document

Section 2 discusses how an image is compressed with the .mic15 specification. In Section 3, image decompression is demonstrated by example with a 16x16 image. In Section 4, the project guidelines are presented (the project is divided into 3 milestones). A brief summary is provided in Appendix A.

2 Image Compression

Figure 1. Flow of basic image compression (down the left) and decompression (up the right).

Figure 1 shows the conceptual flow for basic image compression and decompression. The relative amount of data at each stage is roughly indicated by the size of the arrow. In general, for image compression, we start with an image in the standard red/green/blue (RGB) format. This is converted to YUV format, where Y represents brightness and U and V are chrominance components (which contain colour information). The YUV image is downsampled and then transformed into the frequency domain. This result is quantized and finally we apply lossless encoding to obtain the compressed information bitstream. Decoding proceeds in the reverse order: lossless decoding and dequantization (restores the frequency domain image), then the inverse signal transform (which brings the image back to the spatial domain), and finally upsampling and colourspace conversion (produces an RGB image).

Compression enables smaller file sizes which reduces storage and transmission costs. We convert the RGB image to YUV because the human eye is more sensitive to brightness than colour, so if we want to obtain more lossy compression (by reducing the quality), it will be more effective to compress the colour information. Additionally, the human eye is less sensitive to high frequency components in an image (compared to low frequencies). Transforming into the frequency domain enables us to compress higher frequency components by more than the lower frequency components. We compress frequency information by applying quantization before applying lossless compression to reduce the file size.

Downsampling and quantization are not identically reversible, so some information is lost during compression. The decompressed image only approximates the original image. A good compression scheme leverages this loss of information to reduce the compressed file size, but will attempt to allow information loss only in a way that does not drastically affect the quality of the decompressed image.

The focus of this project is the hardware implementation of an image decompression algorithm. The particular format (.mic15) is not meant to rival existing compression standards for images. Simplifying choices have been made in developing the specification to facilitate a more straightforward hardware implementation. This limits the capabilities in terms of the achievable compression/quality tradeoff. Nevertheless, the concepts are generalizable to the compression schemes that are used in practice [1-4]. The following subsections will discuss each stage of image compression in more detail.
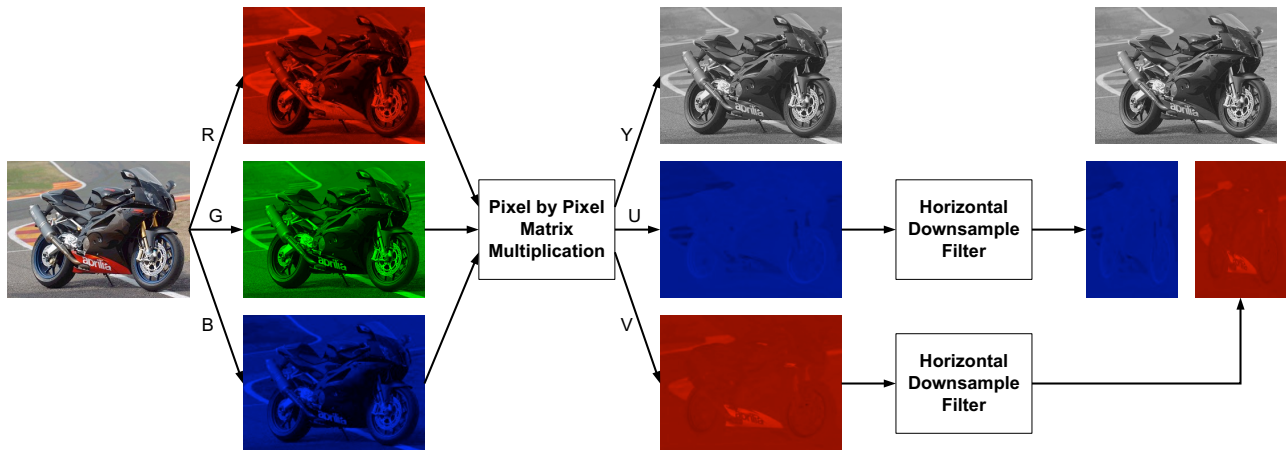
2.1   Colourspace Conversion and Downsampling

Figure 2 shows how a 320x240 image can be decomposed into its Red (R), Green (G), and Blue (B) components. Each pixel (which is composed of one R, one G, and one B value) is independently transformed into the YUV colourspace. Each resulting pixels contains one Y (brightness), one U (blue-chroma), and one V (red-chroma). The chroma components contain only colour info (no brightness). In Figure 2, the bottom of the motorcycle is red, and the corresponding bright area in the V image indicates there are large values at these pixels which represents that there is a strong red colouring. Note this says nothing about whether it is bright red or dark red, as the brightness comes only from Y.

Each RGB pixel is converted to a YUV pixel by performing the following matrix multiplication:

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.257 & 0.504 & 0.098 \\ -0.148 & -0.291 & 0.439 \\ 0.439 & -0.368 & -0.071 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix} \tag{1}$$

The terminology YUV originates from the video transmission field and different notations (depending on the video/colour/transmission standard) can be found in the literature (such as YIQ, YPbPr, YCbCr).

Figure 2. Colourspace conversion (RGB to YUV) and horizontal downsampling of U and V.

The human eye is much more sensitive to brightness than colour (due to the presence of more rods than cones in the eye). For this reason, we choose to downsample U and V (the chroma components) to reduce the amount of data while having little effect on how the image is perceived. We horizontally downsample by 2, so the U and V images become half the original width (no vertical downsampling so the height is unchanged). Therefore, only 2/3 of the total data remains.

2.2   Signal Transform (into the Frequency Domain) and Quantization

The next stage of compression involves transforming the image from the spatial domain to the frequency domain. High spatial frequencies (which are brightness/colour transitions that occur in a small amount of space) are not as noticeable to the human eye, so they may be reduced in accuracy (or even removed) without drastically affecting the overall quality of the image.

In the .mic15 specification, we use a 2 dimensional discrete cosine transform (DCT) and we work on blocks of 8x8 pixels (each 8x8 block is processed independently, we do not consider images with heights and widths not divisible by 8). The 2D DCT is computed with the following matrix multiplications:

$$\boldsymbol{S'} = \boldsymbol{CSC^T} \quad \text{where each element} \ \ [\boldsymbol{C}]_{i,j} = \begin{cases} \sqrt{\dfrac{1}{8}} \ \cos\left(\dfrac{i\pi}{8}(j + 0.5)\right) & \text{if } \ i = 0 \\[3mm] \sqrt{\dfrac{2}{8}} \ \cos\left(\dfrac{i\pi}{8}(j + 0.5)\right) & \text{otherwise} \end{cases} \tag{2}$$

$\boldsymbol{S}$ is the original 8x8 block (spatial domain) and $\boldsymbol{S'}$ is the transformed 8x8 block (frequency domain). In Equation 2 above, i and j are the row and column indexes respectively, each goes from 0 to 7 inclusive.

To obtain compression, we quantize $\boldsymbol{S'}$. Each element in $\boldsymbol{S'}$ is divided by a (possibly) different quantization coefficient and then rounded to the nearest integer. A larger coefficient means that after division we obtain a smaller magnitude integer which requires fewer bits to be stored. The top left corner corresponds to frequency 0. As we move down and to the right in the matrix, the frequencies increase. Thus we should choose smaller quantization coefficients for the upper left part of the matrix and large coefficients for the lower right part to exploit the perception of the human eye.

For typical images, many values of S' will become 0 after quantization, and these zeros can be stored in an efficient manner, as will be shown in Section 2.3. Even if nonzero, the division results in an integer that requires fewer bits to be represented. Two possible quantization matrices can be used in .mic15:

$$Q_0 = \begin{bmatrix} 8 & 4 & 8 & 8 & 16 & 16 & 32 & 32 \\ 4 & 8 & 8 & 16 & 16 & 32 & 32 & 64 \\ 8 & 8 & 16 & 16 & 32 & 32 & 64 & 64 \\ 8 & 16 & 16 & 32 & 32 & 64 & 64 & 64 \\ 16 & 16 & 32 & 32 & 64 & 64 & 64 & 64 \\ 16 & 32 & 32 & 64 & 64 & 64 & 64 & 64 \\ 32 & 32 & 64 & 64 & 64 & 64 & 64 & 64 \\ 32 & 64 & 64 & 64 & 64 & 64 & 64 & 64 \end{bmatrix} \quad Q_1 = \begin{bmatrix} 8 & 2 & 2 & 2 & 4 & 4 & 8 & 8 \\ 2 & 2 & 2 & 4 & 4 & 8 & 8 & 16 \\ 2 & 2 & 4 & 4 & 8 & 8 & 16 & 16 \\ 2 & 4 & 4 & 8 & 8 & 16 & 16 & 16 \\ 4 & 4 & 8 & 8 & 16 & 16 & 16 & 32 \\ 4 & 8 & 8 & 16 & 16 & 16 & 32 & 32 \\ 8 & 8 & 16 & 16 & 16 & 32 & 32 & 32 \\ 8 & 16 & 16 & 16 & 32 & 32 & 32 & 32 \end{bmatrix} \tag{3}$$

S' is divided element-wise by one of the quantization matrices (suppose we pick Q_0) and then it is rounded to the nearest integer:

$$Z = round(S' ./ Q_0) \tag{4}$$

If we look at each element of Z:

$$[Z]_{i,j} = round([S']_{i,j} / [Q_0]_{i,j}) \tag{5}$$

Z will later be losslessly coded.
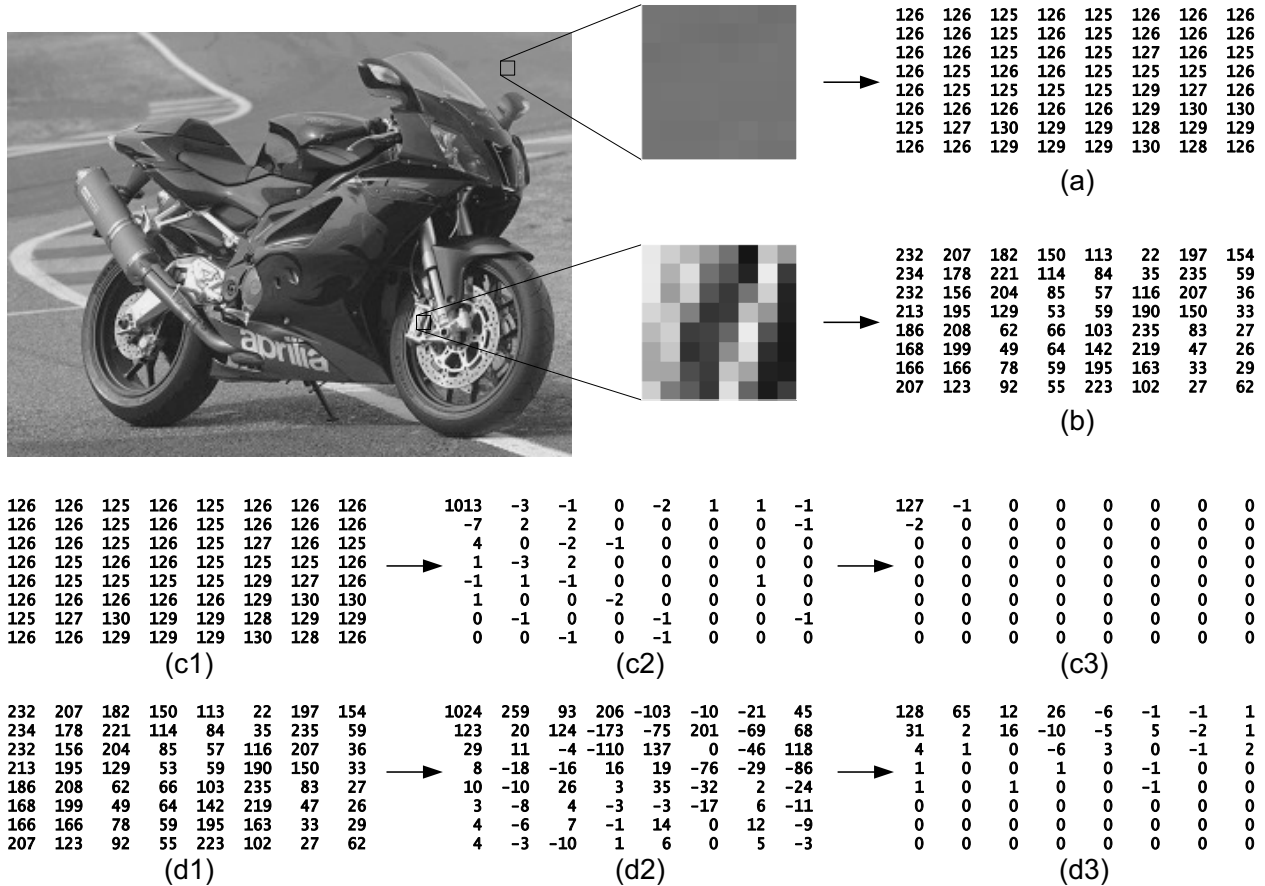

(a)

(b)

(c1)

(c2)

(c3)

(d1)

(d2)

(d3)

Figure 3. DCT (c1→c2 and d1→d2) and quantization with Q_0 (c2→c3 and d2→d3) of 2 blocks of Y data.

After dividing each colour plane (Y, U, and V) into blocks of 8x8 pixels, we perform DCT and quantization to each block.

Figure **3** shows this on 2 blocks of Y data. The image is 320x240, so there will be (320/8)*(240/8) = 1200 Y blocks and 600 blocks each of downsampled U and downsampled V (since these planes are half as wide). All the Y blocks are processed, then all the U, and then finally all the V blocks. Within each colour plane, we go across a row of blocks first, then down to the next row. Note 1 row of blocks is 8 pixels high.

The block in Figure 3(a) is nearly uniform, so after DCT, in Figure 3(c2) there is a large value for frequency 0 and small values for the high frequencies. After quantization, we end up with mostly zeros, which can be stored efficiently. Many images contain nearly uniform blocks, so the DCT followed by quantization provides a way to represent the image with much less data. Although this leads to reduced quality of the decompressed image, the major features of the original block are still preserved.

The block in Figure 3(b) contains more variation due to the details of the motorcycle's wheel. The DCT and quantization results are shown in Figure 3(d2) and Figure 3(d3) respectively. In the presence of more details (captured by the higher frequencies), more data is needed to represent the block (compared to the block from Figure 3(a)). Even so, the amount of data (in Figure 3(d3) is reduced from that required to represent the intensity of each pixel explicitly (the block in Figure 3(b)).

2.3 Lossless Coding

In the final stage of decoding, we need a mechanism for efficiently storing the data after DCT and quantization. We start with a simple 8 byte header which indicates the image's width and height and which quantization matrix was used. After this, the losslessly coded blocks are packed into the bitstream one after another. To losslessly code one block, the elements of Z (see Equation 4) are read out of the block in the order shown in Figure 4. This is known as the scan pattern.
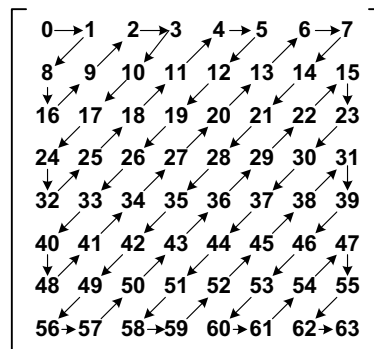
Figure 4. Scan pattern (order of values to be read from an 8x8 block).

Many images naturally have small values in the high frequencies, so after computing the DCT and then quantizing, we typically have many zeros in the lower right part of the matrix. The above scan pattern, which is standard for many mainstream video/image compression schemes, deals with the low frequencies first (upper left) and the high frequencies last (lower right). This is beneficial because in this order, we can get many consecutive zeros (from the high frequency part), which can be efficiently coded. For each 8x8 block, as we follow the order of the scan pattern, values are encoded as follows and a variable length prefix-coded header indicates what data will follow (a higher priority is given to the cases higher in the list):

1. Only zeros remain in the block, output the ZEROS_TO_END header (bits 011).
2. A run of at least 5 zeros exists but some nonzero coefficients still remain in the block. Output the ZERO_RUN_LONG header (bits 010) and then if
    a. The run of zeros is 16 or more in length, output the 4 bits 0000, now the run of zeros will be 16 elements shorter, so repeat step 2 if necessary.
    b. The run of zeros is less than 16 in length (1-15 inclusive), output a 4 bit unsigned number indicating the length of the run.
3. A run of at most 4 zeros exists but some nonzero coefficients still remain in the block. Output the ZERO_RUN_SHORT header (bits 00) followed by a 2 bit unsigned number indicating the length of the run (for length 4, the bits 00 are used).
4. There is a value between -4 and 3 inclusive, output the 3_BIT header (bits 11) followed by the 3 bit signed value.
5. There is a value between -16 and 15 inclusive, output the 5_BIT header (bits 101) followed by the 5 bit signed value.
6. There is a value between -256 and 255 inclusive, output the 9_BIT header (bits 100) followed by the 9 bit signed value.

In the above encoding, the first bit indicates whether we have a run of zeros or a value.

Figure 5 shows the coding of the final (quantized) blocks from Figure 3, in both cases the blocks are scanned according to Figure 4. For the first block, the first value (127) needs to be coded as 9 bits signed so we output 100 (the header) followed by 001111111 (the 9 bit signed representation of 127). The next value is -1 which can be represented on 3 bits signed, so we output 11 (header) and then 111 (-1 on 3 bits signed). The next value is -2 which is also representable on 3 bits signed. Following a similar approach, we output 11 (header) and then 110 (-2 on 3 bits signed). Now only zeros remain in this block, so we add 011 (ZEROS_TO_END header) to the bitstream to finish this block.
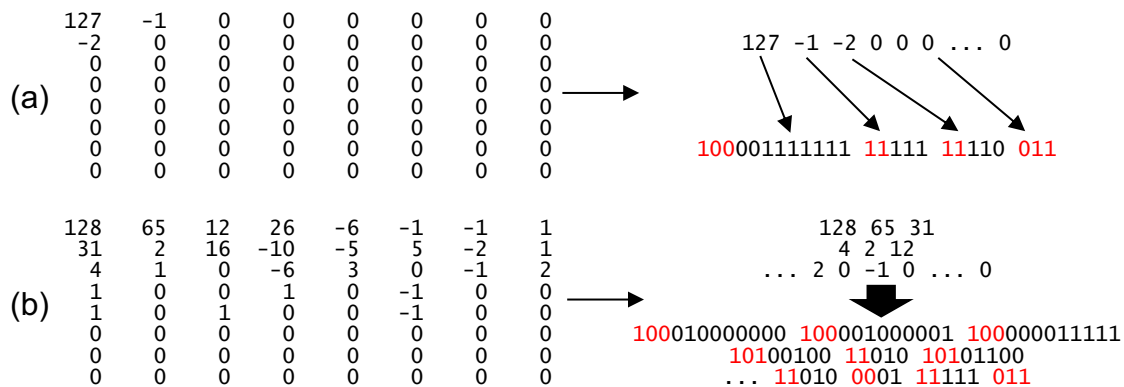
Figure 5. Lossless coding of each block from (header bits are coloured red for illustrative purposes only).

Coding of the second block from Figure 3 proceeds in the same way, however more data is required due to the presence of more nonzero value and also the typically larger magnitude of the values. As before, encoding proceeds until the last nonzero value in the scanned sequence (-1) is reached, after which a ZEROS_TO_END header is placed in the bitstream. When the last block of the downsampled V plane has been coded, zero padding ensures the file ends at the end of a 16-bit word (for compliance with the 16-bit wide memory we are using).

3   Image Decompression

In this section, the full decompression process for an image of size 16 x 16 is performed for the purpose of illustrating the flow of data from one stage to another and to elaborate the internal details of each step in the decompression. Since the aim of this project is the hardware implementation of the decompression specification, ***during the decompression we only use fixed point arithmetic***, which has a simpler hardware design and generally uses fewer logic resources compared to floating point.

3.1   Lossless Decoding and Dequantization (Milestone 3 in Hardware)

Our reference image "example.ppm" is shown in Figure 6. The encoded bitstream is given in Figure 7. The header is 8 bytes. The first 4 bytes must be "DEADBEEF" in hex, which identifies a .mic15 file. After this, in the following 2 bytes, the most significant bit indicates which quantization matrix to use (in this example, bit 0 means use Q_0) and the 15 least significant bits indicate the width (bits 000 0000 0001 0000 indicate a width of 16). The next 2 bytes indicate the height, which is also 16 in our example. After the header, the main content of the image, the sequence of compressed blocks, begins.

Figure 6. The reference image example.ppm to be compressed.

```
DE AD BE EF 00 10 00 10 87 4A AA 7C CF 6D B5 2E
7D E1 CD DE 4B DD CE 7F 92 E6 52 FC 72 7F 1F 2B
F2 7F 1F E1 EE DF D4 95 F7 1D A6 A5 F9 5C E7 7F
EF BE 3F 1F 8D 29 64 F3 94 DE 1F 87 C3 49 FC 5F
D4 39 D4 7B 70 29 DB 8E E7 DE FD BF 75 9D 0F F2
59 1A 4C 96 72 39 4F E1 CA 9D 27 F8 FC 73 10 74
DA B8 B0 CD D7 6E 8B 36 FF FE 73 9D E7 A3 FC F3
29 7F 9C E7 E3 91 F2 BF 27 F1 FA 20 A0 5A 06 6B
AC EA E9 7C 3F CE 79 4B 49 DB AB AF 6C FE 79 1F
8E 7C 3F 40 3F 71 1F 03 F6 D5 D4 F0 23 3D B4 F7
5E D6 6E 7B 9D EA 93 3F DF FE 3F 1F E4 73 F2 F8
E4 B2 39 70 FD 55 9B 61 B4 B6 1E FB C3 49 FC E7
34 9A F9 E4 B3 FF 8F FF 97 0F 16 D4 B7 5E B9 A7
EE 87 E3 B2 FF FC 39 FA 6F 8F F2 C0
```

Figure 7. The compressed bitstream example.mic15, the order of the bytes is across first and then down.

Figure 8 depicts the block decoding process. Variable length prefix coding is used for the header, which means depending on the first few bits of the header, we may need to read additional bits to determine the remainder of the header. We start by reading 2 bits: if we get 11 then there is a 3 bit value that follows; if we get 00 then there is short run of zeros and the 2 bits that follow indicate if the run contains 1, 2, 3 or 4 zeros; if we get 01 or 10 then we need to read more bits to complete the header. In the case where the first two bits are 10, if the next bit we read is 0 (total header is 100) then a 9 bit value follows, otherwise the total header is 101 and a 5 bit value follows. In the case where the first two bits are 01, if the next bit we read is 0 (total header is 010) then we have a 4-bit run of zeros (the run could be 1-16 zeros in length indicated by the 4 bits that follow), otherwise the total header is 011 so we have a run of zeros to the end of the block. Following this procedure, values are decoded one after another and

placed in the 8x8 block according to the scan pattern of Figure 4. A block is complete either when a ZEROS_TO_END header is decoded (in which case the rest of the block is filled with 0s), or when 64 values (including runs of zeros) have been decoded, making the block full. Note that the values are signed (2's complement format).

Alternatively, knowing the next 3 bits in the bitstream, we can decode the header in one go. Reading 11X (where X is don't care) means we have a single 3 bit value, and actually the X is the most significant bit of that 3 bit value (note we do not discard this X but they do not affect the decoding of the header). Likewise, 101 is for a 5 bit value, 100 is for a 9 bit value, 011 is for a run of zeros to the end, 010 is for a 4 bit run of zeros, and 00X is for a 2 bit run of zeros.

After the .mic15 header, the bitstream begins with "100001110100101010101010..." ("87 4A AA ..." in hex). Figures 9 and 10 show the results of the decoding example.mic15. The Y blocks appear first in the bitstream, row by row. Y 0,0 contains Y data for pixel rows 0-7, columns 0-7 of the Y plane from the downsampled image (which is equivalent to the Y plane from the converted image since Y is not downsampled). Similarly Y 0,1 contains rows 0-7, columns 8-15; Y 1,0 contains rows 8-15, columns 0-7; Y 1,1 contains rows 8-15, columns 8-15.
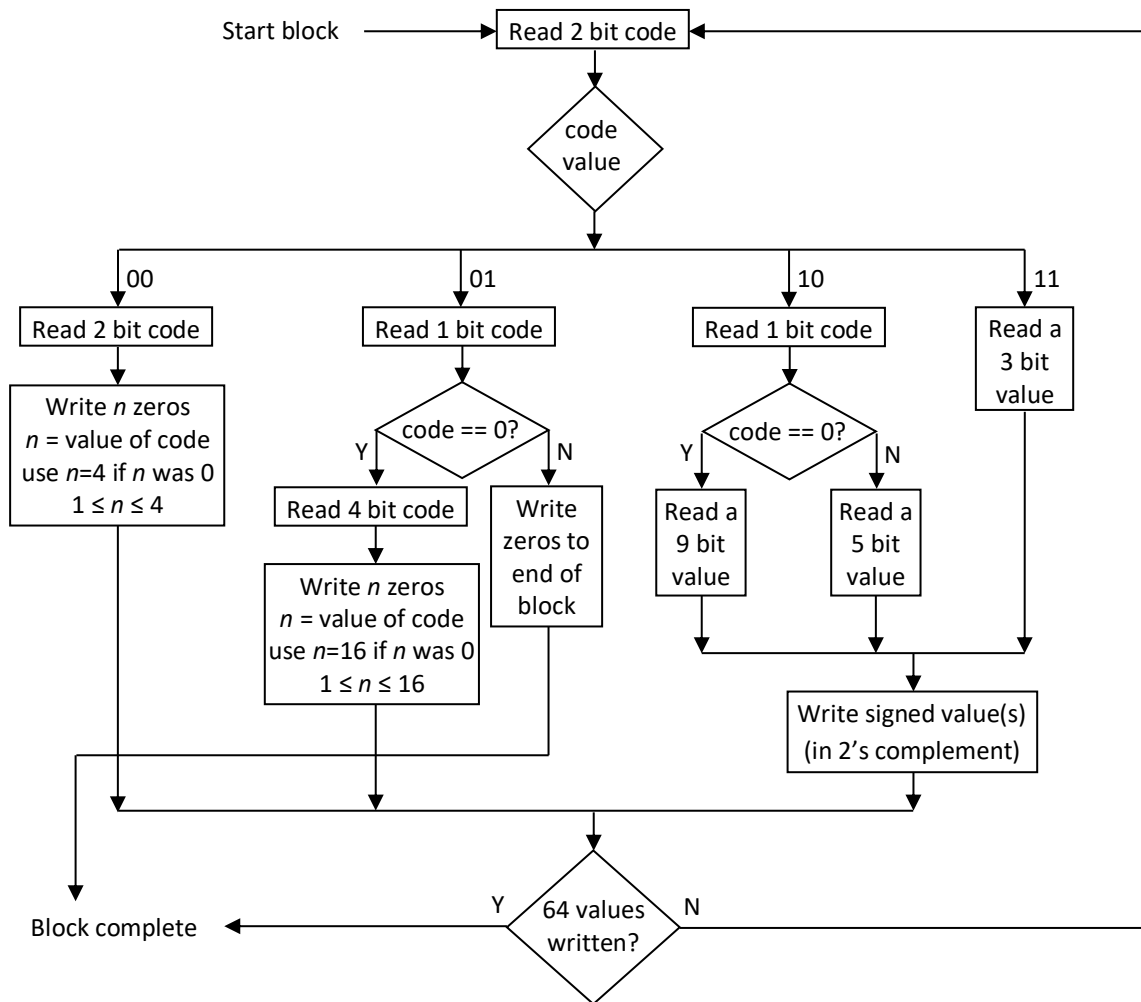

Figure 8. Lossless decoding of a block based on the prefix code.

```
Y 0 0 -----------------------------------------------------------------------------------------------

100001110100 : 116    11101    : -3      0101011 : 0 0 0
10101010     : 10     11001    : 1                 0 0 0
10100111     : 7      11001    : 1                 0 0 0
11001        : 1      11111    : -1                0 0 0
100111101101 : -19    11001    : 1       11110   : -2        116   10  -10    5    0    0    0    0
10110110     : -10    0010     : 0 0     0100111 : 0 0 0       7  -19    1    1   -2    0    0    0
10100101     : 5      11001    : 1                 0 0 0       1   -2   -5   -3    1    0    0    0
11001        : 1      0100101  : 0 0 0             0          -2    1    1   -4   -1    0    0    0
11110        : -2                0 0     11110   : -2    (a)   0    1    0    0   -2    0    0    0
11110        : -2     11111    : -1      0011    : 0 0 0      -1    0    1    0    0   -2    0    0
0001         : 0      0001     : 0       11111   : -1          1    0   -1    0    0    0   -2    0
11001        : 1      11001    : 1                             0    0    0    0    0    0    0   -1
10111011     : -5     0011     : 0 0 0
11001        : 1      11111    : -1
0010         : 0 0    0001     : 0
11110        : -2     11110    : -2


Y 0 1 -----------------------------------------------------------------------------------------------

100001111011 : 123    11111    : -1      11111   : -1
10110111     : -9     0001     : 0       0000    : 0 0 0
11110        : -2     11111    : -1                0
10100100     : 4      0001     : 0       11111   : -1
10111000     : -8     11111    : -1      0000    : 0 0 0      123   -9   -8   -3    3   -1    1    0
11101        : -3     0001     : 0                 0          -2   15    6    1   -3    0    0    0
10100110     : 6      10100101 : 5       11010   : 2           4    5   -7   -2    0    0   -1    0
10100101     : 5      0010     : 0 0     0100111 : 0 0 0      -1    0   -1    5    1    0    0    0
11111        : -1     11001    : 1                 0 0 0  (b)  0    0    0    1   -2    0    0    0
0010         : 0 0    0011     : 0 0 0             0          -1   -1    0    0   -1    2    0    0
10111001     : -7     11001    : 1       11110   : -2          0    0    0    0    0    0   -2    0
11001        : 1      11001    : 1       0010    : 0 0         0    0    0    0    0    0   -1    2
11011        : 3      0100110  : 0 0 0   11111   : -1
11111        : -1                0 0 0   11010   : 2
11101        : -3     11110    : -2
11110        : -2     0001     : 0


Y 1 0 -----------------------------------------------------------------------------------------------

100001110011 : 115    11010    : 2                 0
10101000     : 8      0001     : 0       11110   : -2
11110        : -2     11111    : -1      0001    : 0
11011        : 3      11001    : 1       11001   : 1
100000010100 : 20     0010     : 0 0     0101001 : 0 0 0      115    8   -3   -8    2    1    0    1
11101        : -3     11001    : 1                 0 0 0       -2   20   -3   -3    2    0    1    0
10111000     : -8     0001     : 0                 0 0 0        3    1   -9    0    1    0    1    0
11101        : -3     10100100 : 4       11010   : 2           -2   -1   -1    4    1    0    0    0
11001        : 1      11001    : 1       0100111 : 0 0 0  (c)  -2    1    0    0   -2    0    0    0
11110        : -2     0010     : 0 0               0 0 0        0    1    0    0    0    2    0    0
11110        : -2     11001    : 1                             0    0    0    0    0    0   -1   -1
11111        : -1     11001    : 1       11111   : -1          0    0    0    0    0    0    0    1
10110111     : -9     0001     : 0       0001    : 0
11101        : -3     11001    : 1       11111   : -1
11010        : 2      0100111  : 0 0 0   0001    : 0
11001        : 1                 0 0 0   11001   : 1


Y 1 1 -----------------------------------------------------------------------------------------------

100010000011 : 131    11001    : 1       0001    : 0
10100110     : 6      11011    : 3       11001   : 1
11010        : 2      11001    : 1       0001    : 0
10111000     : -8     11101    : -3      11110   : -2
10110000     : -16    0001     : 0       0101011 : 0 0 0      131    6    1   -6   -1    1    0    0
11001        : 1      11111    : -1                0 0 0        2  -16   -3   -1    1    0    0    0
10111010     : -6     11001    : 1                 0 0 0       -8   -6   -9    1    1    0    0    0
11101        : -3     11100    : -4                0 0          0    1    3   -4   -1    0    0    0
10111010     : -6     11001    : 1       11110   : -2    (d)    0    1    1    1   -2    0    0    0
0010         : 0 0    0100101  : 0 0 0   0100111 : 0 0 0       -3   -1    1    0    0   -2    0    0
11001        : 1                 0 0               0 0 0        0    1    1    0    0    0   -2    0
10110111     : -9     11111    : -1                0          -1    0    0    0    0    0    0   -2
11111        : -1     11001    : 1       11110   : -2
11111        : -1     11001    : 1       0011    : 0 0 0
11001        : 1      11001    : 1       11110   : -2
11001        : 1      11111    : -1
```

Figure 9. Lossless decoding of the Y blocks in example.mic15. Header bits are coloured in red for illustrative purposes only, the bitstream has no marker for header bits versus data bits.

Next in the bitstream comes the data for the U and V planes of the downsampled image, recall that they have half the columns of the Y plane due to downsampling. In the same way as for Y, U 0,0 contains U data for pixel rows 0-7, columns 0-7 of the downsampled image; U 1,0 contains rows 8-15, columns 0-7; V 0,0 contains V data for rows 0-7, columns 0-7; V 1,0 contains rows 8-15, columns 0-7.

```
U 0 0 -----------------------------------------------------------------------------------

100010000010 : 130      10100100 : 4       11110   : -2
100000010110 : 22       11101    : -3      0001    : 0
100000011001 : 25       10111010 : -6      11111   : -1
10101110     : 14       10111010 : -6      0100000 : 0 0 0
10110011     : -13      11110    : -2              0 0 0          130   22   11    5    4   -3    1    0
10101011     : 11       11011    : 3               0 0 0           25  -13   -2    5   -6    0   -1    0
10100101     : 5        0011     : 0 0 0           0 0 0           14    0   -4   -6    0    0    0    0
11110        : -2       11111    : -1              0 0 0    (a)    -1    1   -2    0    1    0    0    0
0001         : 0        0011     : 0 0 0           0               1    3   -1   -2    0    0   -1    0
11111        : -1       11001    : 1       0001    : 0             0    0    0    0    0    0    0    0
11001        : 1        0001     : 0       11111   : -1            0   -1    0    0    0    0    0    0
11001        : 1        11111    : -1      011     : zeros         0    0    0    0    0    0    0    0
11100        : -4       0001     : 0               to
10100101     : 5        11001    : 1               end


U 1 0 -----------------------------------------------------------------------------------

100010001111 : 143      11001    : 1       0001    : 0
100000011111 : 31       11011    : 3       11001   : 1
10110110     : -10      11010    : 2       11111   : -1
10101110     : 14       10100100 : 4       0010    : 0 0
10100111     : 7        11001    : 1       11111   : -1           143   31   17  -19    1    3    1    0
100000010001 : 17       11111    : -1      0001    : 0           -10    7    7   -3    2   -1    1    0
100111101101 : -19      11011    : 3       11001   : 1            14   -6   -7    4    0   -1    0    0
10100111     : 7        11111    : -1      0010    : 0 0   (b)    -2    1    1   -1    0    1    0    0
10111010     : -6       11111    : -1      11001   : 1            2   -1    0    0    0    0    0    0
11110        : -2       0001     : 0       0001    : 0            3   -1   -1    1    0    0    0    0
11010        : 2        11111    : -1      11001   : 1           -1    0    0    0    0    0    0    0
11001        : 1        0001     : 0       011     : zeros        1    0    0    0    0    0    0    0
10111001     : -7       11111    : -1              to
11101        : -3       11001    : 1               end


V 0 0 -----------------------------------------------------------------------------------

100001111110 : 126      11001    : 1       11111   : -1
10101010     : 10       11001    : 1       11001   : 1
11001        : 1        11001    : 1       011     : zeros
10110110     : -10      10100100 : 4               to
0001         : 0        11010    : 2               end
10110100     : -12      11111    : -1                            126   10  -12  -10    1    1   -1   -1
10110110     : -10      0011     : 0 0 0                           1    0    0   -1    1    1    0    0
0001         : 0        11001    : 1                             -10   -3    4    4    0   -1    0    0
11101        : -3       0010     : 0 0   (c)                      -2    0    2    0   -1    0    0    0
11110        : -2       11001    : 1                             -2   -1    1    1    0    0    0    0
11110        : -2       11111    : -1                             0    0    0    0    0    0    0    0
0001         : 0        11111    : -1                             0    0    0    0    0    0    0    0
10100100     : 4        0001     : 0                              0    0    0    0    0    0    0    0
11111        : -1       11111    : -1


V 1 0 -----------------------------------------------------------------------------------

100001111000 : 120      11111    : -1      011     : zeros
10110110     : -10      11111    : -1              to
10100101     : 5        11110    : -2              end
10111010     : -6       0001     : 0
11110        : -2       11001    : 1                             120  -10   -7    7    0   -1   -1    0
10111001     : -7       11111    : -1                             5   -2   -3    0   -1    0   -1    0
10100111     : 7        0100110  : 0 0 0                          -6    2    3   -2    0    1    0    0
11101        : -3               0 0 0                             0    0    0    0    0    0    0    0
11010        : 2                         (d)                     -1    1    0    0    0    0    0    0
0001         : 0        11111    : -1                            -1    0    0    0    0    0    0    0
11111        : -1       0001     : 0                              0    0    0    0    0    0    0    0
0001         : 0        11111    : -1                             0    0    0    0    0    0    0    0
11011        : 3        11001    : 1
0010         : 0 0
```
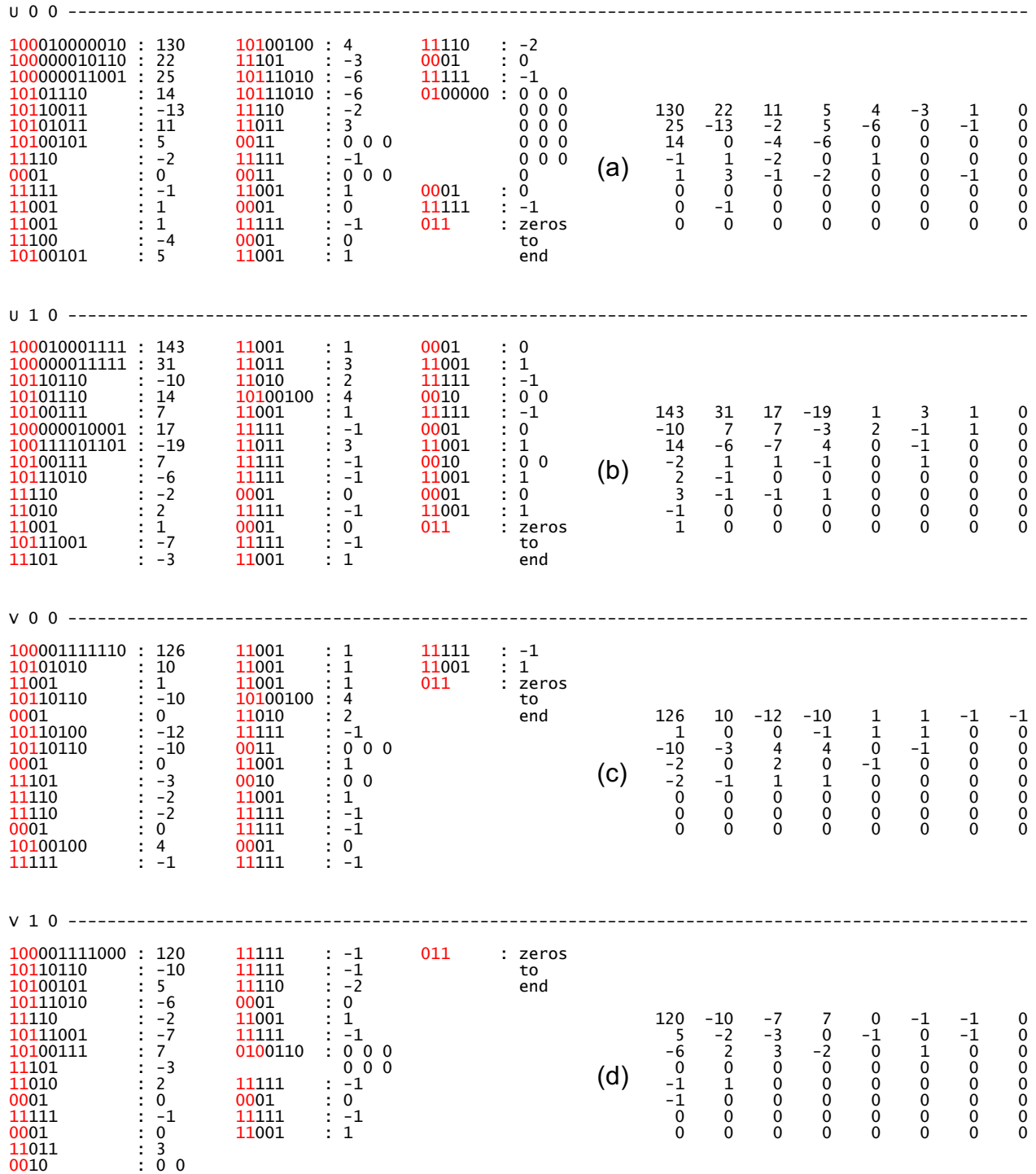
Figure 10. Lossless decoding of the downsampled U and V blocks in example.mic15. Header bits are coloured in red for illustrative purposes only, the bitstream has no marker for header bits versus data bits.

Upon completion of decoding, we have 8 blocks of data, 4 for Y (16/8 x 16/8), 2 for U and 2 for V. The matrices in the rightmost column (containing 8x8 matrices) of Figures 9 and 10 collectively make up the quantized image. From the flow illustrated in Figure 1, the next step is dequantization, which leads to the transformed image. This is done using pointwise multiplication between the losslessly decoded data (matrices in the rightmost column above) and the appropriate quantization matrix (Q_0 in this case). For matrices A, B and C, pointwise (or element-wise) multiplication is defined in Equation 6 below.

$$A = B .* C \quad \Longleftrightarrow \quad [A]_{i,j} = [B]_{i,j} * [C]_{i,j} \tag{6}$$

The quantized images are shown on the leftmost column in Figure 11 and the result of dequantization is shown in the central column.

3.2 IDCT (Inverse Discrete Cosine Transform) (Milestone 2 in Hardware)

After dequantizing the blocks, the IDCT must be performed to recover the downsampled image. The IDCT is defined in Equation 7:

$$S = (int)\frac{1}{65536}\left(C^T \times (int)\frac{1}{256}(S'C)\right) \tag{7}$$

where input S' is the dequantized 8x8 block, and the output S is the block of 8x8 samples from the downsampled image. The element on the ith row and j^{th} column of the 8x8 matrix C is:

$$[C]_{i,j} = \begin{cases} (int)\left(\sqrt{\frac{1}{8}}\cos\left(\frac{i\pi}{8}(j+0.5)\right)\times 4096\right) & \text{if } i = 0 \\ (int)\left(\sqrt{\frac{2}{8}}\cos\left(\frac{i\pi}{8}(j+0.5)\right)\times 4096\right) & \text{otherwise} \end{cases} \tag{8}$$

$$C = \begin{bmatrix} 1448 & 1448 & 1448 & 1448 & 1448 & 1448 & 1448 & 1448 \\ 2008 & 1702 & 1137 & 399 & -399 & -1137 & -1702 & -2008 \\ 1892 & 783 & -783 & -1892 & -1892 & -783 & 783 & 1892 \\ 1702 & -399 & -2008 & -1137 & 1137 & 2008 & 399 & -1702 \\ 1448 & -1448 & -1448 & 1448 & 1448 & -1448 & -1448 & 1448 \\ 1137 & -2008 & 399 & 1702 & -1702 & -399 & 2008 & -1137 \\ 783 & -1892 & 1892 & -783 & -783 & 1892 & -1892 & 783 \\ 399 & -1137 & 1702 & -2008 & 2008 & -1702 & 1137 & -399 \end{bmatrix} \tag{9}$$

Evaluating all cases in Equation 8 produces Equation 9. Equation 7 is defined similarly to the DCT from Equation 2, however the important differences are the intermediate and final scalar divisions, and the use of fixed-point coefficients. To re-iterate, the reason for choosing fixed-point (i.e. integer) operations is that they facilitate a more efficient hardware implementation when compared to floating-point.

Fixed-point, however, brings in necessary approximations that we achieve by using an intermediate bit-width larger than the one necessary to store the IDCT outputs. For example, the cosine coefficients (which are between -1 and 1) are left-shifted by 12 positions (i.e. multiplied by 4096 as shown in Equation 7) to obtain an integer-only fixed point value before processing (-4096 to 4096). Because the sample matrix is multiplied on both sides by the coefficient matrix the data will be left-shifted by 24 positions in total. The first adjustment of a right shift by 8 positions is provided after the post-multiplication $S'C$ and the second adjustment is given by a right shift by 16 positions after the pre-multiplication $C^T(S'C)$. The reason why the first adjustment is only on 8 bits is because it retains more precision and thus it is more immune to the truncation errors.

Finally, **clipping** is used to ensure that rounding and overflows that have lead to values out of the 8 bit unsigned range (0 to 255) are addressed by saturation (i.e. values smaller than 0 are forced to 0 and values greater than 255 are forced to 255). The result of dequantization and IDCT are as follows:

```
Y 0,0 ----------------------------------------------------------------------------------------

116   10  -10    5    0    0    0    0        928   40  -80   40    0    0    0    0          7  142  145  128  133  136  140  127
  7  -19    1    1   -2    0    0    0         28 -152    8   16  -32    0    0    0        131    8  122  139  129  151  134  131
  1   -2   -5   -3    1    0    0    0          8  -16  -80  -48   32    0    0    0        122  116   23  152  195  157  139   97
 -2    1    1   -4   -1    0    0    0  →     -16   16   16 -128  -32    0    0    0   →    134  139  111   17  131  163  112   89
  0    1    0    0   -2    0    0    0          0   16    0    0 -128    0    0    0        133  128  150  121   36  139  124   64
 -1    0    1    0    0   -2    0    0        -16    0   32    0    0 -128    0    0        115  140  135  167  146   33  107   79
  1    0   -1    0    0    0   -2    0         32    0  -64    0    0    0 -128    0        146  120  122  107  120   96    0  127
  0    0    0    0    0    0    0   -1          0    0    0    0    0    0    0  -64        133  122  136  176  158  116  101    3

Y 0,1 ----------------------------------------------------------------------------------------

123   -9   -8   -3    3   -1    1    0        984  -36  -64  -24   48  -16   32    0        130  154  125  134  145  139  156    5
 -2   15    6    1   -3    0    0    0         -8  120   48   16  -48    0    0    0        148  134  153  152  143  129    0  163
  4    5   -7   -2    0    0   -1    0         32   40 -112  -32    0    0  -64    0        103  138  147  135  130   10  149  152
 -1    0   -1    5    1    0    0    0  →      -8    0  -16  160   32    0    0    0   →    108   85  159  109    1  195  119  147
  0    0    0    1   -2    0    0    0          0    0    0   32 -128    0    0    0        139   96  109   33  182  144  110  139
 -1   -1    0    0   -1    2    0    0        -16  -32    0    0  -64  128    0    0        133   82   18  164  170  153   89  153
  0    0    0    0    0    0   -2    0          0    0    0    0    0    0 -128    0         97    7  144  168  160  126  138  142
  0    0    0    0    0    0   -1    2          0    0    0    0    0    0  -64  128         12  145  153  189  172  112  118  153

Y 1,0 ----------------------------------------------------------------------------------------

115    8   -3   -8    2    1    0    1        920   32  -24  -64   32   16    0   32        142   94  171  173  128  109   54   13
 -2   20   -3   -3    2    0    1    0         -8  160  -24  -48   32    0   32    0        128  111  175  141  169   80    8  143
  3    1   -9    0    1    0    1    0         24    8 -144    0   32    0   64    0        131  146  154  168   95   14   99  143
 -2   -1   -1    4    1    0    0    0  →     -16  -16  -16  128   32    0    0    0   →    126  144  155  114   13   63  146  101
 -2    1    0    0   -2    0    0    0        -32   16    0    0 -128    0    0    0        102  139  104   15  122   96  143  122
  0    1    0    0    0    2    0    0          0   32    0    0    0  128    0    0        124  111    8  136  137  128  132  143
  0    0    0    0    0    0   -1   -1          0    0    0    0    0    0  -64  -64        139   14  134  139  154  107  153  125
  0    0    0    0    0    0    0    1          0    0    0    0    0    0    0   64         15  120  150  127  127  144  127  135

Y 1,1 ----------------------------------------------------------------------------------------

131    6    1   -6   -1    1    0    0       1048   24    8  -48  -16   16    0    0         19  133  126  120  113  121  141  152
  2  -16   -3   -1    1    0    0    0          8 -128  -24  -16   16    0    0    0        110    7  179  202  181  151  140  141
 -8   -6   -9    1    1    0    0    0        -64  -48 -144   16   32    0    0    0        141  149   37  163  136  120  134  152
  0    1    3   -4   -1    0    0    0  →       0   16   48 -128  -32    0    0    0   →    157  164  169   29  141  147  157  154
  0    1    1    1   -2    0    0    0          0   16   32   32 -128    0    0    0        173  190  186  152    4  147  153  132
 -3   -1    1    0    0   -2    0    0        -48  -32   32    0    0 -128    0    0        178  193  182  135  108    6  162  160
  0    1    1    0    0    0   -2    0          0   32   64    0    0    0 -128    0         98  115  135  135  127  135   18  145
 -1    0    0    0    0    0    0   -2        -32    0    0    0    0    0    0 -128        152  132  131  144  145  139  139   13

U 0,0 ----------------------------------------------------------------------------------------

130   22   11    5    4   -3    1    0       1040   88   88   40   64  -48   32    0        131  185  168  178  185  159  168  154
 25  -13   -2    5   -6    0   -1    0        100 -104  -16   80  -96    0  -32    0        168  149  130  104  149  193  156  150
 14    0   -4   -6    0    0    0    0        112    0  -64  -96    0    0    0    0        168  124   87   57  121  187  154  150
 -1    1   -2    0    1    0    0    0  →      -8   16  -32    0   32    0    0    0   →    175  154   86   80  111  110  113  110
  1    3   -1   -2    0    0   -1    0         16   48  -32  -64    0    0  -64    0        182  140   86   97  114   79   72  101
  0    0    0    0    0    0    0    0          0    0    0    0    0    0    0    0        187   94   89   91  116  105   54  133
  0   -1    0    0    0    0    0    0          0  -32    0    0    0    0    0    0        193  122  138  123  114   86   41  143
  0    0    0    0    0    0    0    0          0    0    0    0    0    0    0    0        159  167  181  174  121   46   61  160

U 1,0 ----------------------------------------------------------------------------------------

143   31   17  -19    1    3    1    0       1144  124  136 -152   16   48   32    0        188  158  194  173  130  126  128  176
-10    7    7   -3    2   -1    1    0        -40   56   56  -48   32  -32   32    0        174  174  192  136   78   62   83  177
 14   -6   -7    4    0   -1    0    0        112  -48 -112   64    0  -32    0    0        177  171  165  113   83   77   90  172
 -2    1    1   -1    0    1    0    0  →     -16   16   16  -32    0   64    0    0   →    183  159  159  116   68   79  119  174
  2   -1    0    0    0    0    0    0         32  -16    0    0    0    0    0    0        186  161  191  137   16   29  130  180
  3   -1   -1    1    0    0    0    0         48  -32  -32   64    0    0    0    0        163  132  168  141   37   53  134  137
 -1    0    0    0    0    0    0    0        -32    0    0    0    0    0    0    0        173  155  172  182  160  171  184  147
  1    0    0    0    0    0    0    0         32    0    0    0    0    0    0    0        139  167  172  174  180  174  165  157

V 0,0 ----------------------------------------------------------------------------------------

126   10  -12  -10    1    1   -1   -1       1008   40  -96  -80   16   16  -32  -32        115  114   90  106   93  105  117  113
  1    0    0   -1    1    1    0    0          4    0    0  -16   16   32    0    0        108  125  139  171  128  104  112  116
-10   -3    4    4    0   -1    0    0        -80  -24   64   64    0  -32    0    0        104  129  169  215  151  106  112  118
 -2    0    2    0   -1    0    0    0  →     -16    0   32    0  -32    0    0    0   →    107  129  164  203  142  110  120  117
 -2   -1    1    1    0    0    0    0        -32  -16   32   32    0    0    0    0        104  139  162  180  126  113  124  114
  0    0    0    0    0    0    0    0          0    0    0    0    0    0    0    0         97  151  165  170  126  114  118  113
  0    0    0    0    0    0    0    0          0    0    0    0    0    0    0    0         99  142  133  145  130  117  106  112
  0    0    0    0    0    0    0    0          0    0    0    0    0    0    0    0        108  122   84  108  130  120   98  110

V 1,0 ----------------------------------------------------------------------------------------

120  -10   -7    7    0   -1   -1    0        960  -40  -56   56    0  -16  -32    0         99  116  100  120  117  108  134   99
  5   -2   -3    0   -1    0   -1    0         20  -16  -24    0  -16    0  -32    0        102  122  106  130  142  132  145  113
 -6    2    3   -2    0    1    0    0        -48   16   48  -32    0   32    0    0         98  122  104  130  160  147  138  110
  0    0    0    0    0    0    0    0  →       0    0    0    0    0    0    0    0   →    100  122  102  127  166  150  123  100
 -1    1    0    0    0    0    0    0        -16   16    0    0    0    0    0    0        109  123  107  128  167  153  122  106
 -1    0    0    0    0    0    0    0        -16    0    0    0    0    0    0    0        113  114  106  122  150  144  123  116
  0    0    0    0    0    0    0    0          0    0    0    0    0    0    0    0        116  103  102  110  119  121  115  114
  0    0    0    0    0    0    0    0          0    0    0    0    0    0    0    0        126  103  105  106  100  104  108  110
```

Figure 11. Dequantization (left to center column) followed by IDCT (center to right column) on each 8x8 block.

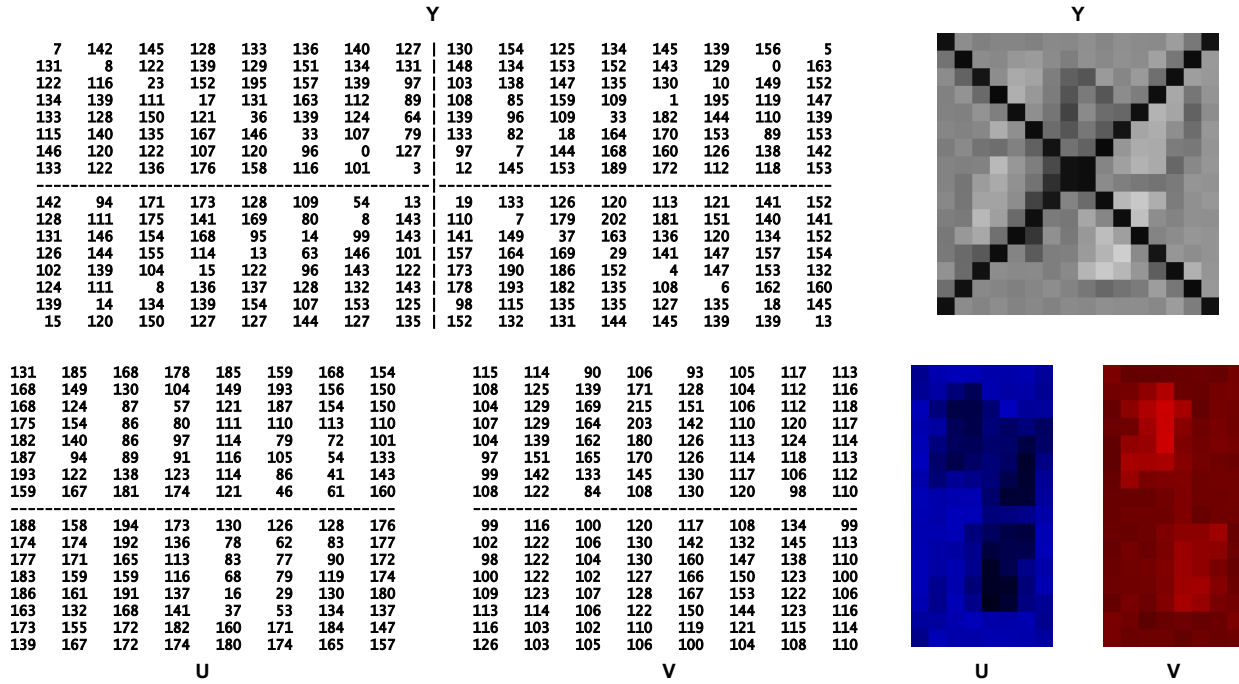## 3.3   Upsampling and Colourspace Conversion (Milestone 1 in Hardware)

Y

```
  7 142 145 128 133 136 140 127 | 130 154 125 134 145 139 156   5
131   8 122 139 129 151 134 131 | 148 134 153 152 143 129   0 163
122 116  23 152 195 139 157  97 | 103 138 147 135 130  10 149 152
134 139 111  17 131 163 112  89 | 108  85 159 109   1 195 119 147
133 128 150 121  36 139 124  64 | 139  96 109  33 182 144 110 139
115 140 135 167 146  33 107  79 | 133  82  18 164 170 153  89 153
146 120 122 107 120  96   0 127 |  97   7 144 168 160 126 138 142
133 122 136 176 158 116 101   3 |  12 145 153 189 172 112 118 153
-------------------------------------|------------------------------------
142  94 171 173 128 109  54  13 |  19 133 126 120 113 121 141 152
128 111 175 141 169  80   8 143 | 110   7 179 202 181 151 140 141
131 146 154 168  95  14  99 143 | 141 149  37 163 136 120 134 152
126 144 155 114  13  63 146 101 | 157 164 169  29 141 147 157 154
102 139 104  15 122  96 143 122 | 173 190 186 152   4 147 153 132
124 111   8 136 137 128 132 143 | 178 193 182 135 135 108   6 162 160
139  14 134 139 154 107 153 125 |  98 115 135 135 127 135  18 145
 15 120 150 127 127 144 127 135 | 152 132 131 144 145 139 139  13
```

```
131 185 168 178 185 159 168 154        115 114  90 106  93 105 117 113
168 149 130 104 149 193 156 150        108 125 139 171 128 104 112 116
168 124  87  57 121 187 154 150        104 129 169 215 151 106 112 118
175 154  86  80 111 110 113 110        107 129 164 203 142 110 120 117
182 140  86  97 114  79  72 101        104 139 162 180 126 113 124 114
187  94  89  91 116 105  54 133         97 151 165 170 126 114 118 113
193 122 138 123 114  86  41 143         99 142 133 145 130 117 106 112
159 167 181 174 121  46  61 160        108 122  84 108 130 120  98 110
-----------------------------------    ---------------------------------
188 158 194 173 130 126 128 176         99 116 100 120 117 108 134  99
174 174 192 136  78  62  83 177        102 122 106 130 142 132 145 113
177 171 165 113  83  77  90 172         98 122 104 130 160 147 138 110
183 159 159 116  68  79 119 174        100 122 102 127 166 150 123 100
186 161 191 137  16  29 130 180        109 123 107 128 167 153 122 106
163 132 168 141  37  53 134 137        113 114 106 122 150 144 123 116
173 155 172 182 160 171 184 147        116 103 102 110 119 121 115 114
139 167 172 174 180 174 165 157        126 103 105 106 100 104 108 110
```

U   **V**

Figure 12. The output of IDCT is the downsampled YUV data.

The output of IDCT is downsampled YUV data, where U and V are horizontally downsampled by 2, as shown in Figure 12. The downsampled data becomes the even columns in the upsampled image, and the odd columns are generated by horizontal interpolation. For each row (rows are processed independently), we interpolate with a filter known as a finite impulse response (FIR) filter, which uses a weighted sum of a finite number of samples to produce each reconstructed sample. In our case that finite number is 6, so the filter is called a 6-tap filter. Given n samples in each row of the U and V planes, we produce $2n$ samples for the corresponding row of the reconstructed plane as follows:

$$U'[j] = \begin{cases} U\left[\frac{j}{2}\right] & j \text{ even} \\ (int)\frac{1}{256}\left(21U\left[\frac{j-5}{2}\right] - 52U\left[\frac{j-3}{2}\right] + 159U\left[\frac{j-1}{2}\right] + 159U\left[\frac{j+1}{2}\right] - 52U\left[\frac{j+3}{2}\right] + 21U\left[\frac{j+5}{2}\right] + 128\right) & j \text{ odd} \end{cases} \tag{10}$$

where U is the downsampled version and U' is the upsampled version. An analogous definition applies for V. In our example with an image of size 16x16, n is 8. In the project, the image will be of size 320x240, so n will be 320/2 = 160. The borders of **each row** are handled by replicating the respective border sample, i.e. $U[0] = U[-1] = U[-2]$, and $U[n-1] = U[n] = U[n+1] = U[n+2]$. Note again the use of integer operations. These coefficients are borrowed from the ISO/IEC 13818-2 document on MPEG2 digital video decoding. Applying this filter to the U and V planes, the result in shown in Figure 13.

Having restored the full Y, U and V planes, the only step which remains is the colourspace conversion from YUV back to RGB. As discussed in section 2.1 (Equation 1), the conversion from RGB to YUV is in the form of a matrix multiplication. In essence, the RGB values of a given pixel are viewed as a vector in 3-space, and the matrix multiplication is a change of basis yielding another vector in 3-space. Since this is a linear transformation and the determinant of the matrix is nonzero, we may find its inverse, which will
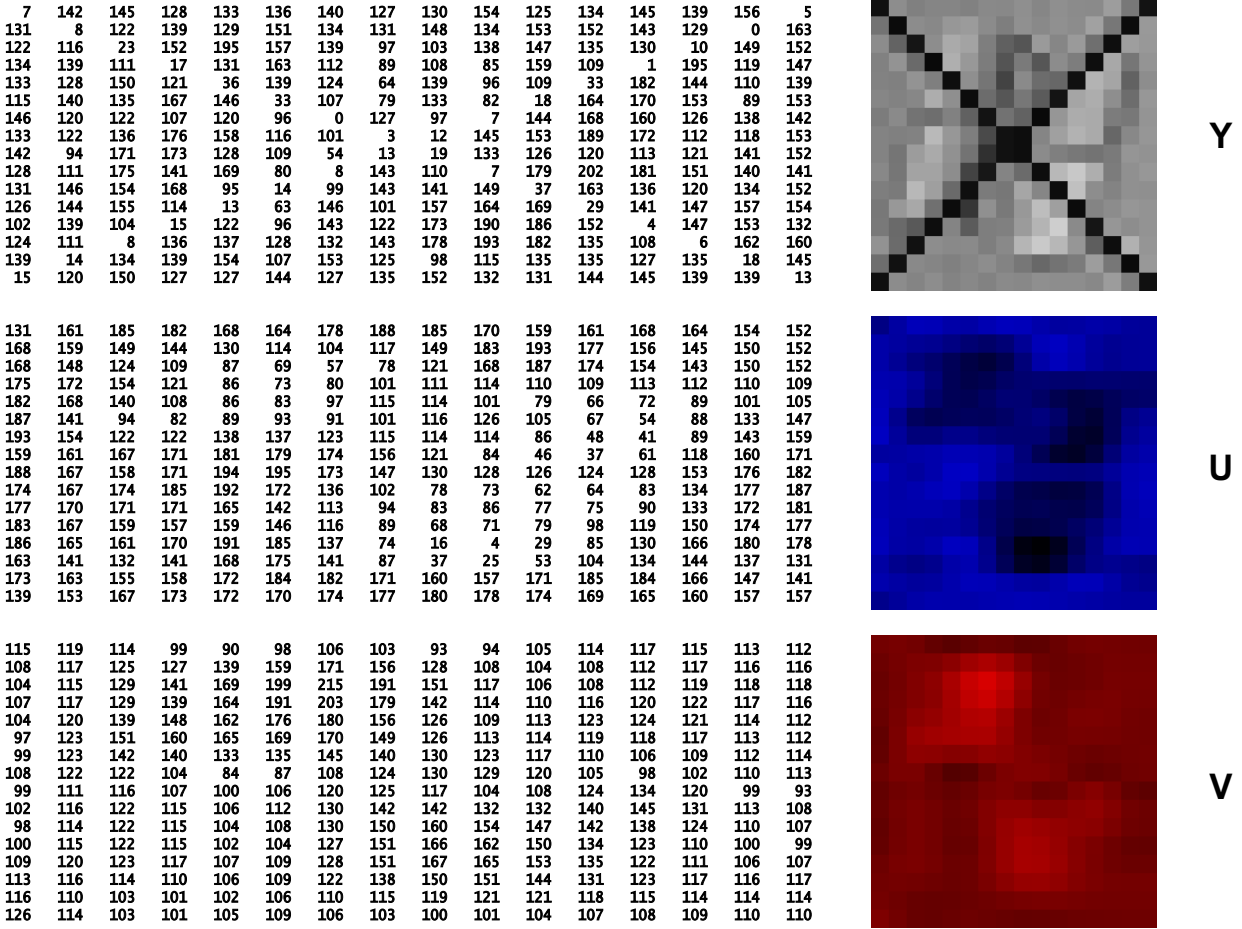


```
  7  142  145  128  133  136  140  127  130  154  125  134  145  139  156    5
131    8  122  139  129  151  134  131  148  134  153  152  143  129    0  163
122  116   23  152  195  157  139   97  103  138  147  135  130   10  149  152
134  139  111   17  131  163  112   89  108   85  159  109    1  195  119  147
133  128  150  121   36  139  124   64  139   96  109   33  182  144  110  139
115  140  135  167  146   33  107   79  133   82   18  164  170  153   89  153
146  120  122  107  120   96    0  127   97    7  144  168  160  126  138  142
133  122  136  176  158  116  101    3   12  145  153  189  172  112  118  153
142   94  171  173  128  109   54   13   19  133  126  120  113  121  141  152
128  111  175  141  169   80    8  143  110    7  179  202  181  151  140  141
131  146  154  168   95   14   99  143  141  149   37  163  136  120  134  152
126  144  155  114   13   63  146  101  157  164  169   29  141  147  157  154
102  139  104   15  122   96  143  122  173  190  186  152    4  147  153  132
124  111    8  136  137  128  132  143  178  193  182  135  108    6  162  160
139   14  134  139  154  107  153  125   98  115  135  135  127  135   18  145
 15  120  150  127  127  144  127  135  152  132  131  144  145  139  139   13
```

Y

```
131  161  185  182  168  164  178  188  185  170  159  161  168  164  154  152
168  159  149  144  130  114  104  117  149  183  193  177  156  145  150  152
168  148  124  109   87   69   57   78  121  168  187  174  154  143  150  152
175  172  154  121   86   73   80  101  111  114  110  109  113  112  110  109
182  168  140  108   86   83   97  115  114  101   79   66   72   89  101  105
187  141   94   82   89   93   91  101  116  126  105   67   54   88  133  147
193  154  122  122  138  137  123  115  114  114   86   48   41   89  143  159
159  161  167  171  181  179  174  156  121   84   46   37   61  118  160  171
188  167  158  171  194  195  173  147  130  128  126  124  128  153  176  182
174  167  174  185  192  172  136  102   78   73   62   64   83  134  177  187
177  170  171  171  165  142  113   94   83   86   77   75   90  133  172  181
183  167  159  157  159  146  116   89   68   71   79   98  119  150  174  177
186  165  161  170  191  185  137   74   16    4   29   85  130  166  180  178
163  141  132  141  168  175  141   87   37   25   53  104  134  144  137  131
173  163  155  158  172  184  182  171  160  157  171  185  184  166  147  141
139  153  167  173  172  170  174  177  180  178  174  169  165  160  157  157
```

U

```
115  119  114   99   90   98  106  103   93   94  105  114  117  115  113  112
108  117  125  127  139  159  171  156  128  108  104  108  112  117  116  116
104  115  129  141  169  199  215  191  151  117  106  108  112  119  118  118
107  117  129  139  164  191  203  179  142  114  110  116  120  122  117  116
104  120  139  148  162  176  180  156  126  109  113  123  124  121  114  112
 97  123  151  160  165  169  170  149  126  113  114  119  118  117  113  112
 99  123  142  140  133  135  145  140  130  123  117  110  106  109  112  114
108  122  122  104   84   87  108  124  130  129  120  105   98  102  110  113
 99  111  116  107  100  106  120  125  117  104  108  124  134  120   99   93
102  116  122  115  106  112  130  142  142  132  132  140  145  131  113  108
 98  114  122  115  104  108  130  150  160  154  147  142  138  124  110  107
100  115  122  115  102  104  127  151  166  162  150  134  123  110  100   99
109  120  123  117  107  109  128  151  167  165  153  135  122  111  106  107
113  116  114  110  106  109  122  138  150  151  144  131  123  117  116  117
116  110  103  101  102  106  110  115  119  121  121  118  115  114  114  114
126  114  103  101  105  109  106  103  100  101  104  107  108  109  110  110
```

V

Figure 13. The result after horizontally upsampling U and V.

provide the transformation back to the RGB basis from the YUV basis. This is applied to each pixel independently. Accounting for the vector addition to first shift the basis, the inverse conversion of the one above is:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = (int)\frac{1}{65536}\left(\begin{bmatrix} 76284 & 0 & 104595 \\ 76284 & -25624 & -53281 \\ 76284 & 132251 & 0 \end{bmatrix}\left(\begin{bmatrix} Y \\ U' \\ V' \end{bmatrix} - \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix}\right)\right) \tag{11}$$

Note, for colour space conversion you should use the upsampled values for the U and V planes (see Equation 10). As in the case of IDCT, an identical clipping function is used to deal with the under/overflow errors. The outputs R, G, and B are each on 8 bits unsigned. The final result is shown in Figure 14.

```
  0  132  127   84   75   91  109   89   76  106   90  115  132  122  139    0
101    0  118  141  149  206  205  178  153  105  121  126  122  113    0  151
 85   95    9  179  255  255  255  194  137  124  117  106  107    0  138  142
103  125  112   18  191  255  231  166  129   57  137   89    0  198  102  133
 97  117  173  154   77  219  208  100  139   62   84   11  186  137   87  117
 65  136  175  226  210   85  172  106  132   52    0  157  163  141   61  133
105  113  145  125  129  104    8  148   97    0  131  148  132   97  116  124
104  113  130  147   95   50   67    0    0  151  146  164  133   70   90  135
100   63  161  149   85   73   31    0    0   97   96  114  122  109   99  102
 88   91  175  124  142   48    0  170  131    0  196  235  219  161  120  113
 85  128  151  156   53    0   99  182  196  196   54  193  155  114  108  124
 83  128  152   93    0   16  149  135  224  226  213   24  137  123  119  114
 69  130   94    0   89   62  147  160  244  255  237  169    0  125  124  101
101   91    0  110  105  100  125  163  223  242  218  143   99    0  150  150
124    0   97  100  119   70  130  106   81  104  127  122  108  116    0  127
  0   98  116   86   92  118   94   98  113   91   95  115  118  112  114    0
```

R

```
  0  141  139  132  151  149  142  126  138  171  133  135  143  139  164    0
134    0  117  137  121  137  111  115  145  132  153  155  149  133    0  171
127  119    8  155  191  129  100   62   85  135  147  136  135    0  154  157
136  134   99    0  121  141   69   54  102   97  188  125    0  219  135  169
134  121  142  113   12  121   95   38  150  119  139   48  218  169  131  165
117  143  133  167  136    0   86   66  142   89   22  203  216  184   95  165
149  114  114   98  113   83    0  124   98    0  174  222  219  158  149  145
140  115  129  188  180  129   97    0    0  166  198  255  232  136  120  154
146   89  178  183  127   99   33    0   11  155  145  125  108  118  150  165
133  105  171  133  170   70    0  146  117    7  212  231  195  152  137  138
139  146  148  170   97    8  100  143  137  150   28  180  146  122  134  154
129  144  154  113    5   67  156   95  156  166  179   21  153  158  168  165
 92  135   93    0  115   86  144  125  194  220  216  169    0  151  157  132
124  115    0  149  143  127  134  155  206  227  209  145  108    0  176  175
135    0  147  153  164  101  152  120   90  109  127  124  117  135    6  156
  0  122  161  133  130  148  129  139  160  137  135  150  151  146  146    0
```

G

```
  0  213  255  239  216  212  245  250  247  245  189  203  230  215  215   35
214   53  165  175  135  128   88  111  196  248  255  255  204  165   25  219
204  156    0  119  125   45    0    0   87  222  255  231  185   23  199  206
232  231  163    0   49   60   14   30   72   52  130   69    0  176   83  114
245  211  180   81    0   52   63   29  114   38    9    0   80   70   54   96
234  170   69   82   72    0   31   18  111   72    0   49   29   78   95  197
255  173  111   93  141  111    0  102   66    0   64   15    0   49  172  209
198  189  218  255  255  219  191   41    0   61    0   17   46   91  183  246
255  169  240  255  255  243  135   34    7  136  124  112  112  172  242  255
223  189  255  255  255  163    6   95    8    0   56   87  101  169  243  255
232  236  247  255  166   25   66   79   54   70    0   64   62  131  226  255
239  227  224  172   59   91  127   20   43   57   79    0  127  196  255  255
217  217  169   83  250  208  165   14    0    0    0   71    0  229  255  235
196  136    0  165  221  225  161   65    4    0   41   90  119   20  188  173
233   68  191  203  249  218  255  213  160  173  225  253  242  215   40  176
 21  171  234  220  217  233  222  237  255  235  226  231  224  207  201   55
```

B

Figure 14. After colourspace conversion, we obtain the final decompress RGB image.

The final decompressed image, as shown on the left (a) in Figure 15, requires 16x16x3 = 768 bytes (plus a header of 13 bytes), whereas the compressed image required only 212 bytes, giving a compression ratio of more than 3x. The original image appears on the right (c). As you can see, there is some reduction in the quality due to information lost during the compression and decompression process. The center image (b) shows the decompressed image for the case when quantization matrix Q_1 from Equation 3 is used (instead of Q_0 as is the case for this example, image (a)), which during compression retains more frequency information for use during reconstruction. The use of this matrix clearly improves the quality, but reduces the compression. This discussion is summarized in the signal to noise ratio (SNR) values and file sizes given for both cases in Table 1.

	Q_0 image	Q_1 image	Original image
SNR (dB)	18.65	20.40	∞
File size (bytes, including header)	220	372	781
Compression ratio	3.55	2.10	1

Table 1. Quality versus compression tradeoff for the images using quantization matrices Q_0 and Q_1.

(a)   (b)   (c)
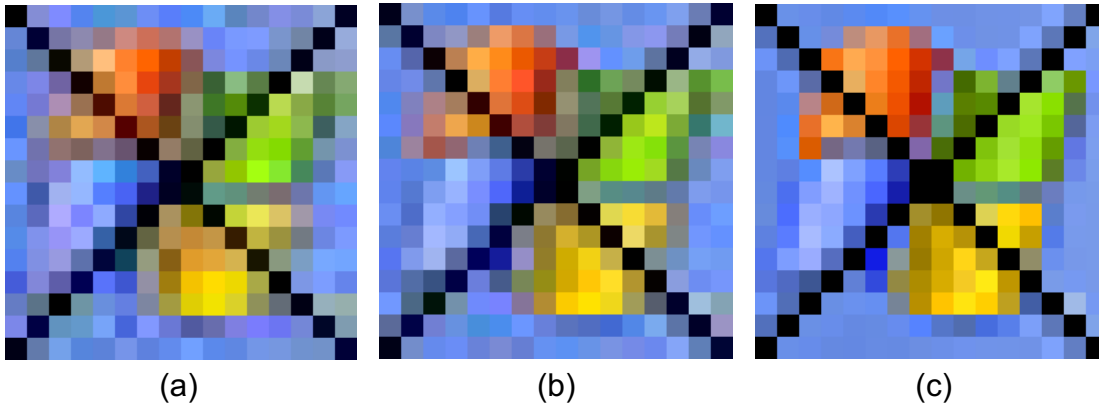
Figure 15. Final decompressed images using quantization matrices Q_0 (a) and Q_1 (b) and the original image (c).

Equation 12 defines the signal to noise ratio where N is the number of pixels, $error$ is the root mean squared error, and the 255 on the numerator is the maximum value of any pixel:

$$SNR\,(dB) = 20 \log_{10} \left(\frac{255}{\sqrt{\frac{error}{N}}} \right) \text{ where } error = \sum_{n=0}^{N-1}(reference\_pixel_n - image\_pixel_n)^2 \qquad (12)$$

This part of the document has provided the barebones of image compression (sufficient to work on the project). Further information on image compression can be found in the following references:

[1] JPEG: Still Image Data Compression Standard, by William B. Pennebaker and Joan L. Mitchell, 1st edition, 2006

[2] Handbook of Data Compression, by David Salomon and Giovanni Motta, 2006

[3] JPEG-1 Standard 25 Years: Past, Present, and Future Reasons for a Success, by Graham Hudson, Alain Léger, Birger Niss, István Sebestyén, Jørgen Vaaben, in Journal of Electronic Imaging, 27(4), 2018

[4] Video Compression Handbook, by Andy Beach, 2nd edition, 2018

4 Project Guidelines

The design task of implementing the overall decoder has been partitioned into three milestones which can be completed each within approx one week. At any stage of the project, the design must compile in Quartus and meet the 50 MHz clock constraint. As part of the validation methodology, implementation will proceed from the VGA display backward to the compressed input. Starting from the display end enables a visual progress check at each milestone, thereby providing the framework for incremental integration of each newly designed module into the overall system.
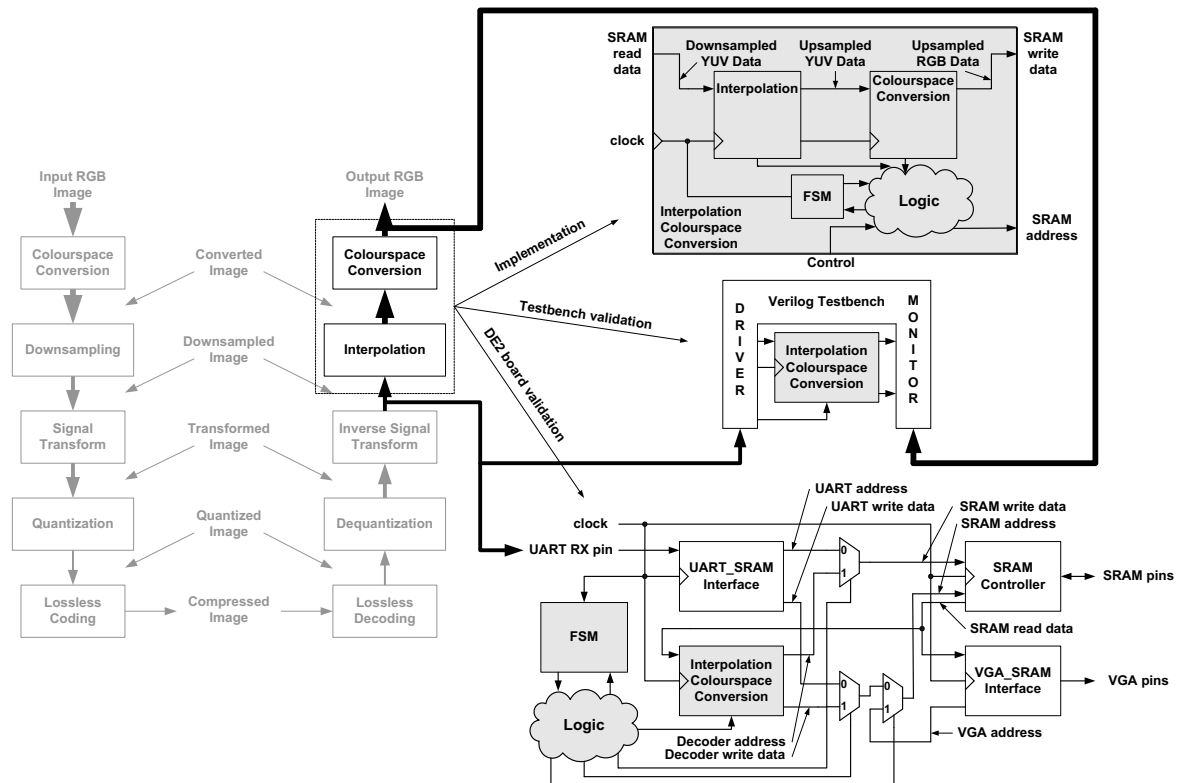
Figure 16. Overview of the upsampling and colourspace conversion hardware implementation (milestone 1).

4.1 The Software Model and its Integration in the Design Process

Starting with a .mic15 file, there are 3 separate source codes, 1 for each milestone. The input/output files are organized exactly like the SRAM in hardware, that is 2^{18} = 262144 locations with 16 bits per location. Each source code reads data from a software model of the SRAM, performs the necessary computation, and then writes the data back to the SRAM software model. The decoding process starts at milestone 3, and the source code "decode_m3" takes a .mic15 file and produces a .sram_d2 file. Continuing into milestone 2, the source code "decode_m2" takes a .sram_d2 file and produces a .sram_d1 file. Finally for milestone 1, "decode_m1" takes a .sram_d1 file and produces a .sram_d0 file and a .ppm file.

By separating the decoding process, we can do part of the decoding in software and part of it in hardware. The decoding software handles the first part of the decoding task and the intermediate data can be passed to a testbench or to the board, where the hardware can take over the remainder of the decoding task to produce the image. In the case of the testbench, detailed feedback can be provided

which aids in tracing implementation errors, while the board provides less feedback, but a full practical operational test. For example, to validate if milestone 1 is working properly in hardware, the .sram_d1 file can be used to initialize the SRAM and after the hardware simulation is finished, the .sram_d0 file can be used to validate if the contents of SRAM are correct.

4.2   Milestone 1: Upsampling and Colourspace Conversion

Figure 16 shows the implementation and validation plan for milestone 1. In this first week, colourspace conversion and interpolation will be tackled as indicated in the portion of the figure which shows the flow from Figure 1. This will also require some modifications to the existing state machines, to grant the decoder access to the external memory (by multiplexing). In fact, all the shaded portions of the figure will have to be built or modified. The SRAM Controller, UART SRAM Interface and VGA SRAM Interface shown in the figure have been provided in lab 5.

Figure 17 shows the memory layout which is used for milestone 1. The last portion of the memory holds the completed RGB image stored in {R0 G0}, {B0 R1}, {G1 B1} … format (as in lab 5 experiment 1). This is where the decompressed image will reside for all three milestones and thus for the completed project as well. Where it differs from the completed project is in the fact that downsampled YUV data is stored in the SRAM as decoder stimuli, since the earlier parts of the decoder are not yet implemented. By default (from the backbone in lab 5), the UART SRAM interface writes data in the SRAM starting at address 0 and the VGA SRAM interface starts reading from address 0. Clearly, the VGA SRAM interface must be modified so that the RGB data is read from the correct segment, as indicated in Figure 17. *Also, the UART receiver in lab 5 experiment 4 strips the header from the .ppm file, **which is no longer needed**.*
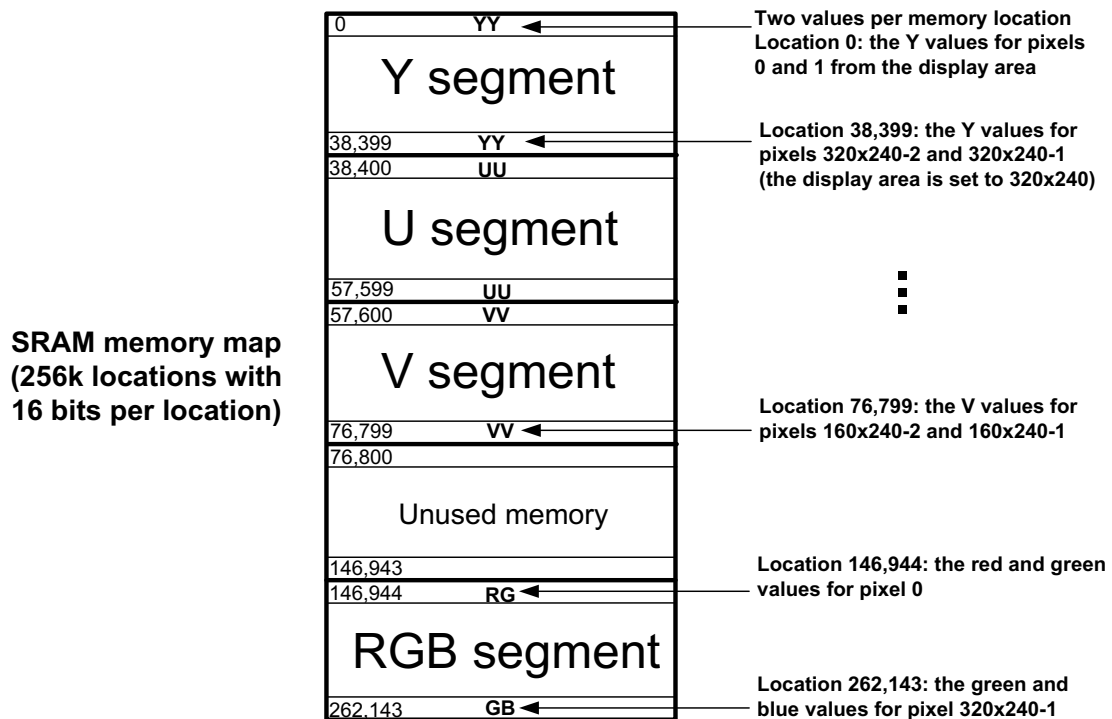
Figure 17. Memory layout for milestone 1.

```
logic [31:0] Mult_op_1, Mult_op_2, Mult_result;
logic [63:0] Mult_result_long;

assign Mult_result_long = Mult_op_1 * Mult_op_2;
assign Mult_result = Mult_result_long[31:0];
```
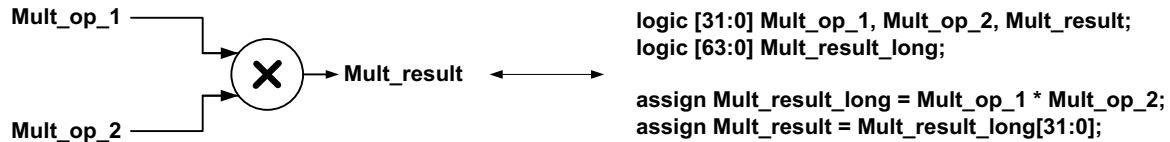
Figure 18. Instantiation of a single 32-bit multiplier.

Figure 18 shows how a single 32-bit integer multiplier can be instantiated in your design. As will be elaborated on soon, to end up with a resource efficient implementation, multipliers must be shared because they are costly in terms of logic resources. Specifically, for this milestone you are given the *constraint of 2 multipliers (with input operands on 32 bits or less). Note, these 2 multipliers are shared among colourspace conversion and upsampling*, thus there will be a total of **two instantiations** of the form for Figure 18 (note, however, you are required to meet utilization constraints and exploit the symmetry in the interpolation filter from Equation 10, as clarified later in this section). Each of these tasks comprises more than one multiplication, so the multipliers for each task must be shared. For this reason, the instantiation given in Figure 18 should be used, and the signals Mult_op_1, Mult_op_2 and Mult_result should be multiplexed.

By explicitly instantiating multipliers, we are certain to have that many multipliers used in hardware. For example, in the following code snippet:

```
always_comb begin
    if (select == 1'b0) a = b*c;
    else a = d*e;
end
```

The multiplications happen at mutually exclusive times, so we could have 1 hardware multiplier with `b` and `d` multiplexed at one input to the multiplier, and `c` and `e` multiplexed at the other input to the multiplier. However, this not explicitly stated, so the computer-aided design (CAD) tool (in our case, Quartus) may choose to instantiate 2 hardware multipliers to compute both `b*c` and `d*e`, and then take these 2 results and multiplex them to obtain the output `a`. To avoid this problem, we can explicitly specify that 1 (and only 1) multiplier should be used by multiplexing the operands:

```
always_comb begin
    if (select == 1'b0) begin
        op1 = b;
        op2 = c;
    end
    else begin
        op1 = d;
        op2 = e;
    end
end
assign a = op1*op2;
```

Next, some architectural examples are provided regarding how the multipliers can be shared.

Figure 19 shows a straightforward implementation of a FIR filter, where the samples are stored in a shift-register structure. In this case each sample undergoes a constant multiplication, and the results are all combined using an adder tree. Although this is attractive from the throughput perspective, as one filtered sample may be obtained every clock cycle, it is costly from the resource standpoint, especially considering that one such filter would be required for each component which must be upsampled (U

and V). Furthermore, we must consider if we can actually receive a new U and a new V sample on every clock cycle, if we cannot then on some clock cycles this hardware will be under-utilized. A similar argument applies to whether or not we can process 1 upsampled U and 1 upsampled V per clock cycle after the FIR filter.
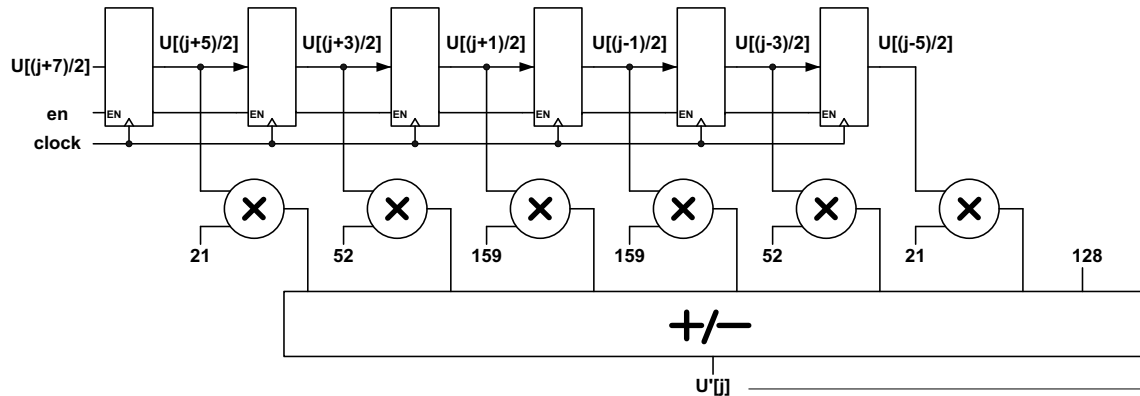
Figure 19. Resource inefficient FIR filter implementation.

In Figure 20, we see how a single multiplier can be shared to accomplish the same computation as Figure 19, but at the expense of throughput. In this case, the boxed portion is known as a Multiply-Accumulate (MAC) unit, which works by always multiplying the two inputs, and adding the result to the register (known as the accumulation register or accumulator), and then storing that result back in the accumulator, to become an operand in the next clock cycle. The FSM guides the selection of both the sample and the constant factor, as well as initialization, which in this case is to account for the +128 in the upsampling equations of Equation 10, also shown in Figure 19. Using this architecture, only one multiplier is required, however, each reconstructed sample requires 7 clock cycles to produce instead of 1 as in the previous case. This is an example of a typical architectural tradeoff between resource usage and throughput.
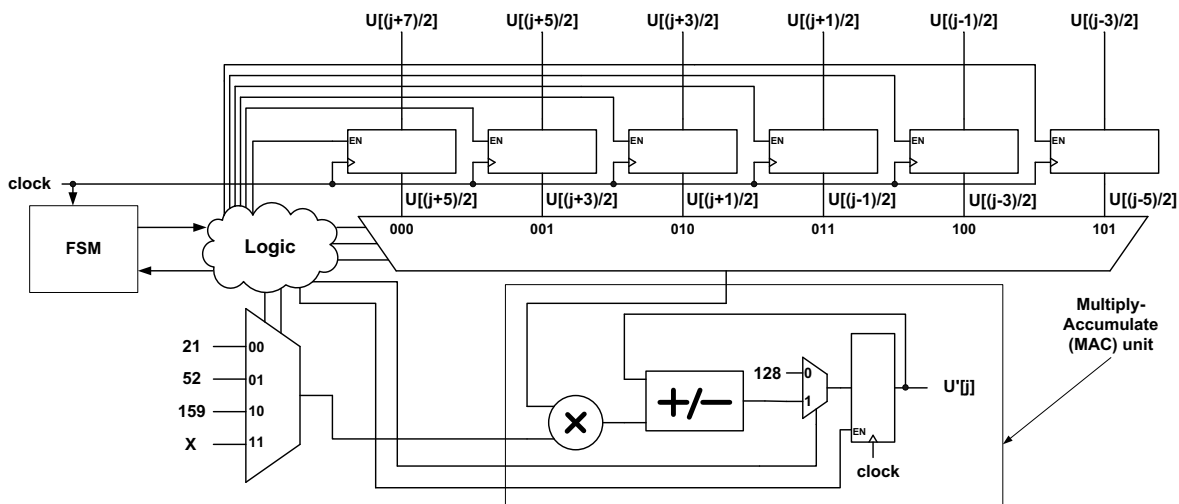
Figure 20. Resource efficient FIR filter implementation.

Figure 21 shows a cost-effective FIR implementation which is similar to Figure 20, but with the important distinction that the multiplexer that selects between the different samples (as set up by the FSM) is eliminated. The same result can be obtained by leveraging the shift structure that is already

present due to the reuse of the majority of the samples in calculating adjacent reconstructed samples. Now instead of the FSM setting up select lines on a mux to obtain a desired sample, the calculation proceeds by holding the shift for the first clock cycle (during initialization of the accumulator to 128), and during the next 6 clock cycles, the samples are circularly shifted, each time the contents of the rightmost register being accumulated. At the end of these 6 clock cycles, each of the data returns to its original register, and the accumulation is complete (a new reconstructed sample has been produced). Although identical to Figure 20 in throughput, elimination of the large sample selector mux makes this design substantially more efficient.
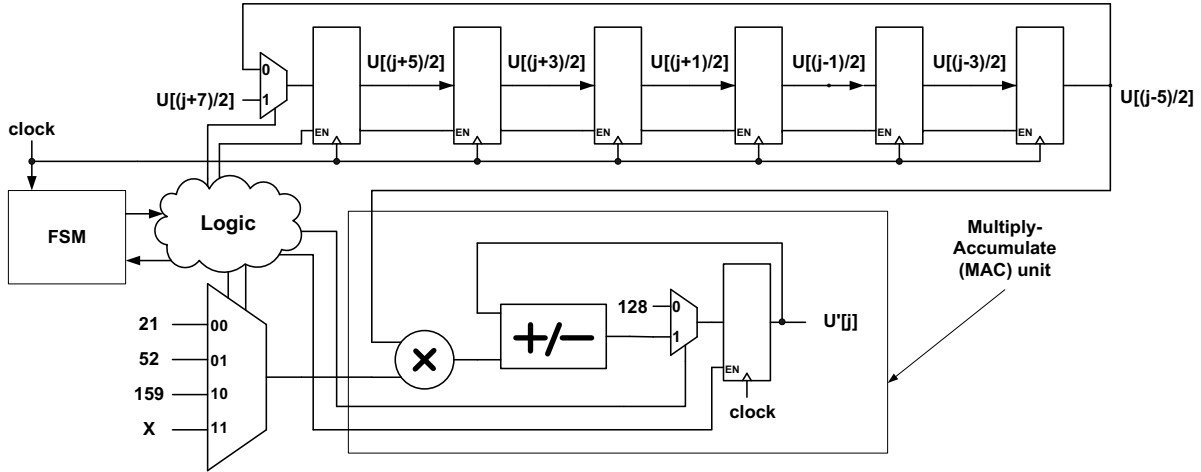
Figure 21. Resource efficient FIR filter implementation.

The average utilization of the 2 multipliers for milestone 1 must be at least 85%. The utilization of a multiplier is defined as the number of clock cycles a multiplier is used to perform calculations divided by the total number of clock cycles for the respective milestone. For clarification purposes, consider the following example on a hypothetical milestone whose duration is 100 clock cycles. Let's assume we use two multipliers. The first multiplier performs calculations for 75 clock cycles, hence its utilization is 75%. The second multiplier performs calculations for 95 clock cycles, hence its utilization is 95%. For this *hypothetical* milestone the average utilization is 85%.

In addition to the above-mentioned utilization constraint, it is **mandatory to exploit the symmetry in the interpolation filter**. The symmetry of the filter's coefficients from Equation 10 can be exploited as:

$$21 \left(U\left[\tfrac{j-5}{2}\right] + U\left[\tfrac{j+5}{2}\right] \right) - 52 \left(U\left[\tfrac{j-3}{2}\right] + U\left[\tfrac{j+3}{2}\right] \right) + 159 (U\left[\tfrac{j-1}{2}\right] + U\left[\tfrac{j+1}{2}\right]) \qquad (13)$$

Note, the 256 scale factor and the 128 offset from Equation 10 are not shown in the equation above whose purpose is **only** to illustrate how symmetry can be exploited. Naturally, the 256 scale factor and the 128 from offset from Equation 10 must be used when interpolating the odd samples for the U and V. Based on the above it can be concluded that the interpolation for the odd samples from the U and V planes can be done with **only 3, rather than 6, multiplications**.

Note also, interpolated U' and V' can take values above 255 and below 0. These interpolated values should **not** be clipped before passing them to the colourspace converter (only the final R, G, B values are clipped to 8 bits unsigned format in milestone 1).

In addition to the FIR filter implementation, we are faced with the challenge of sharing a multiplier for colourspace conversion. Figure 22 shows the straightforward way to implement Equation 11, with the advantage of high throughput (one full RGB pixel per clock cycle). However, due to the constraints of using only **two multipliers** for both interpolation and colourspace conversion, this solution is not suitable for our implementation.
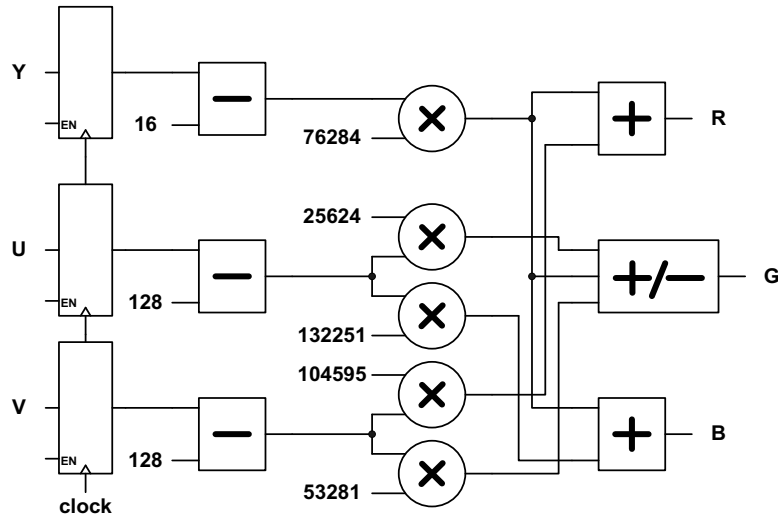
Figure 22. Resource inefficient colourspace conversion implementation.

In the same way that the MAC concept may be used to share multiplications for the FIR filters, it may be used for colourspace conversion. The data path for this is shown in Figure 23. In this case, the use of the mux between samples is sufficient since there are fewer samples from which to select, and the logic for the shift structure is not already in place as was the case for the FIR filter.
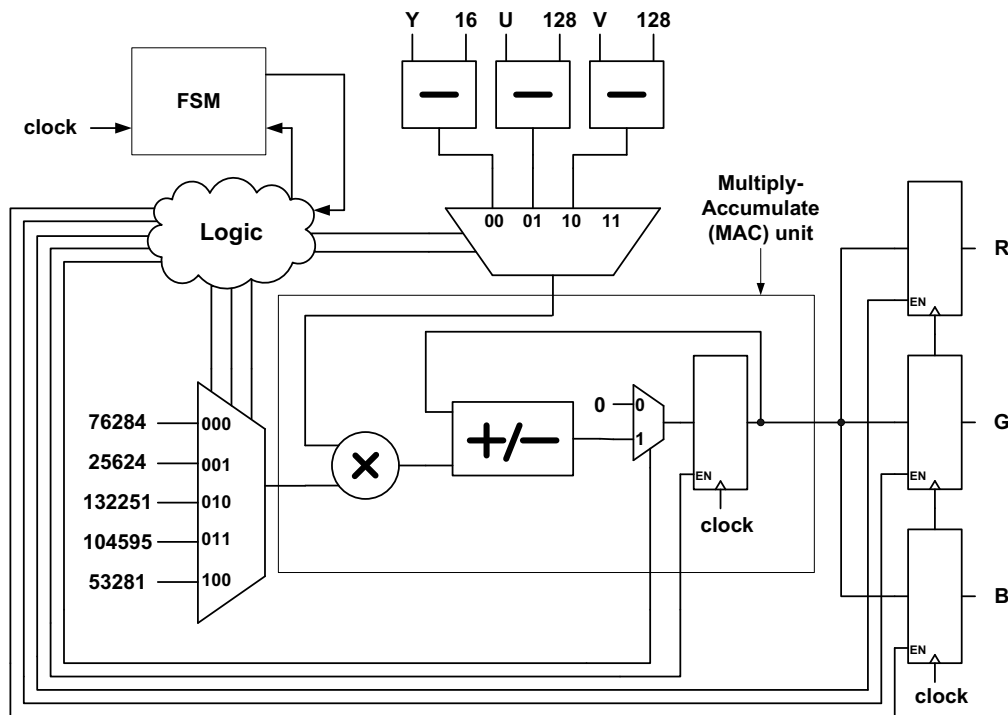
Figure 23. Resource efficient colourspace conversion implementation.

As emphasized during lab 5, state tables are a powerful way of capturing and synthesizing information about a state machine. Table 2 provides a good starting point for a state table that can be used for milestone 1. ***You are very strongly urged to use state tables throughout development, verification and debugging.***

State code / clock cycle	0	1	2	3	4	5	…
SRAM_address							
SRAM_read_data							
SRAM_write_data							
SRAM_we_n							
R							
G							
B							
Y							
U'							
U[(j+5)/2]							
U[(j-5)/2]							
V'							
V[(j+5)/2]							
V[(j+5)/2]							
…							

Table 2. A starting point for the state table in milestone 1.

As it is the case for any digital design project, one should not be wasteful with hardware resources. In your project report you will need to justify your design decisions, e.g., the need for registers, and their purpose.

4.3   Milestone 2: IDCT

Figure 24 shows the overview for milestone 2 which is the implementation of IDCT. As before, the shaded portions of the figure indicate what needs to be built or modified. In particular, notice that the FSM and the logic in the top state machine (bottom portion of the figure) do not need to be modified, since in the previous milestone you have made provision for the decoder circuitry (all of which will eventually reside in the block currently labeled "Partial Decoder") to access the SRAM.

As discussed in Section 4.1, the software model can be used to generate the necessary initialization and verification data for the SRAM. This data is used by the testbench for validation, and it can be sent to the board with a working design to get visual confirmation that the IDCT and upsampling and colourspace conversion are working together.
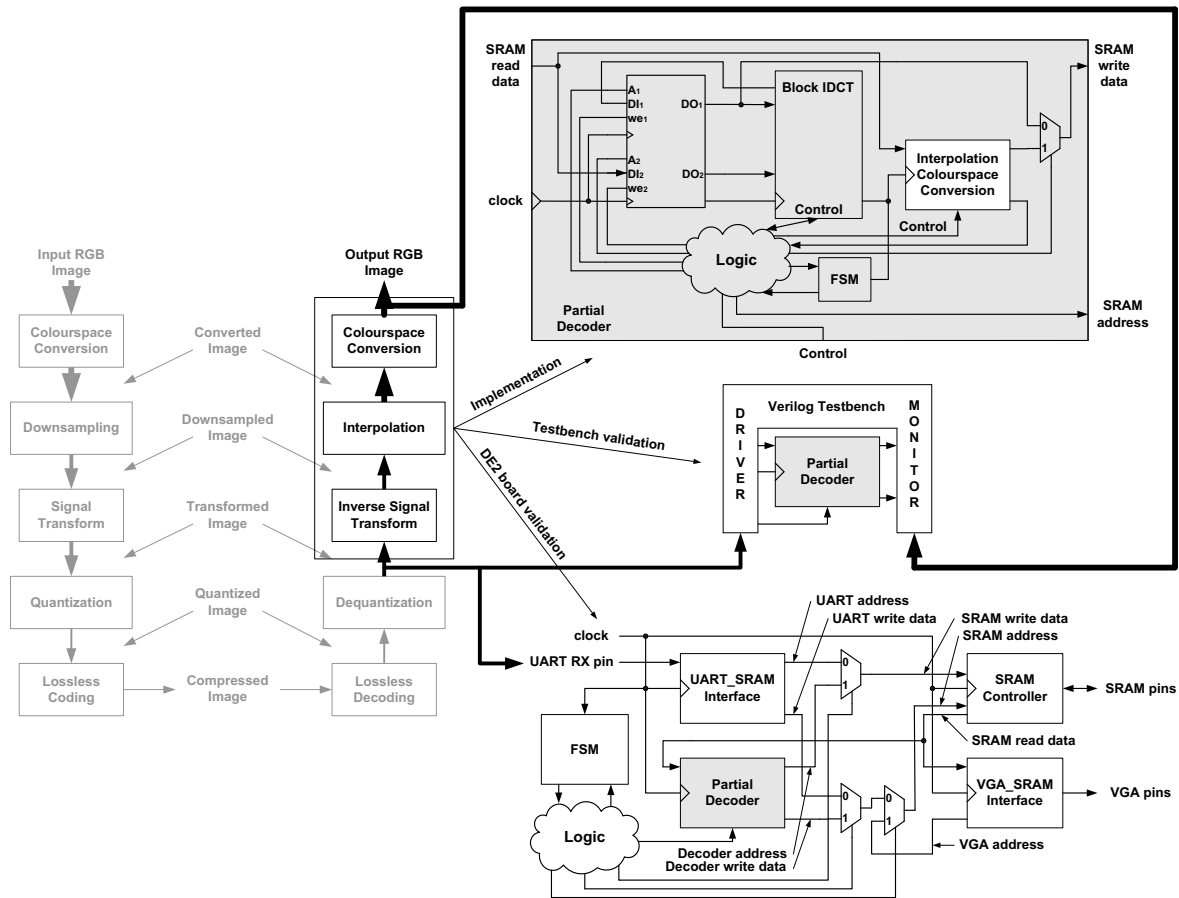
Figure 24. Overview of the IDCT implementation (milestone 2).

In Figure 25, the memory map for milestone 2 is provided, which is similar to that for milestone 1. The pre-IDCT data is stored as 1 value per memory location whereas the post-IDCT data (YUV) is stored as 2 values per memory location. Note that after IDCT is complete, the RGB data computed in milestone 1 will overwrite some the pre-IDCT data (used to initialize the SRAM for milestone 2).

Like milestone 1, the blocks are divided into segments of Y, segments of (downsampled) U, and segments of (downsampled) V. However, way the data is accessed is different. In milestone 2, we want to fetch an entire 8x8 block of pre-IDCT data, perform IDCT and write it back to the YUV memory space. To determine the addressing for writing post-IDCT samples back to the memory, observe Figure 12 and note that the block from block row 0, block column 0 of the Y plane (Y 0,0) contains data from row 0, row1, … row 7 of the image, all in columns 0 to 7 of the image. Extending this to the case of a 320x240 image, and noting that we have two samples per address, our write addressing for block 0 should be: 0 … 3, …, 1120 … 1123 (as shown in Figure 26). For the second block of the first block row (Y 0,1), we have: 4 … 7, …, 1124 … 1127. Once all the Y blocks have been processed, we proceed to U and V, with the important distinction that these two planes are downsampled and thus contain half the number of columns which Y contained. Thus U 0,0 would reside in addresses (38400+): 0 … 3, …, 560 … 563. The last block V 29,19 would reside in addresses (57600+): 18636 .. 18639, …, 19196 ... 19199.

0	YY
	Y segment
38,399	YY
38,400	UU
	U segment
57,599	UU
57,600	VV
	V segment
76,799	VV
76,800	
	YUV Pre-IDCT blocks
230,399	
230,400	
	Unused memory
262,143	

Two values per memory location
Location 0: the Y values for pixels 0 and 1 from the display area

Location 38,399: the Y values for pixels 320x240-2 and 320x240-1 (the display area is set to 320x240)

Location 76,799: the V values for pixels 160x240-2 and 160x240-1

SRAM memory map (256k locations with 16 bits per location)

Figure 25. Memory layout for milestone 2.

320 pixels – 320 addresses

240 pixels – 240 rows

**Pre-IDCT memory
Y segment: 320x240**

**Pre IDCT data:
one value per location, 320x240, offset 76800**

**Post IDCT data:
two values per location, 320x240, offset 0**

320 pixels – 160 addresses

240 pixels – 240 rows

**Post-IDCT memory
Y segment: 320x240**

76800	76801	...	76806	76807
Y0	Y1		Y6	Y7
77120				77127
Y320				Y327

0	1	2	3
Y0 Y1	Y2 Y3	Y4 Y5	Y6 Y7
160			163
Y320 Y321			Y326 Y327

78720			78727
Y1920			Y1927
79040	79041	...	79046	79047
Y2240	Y2241		Y2246	Y2247

Block IDCT

960			963
Y1920 Y1921			Y1926 Y1927
1120	1121	1122	1123
Y2240 Y2241	Y2242 Y2243	Y2244 Y2245	Y2246 Y2247

Figure 26. Reading pre-IDCT values and writing back YUV data to the external SRAM.

Like writing, the read addressing will also jump as we move from one pixel row to another within the same 8x8 block. However, now only 1 value is stored per memory location. To go across a row, the address simply increments. Within the same pixel column, to go down a pixel row (still within same 8x8 block), the address increases by 320 (for Y, but only by 160 for U and V). Finally we add the appropriate offset depending on which colour segment we are in. Thus to read block Y 0,0 we use addresses (76800+): 0 … 7, …, 2240 … 2247 (as in Figure 26). Likewise to read block Y 0,1 we use (76800+): 8 … 15, …, 2248 … 2255. On the next block row, to read block Y 1,0 we use (76800+): 2560 … 2567, …, 4800 … 4807. For the block U 0,0 we use (153600+): 0 … 7, …, 1120 … 1127 (please note for U and V we have half the columns, hence there are half the number of blocks per row).
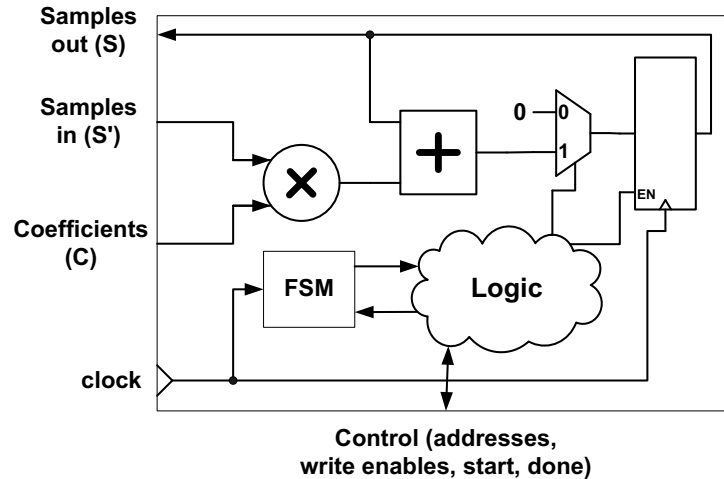
Figure 27. MAC unit for block IDCT.

Figure 27 shows a MAC unit which may be used for calculating part of the IDCT on a single block of samples. Recall that the IDCT is simply a pair of matrix multiplications. Since a matrix multiplication with a constant coefficient matrix is nothing more than the sum of a number of products of the samples with constants, the MAC unit will meet the architectural need. The role of the FSM is to initialize the accumulator at the appropriate times, and to set up the addresses properly to obtain the correct sample and coefficient in each clock cycle. Using such a unit, the pre- and post matrix multiplication can be done concurrently (the number of multipliers for this milestone is clarified below).

To facilitate a simple hardware implementation, we can read from dual-port memories both and the fixed point cosine coefficients (Equation 9) and the data value (pre-IDCT values or intermediate values after the first matrix multiplication). It is your task to determine a suitable memory layout for the dual-port RAMs. Because you are given this freedom, you must provide the appropriate .hex or .mif file to specify the dual-port memory initialization, in particular for the fixed-point cosine coefficients.

To maximize the utilization from the embedded memories, it is recommended that both ports are used and that the memory is organized on 32 bits per location (which is the maximum width allowed). It is your choice as to whether the results after the second matrix multiplication are written directly to the SRAM or buffered first in a dual-port RAM.

In this milestone, *you may use 3 dual-port RAMs (of 4Kb capacity and not more than 32 bits per location) and only 3 multipliers are allowed (with input operands on 32 bits or less).* Note also, *the average utilization of the 3 multipliers for milestone 2 must be at least 85%.*

You are encouraged to use a state table such as the one in Table 3 during your development.

State code / clock cycle	0	1	2	3	4	5	...
SRAM_address							
SRAM_read_data							
SRAM_write_data							
SRAM_we_n							
Address_0							
Data_in_0							
Write_en_0							
Data_out_0							
Address_1							
Data_in_1							
Write_en_1							
Data_out_1							
S							
S'							
C							
...							

Table 3. A starting point for the state table in milestone 2.

4.4   Milestone 3: Lossless Decoding and Dequantization
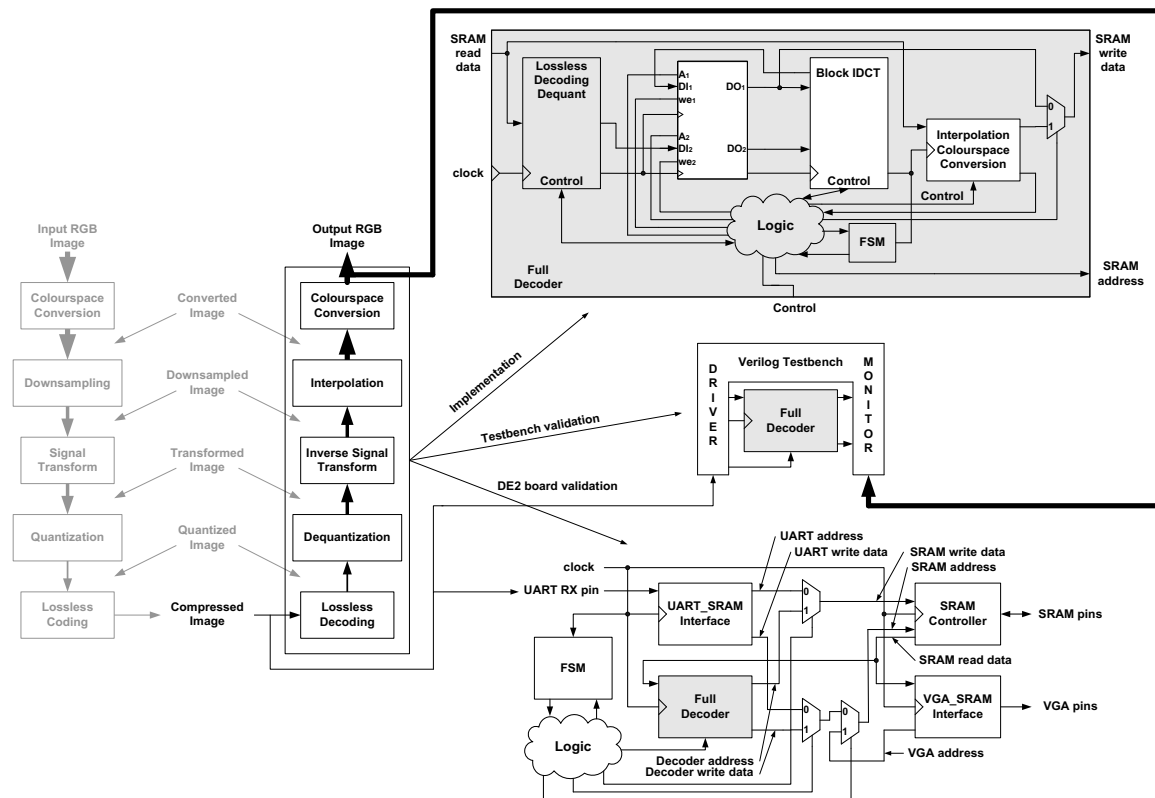
Figure 28. Lossless decoding, dequantization, and complete integration (milestone 3).

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Finally, once colourspace conversion, interpolation and IDCT are complete, we can move on to lossless decoding, where the compressed bitstream itself is parsed and the raw blocks are extracted and dequantized before being passed to the block IDCT, which completes the IDCT and writes the complete block of YUV data (belonging to the downsampled image of Figure 1) back to the SRAM. Once this milestone is complete, you will have a working image decoder.

SRAM memory map (256k locations with 16 bits per location)

0 YY ◄	**Two values per memory location** **Location 0: the Y values for pixels** **0 and 1 from the display area**
Y segment	
38,399 YY ◄	**Location 38,399: the Y values for** **pixels 320x240-2 and 320x240-1** **(the display area is set to 320x240)**
38,400 UU	
U segment	
57,599 UU	
57,600 VV	
V segment	
76,799 VV ◄	**Location 76,799: the V values for** **pixels 160x240-2 and 160x240-1**
76,800	
Compressed Image Bitstream	
76,800 + file_bytes/2 - 1	
76,800 + file_bytes/2	
Unused memory	
262,143	

Figure 29. Memory layout for milestone 3.

Because the decoding process works on blocks of 8x8, after a block is decoded, it is immediately passed to block IDCT (milestone 2) by buffering into an embedded memory that is written to by milestone 3 and read from by milestone 2. The SRAM read address logic from milestone 2 will no longer be needed when milestones 2 and 3 work concurrently. Nevertheless, it is very important to note that you are strongly recommended to get milestone 3 working independently before integrating it to work concurrently with milestone 2. This will give you the chance to first understand the functionality and work out the implementation details for the lossless decoder and the dequantizer, and only then you can focus on dealing with concurrency-related that will arise while doing the integration with milestone 2.

The memory layout for milestone 3 is shown above in Figure 29. No memory is allocated for the pre-IDCT data, rather this is processed by milestone 2 before being written back to the SRAM. After this, the RGB data generated by milestone 1 may overwrite the compressed image bitstream.

The basic decoding process is captured in Figure 8, at the beginning of the image decompression example. This flow chart can be used to construct a state table for guiding your state machine implementation. Part of the challenge of the lossless decoding is implementation of a serializer which enables extraction of the coefficient data, by reading 16 bit words stored in the SRAM and delivering them to the decoder in a serial fashion. Figure 30 shows the basic architecture of the serializer. A custom FSM is required to drive the SRAM address and to increment it only if all the bits have been extracted from the current memory location. A 32-bit shift-register can be used to buffer the data on-chip, as codes and values may span 2 memory locations. In each clock cycle, the mux network will

choose which bits from the location will be processed and therefore also shifted out of the 32-bit shift-register. Note the shifting of bits in this 32-bit buffer may happen over more than one clock cycle, depending on your FSM (for example, we may shift out 6 bits by doing a shift by 3 on two consecutive clock cycles).
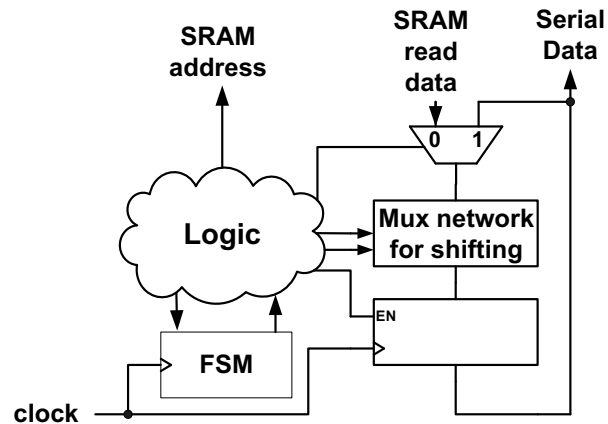

Figure 30. SRAM data serialized for extracting coefficients.

Once the coefficients have been extracted they must be dequantized before being placed in the dual-port RAM to await the block IDCT. Due to the special structure of the two possible quantization matrices (as in Equation 3), which contain only powers of two, a barrel shifter structure can be used to implement the dequantization (the type of the quantization matrix must also be used as an input to this barrel shifter). Furthermore, note the scan sequence of Figure 4 must be implemented so that the values are delivered from the bitstream to the correct locations in the 8x8 block.

To facilitate an easier integration between block IDCT and lossless decoding and quantization, **_you are allowed one extra dual-port RAM (of 4Kb capacity and not more than 32 bits per location), thus a total of 4 dual-port RAMs can be used in milestones 2 and 3 together_**. This extra RAM can be used for loading the out-of-order pre-IDCT values, and then during the clock cycles when milestone 2 does not need to fetch pre-IDCT values, the content from this extra embedded RAM can be loaded into the embedded RAM shared between milestones 2 and 3. You may also choose to write directly to the embedded RAM shared between milestones 2 and 3 (without the additional embedded RAM), however this requires more design effort to ensure no scheduling conflicts between writing from milestone 3 and reading from milestone 2.

To handle a runs of zeros, there are two basic approaches. One method is to simply write a sequence of zeros when it happens (in different memory locations, and thus over several clocks). The other method is to initialize all values to zero, and then when a run of zeros is decoded, we can skip over that many memory locations.

Finally, successful implementation of the lossless decoding and dequantization relies heavily on getting your state machine to work properly, and synchronizing the signals between the state machine and the dual-port RAMs (used for IDCT), the serializer, the top level state machine, etc.

ENJOY!

5 Appendix A: Summary of Data Flow and Constraints

The 3DQ5 project must compile in Quartus and it is expected to operate correctly at the 50 MHz clock frequency.

5.1 Milestone 1

Input: data is represented as *8 bits unsigned*. Each SRAM location contains 2 values. There are separate sections for Y, U, and V. Within each section data is stored in raster-scan order (across first, then down).

Computation: it is advised to do *all arithmetic on 32 bits signed*. Upsample the odd values of U and V (no clipping here). Each pixel is independently converted from YUV to RGB, after this clipping to *8 bits unsigned* is done. In this milestone you **must exploit the symmetry in the interpolation filter** and use only *2 multipliers* with at least 85% utilization.

$$U'[j] = \begin{cases} U\left[\frac{j}{2}\right] & j\ even \\ (int)\frac{1}{256}\left(21U\left[\frac{j-5}{2}\right] - 52U\left[\frac{j-3}{2}\right] + 159U\left[\frac{j-1}{2}\right] + 159U\left[\frac{j+1}{2}\right] - 52U\left[\frac{j+3}{2}\right] + 21U\left[\frac{j+5}{2}\right] + 128\right) & j\ odd \end{cases}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = (int)\frac{1}{65536}\left(\begin{bmatrix} 76284 & 0 & 104595 \\ 76284 & -25624 & -53281 \\ 76284 & 132251 & 0 \end{bmatrix}\left(\begin{bmatrix} Y \\ U' \\ V' \end{bmatrix} - \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix}\right)\right)$$

Output: each of R, G and B are *8 bits unsigned*. Data for 2 pixels requires 3 SRAM locations to store. The memory layout of the RGB segment resembles lab 5 experiment 1 (see Figure 17 for starting address).

5.2 Milestone 2

Input: data is represented as *16 bits signed*.

Computation: it is advised to do *all arithmetic on 32 bits signed*. There are 2 matrix multiplications per output 8x8 block, after which each value is clipped to *8 bits unsigned*. Take note of the SRAM access pattern since data is processed in blocks of 8x8. *Up to 3 dual-port memories* (of 4Kb capacity and not more than 32 bits per location) can be used and it is your choice on how these are organized. In this milestone you must use *3 multipliers* with at least 85% utilization.

$$S = (int)\frac{1}{65536}\left(C^T \times (int)\frac{1}{256}(S'C)\right)$$

Output: *8 bits unsigned* values are written to the SRAM, 2 values per SRAM location.

5.3 Milestone 3

Input: the .mic15 file is a *bitstream*, to get the next bit we go from most significant bit to least significant bit within the same SRAM location, then only go to the next SRAM location.

Computation: decode each 8x8 block independently. Each prefix code may produce several values. Values are processed in the zigzag order for each block. For each value, once the position in the 8x8 block is known, dequantization is applied. Which quantization matrix to use must be extracted from the .mic15 header. *One extra dual-port memory* (same as the 3 memories from milestone 2) may be used.

Output: each dequantized value is represented as *16 bits signed*. Before you integrate milestone 3 into milestone 2, it is strongly recommended that you implement it separately, in which case take note of the SRAM access pattern since data is processed in blocks of 8x8.