APPLICATION NOTE

JPEG ALGORITH BASELINE ON EMBEDDED SYSTEMS

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INTRODUCTION

This Application Note concerns the algorithm for the sequential DCT-based mode of operation: 8 x 8 sample blocks. After a block has been transformed by the forward DCT, quantized and prepared for entropy encoding, all 64 of its quantized DCT coefficients can be immediately entropy encoded and output as part of the compressed image data, in order to minimize storage requirements.

This algorithm is described figure 1:

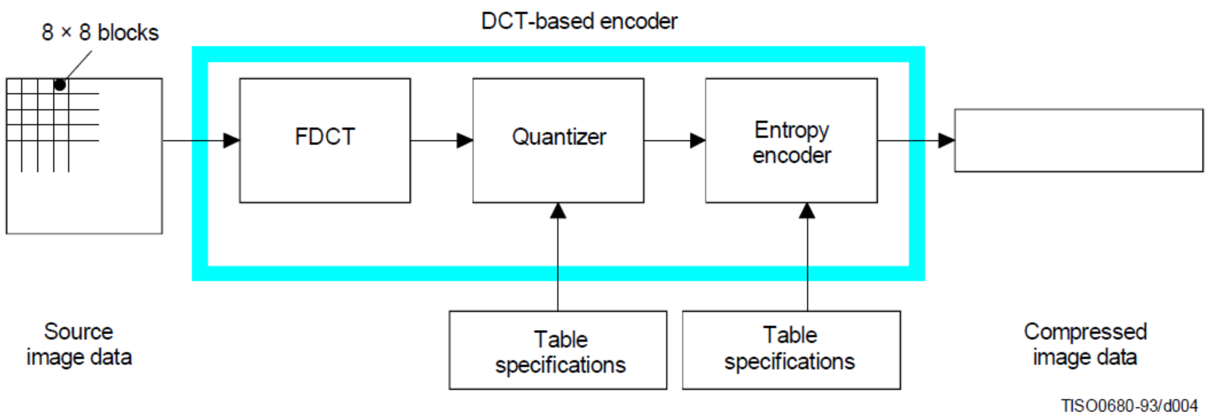


Figure 1 : Algorithm of JPEG

DOWNSAMPLING

For the JPEG, the image must be in YCbCr (RGB should be converted), the Y is for the luminance, the Cb for the Chrominance blue and Cr for the Chrominance red. The human the eye seems to be more sensitive at the luminance (Y) of a colour than at the nuance (Cb or Cr) of that colour. Thanks to this, encoders can be designed to compress images more efficiently. The Cb and Cr are reduced, the ratios at which the downsampling is usually done for JPEG images are 4:4:4 (no downsampling), 4:2:2 (reduction by a factor of 2 in the horizontal direction), or (most commonly) 4:2:0 (reduction by a factor of 2 in both the horizontal and vertical directions) as in figure 2.

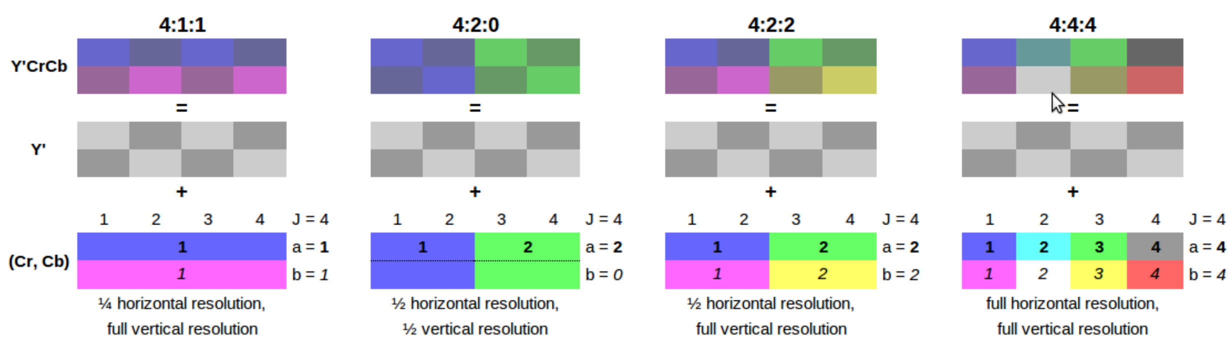
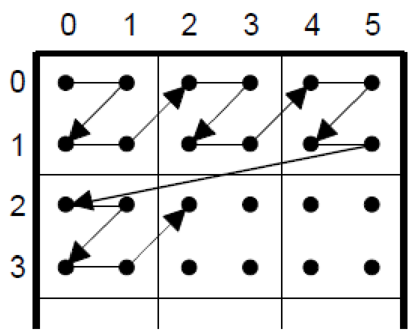


Figure 2 : Downsampling components

Next, components Y, Cb and Cr will be process separately but with a similar manner.

BLOCK SPLITTING

After the downsampling, each components must be split into 8x8 blocks, it means if the number of pixels is not a multiple of 8 the encoding process shall extend the number of columns to complete the right-most sample blocks with the right-most column of the image and extend the number of lines to complete the bottom-most block-row with the bottom-most line of the original image. These blocks will be treated in the order figure 3.



1st: Block [0][0]

2nd: Block [0][1]

3rd: Block [1][0]

4th: Block [1][1]

5th: Block [0][2]

Etc

Figure 3 : Order of process for the blocks

Depending on chroma subsampling:

- For 4:4:4 no subsampling : (Minimum Coded Unit) MCU blocks of size 8x8
- For 4:2:2 blocks of size 16×8 (figure 4)
- For 4:2:0 blocks of size 16x16 (figure 5)

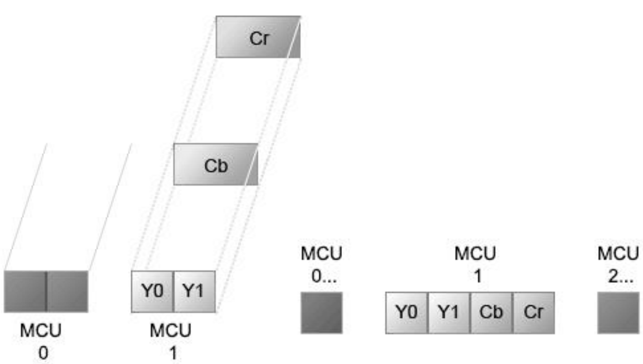


Figure 4 : Compression 4:2:2

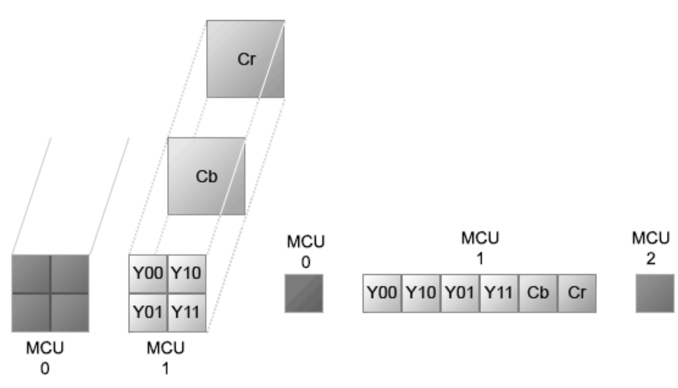


Figure 5 : Compression 4:2:0

DISCRETE COSINE TRANSFORM

Next, each 8×8 block of each component (Y, Cb,Cr) is converted to a frequency-domain representation. Before the DCT, All 8-bit unsigned values (Y,Cb,Cr) in the image are "level shifted": they are converted to an 8-bit signed representation, by subtracting 128 from their value.

$$G_{u,v} = \frac{1}{4}\alpha(u)\alpha(v)\sum_{x=0}^{7}\sum_{y=0}^{7} g_{x,y} \cos\left[\frac{(2x+1)u\pi}{16}\right] \cos\left[\frac{(2y+1)v\pi}{16}\right]$$

u is the horizontal spatial frequency, for the integers $0 \leq u < 8$.

v is the vertical spatial frequency, for the integers $0 \leq v < 8$.

$\alpha(u) = \begin{cases} \frac{1}{\sqrt{2}}, & \text{if } u = 0 \\ 1, & \text{otherwise} \end{cases}$ is a normalizing scale factor to make the transformation orthonormal

$g_{x,y}$ is the pixel value at coordinates (x, y)

$G_{u,v}$ is the DCT coefficient at coordinates (u, v).

QUANTIZATION

After the DCT is computed for a block, each of the 64 resulting DCT coefficients is quantized by a uniform quantizer. This allows one to greatly reduce the amount of information in the high frequency components. Each value in the 8x8 block is divided by a constant for that component (quantization tables are not for the Y and the CbCr). Example of matrix of quantization figure 6:

$$Q = \begin{bmatrix} 16 & 11 & 10 & 16 & 24 & 40 & 51 & 61 \\ 12 & 12 & 14 & 19 & 26 & 58 & 60 & 55 \\ 14 & 13 & 16 & 24 & 40 & 57 & 69 & 56 \\ 14 & 17 & 22 & 29 & 51 & 87 & 80 & 62 \\ 18 & 22 & 37 & 56 & 68 & 109 & 103 & 77 \\ 24 & 35 & 55 & 64 & 81 & 104 & 113 & 92 \\ 49 & 64 & 78 & 87 & 103 & 121 & 120 & 101 \\ 72 & 92 & 95 & 98 & 112 & 100 & 103 & 99 \end{bmatrix}.$$

Figure 6 : Matrix of quantization for the luminance

THE ZIG ZAG

Then the 64 blocks component are arranging in zig zag order to have a vector of 64 values, as in figure 7:

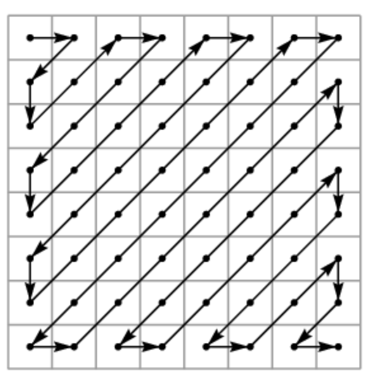


Figure 7 : Zig-Zag algorithm

THE RLE

On this new vector of 64 coefficient is employing the run-length encoding (RLE) algorithm, in order to groups similar frequencies together, inserting length coding zeros. The first coefficient of the vector (the DC coefficient) is coded a bit differently than for the 63 others (AC).

Example: let's say the vector of 64 values:

450,57,45,0,0,0,0,23,0,-30,-16,0,0,1,0,0,0, 0 , 0 ,0 , only 0,..,0

-The First value 450 is the DC, it will be treat later.

-The AC coefficients are processed : (0,57) ; (0,45) ; (4,23) ; (1,-30) ; (0,-16) ; (2,1) ; EOB

Nb: The JPG Huffman coding makes the restriction (you'll see later why) that the number of previous 0's to be coded as a 4-bit value, so it can't overpass the value 15 (0xF). (15,0) is a special coded value which indicates that there follows 16 consecutive zeroes.

HUFFMAN CODING

This is the final step for the entropy code of the block. Huffman Coding is a statistical technique that attempts to reduce the number of bits required. The encoding process is not exactly the same for the DC and AC.

THE AC COEFFICIENTS

First the value of the AC will be compare to a table (figure 8) and transcode the value so that it can be stored with the minimum size in bits.

Values	Category	Bits for the value
0	0	-
-1,1	1	0,1
-3,-2,2,3	2	00,01,10,11
-7,-6,-5,-4,4,5,6,7	3	000,001,010,011,100,101,110,111
-15,..,-8,8,..,15	4	0000,..,0111,1000,..,1111
-31,..,-16,16,..,31	5	00000,..,01111,10000,..,11111
-63,..,-32,32,..,63	6	.
-127,..,-64,64,..,127	7	.
-255,..,-128,128,..,255	8	.
-511,..,-256,256,..,511	9	.
-1023,..,-512,512,..,1023	10	.

Figure 8 : Value and category

For the previous example: (0,57) ; (0,45) ; (4,23) ; (1,-30) ; (0,-8) ; (2,1) ; (0,0)

- 57 is in the category 6 and it is bit-coded 11100, so we'll encode it like (6, 111001)
- 45, similar, will be coded as (6, 101101), etc

The strings of pairs will be: (0,6), 111001 ; (0,6), 101101 ; (4,5), 10111; (1,5), 00001; (0,4) , 0111 ; (2,1), 1 ; (0,0)

The 2 values in the bracket will be use to get the Huffman code in the Table for luminance (or Chrominance) AC coefficients. The category will have a special code, the JPEG standard provide tables for the DC luminance (Annex figure 19), AC luminance (Annex figure 22), DC chrominance (Annex figure 20), AC chrominance (Annex figure 23)

Example: with the (0,6), 111001; the equivalent of (0,6) is the Huffman code = 111000 so at the end the code for 57 will be : 111000 111001

This process is the same for the 63 AC coefficients, then this code is writing in the JPG file, as a stream of bits: the Huffman code of this byte, followed by the remaining bit-representation of that number.

THE DC COEFFICIENT

DC is the coefficient in the quantized vector corresponding to the lowest frequency in the image, it's like an average value for that block of image samples. There's a close connection between the DC coefficient of consecutive blocks, so the JPEG standard request to subtract the DC_i with the DC_{i-1} and encode in the JPG file the difference between the DCs of consecutive 8x8 blocks (figure 9).

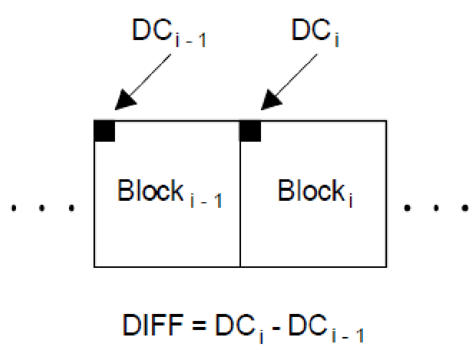


Figure 9 : Difference with the DC

NB: the first DC coefficient can't be subtract with the DC before. This first DC_{i-1} will be equal to 0.

Then the process will be the same as for the AC coefficient except that the value to encode will be the difference, and this time the Huffman table used are the one for the DC coefficients (one for the luminance and one for the 2 chrominances):

Diff = (category, bit-coded representation)

Then Diff will be coded as (Huffman_code(category) , bit-coded representation).

And in the final JPEG file, the DC are encoded first then the ACs.

THE MARKERS

Markers serve to identify the different parts of the compressed data formats. All markers are assigned two-byte codes: an X'FF' byte followed by a byte which is not equal to 0 or X'FF.

NB: In the entropy coded segment of the image, if an 0xFF appear, the JPEG standart demands to add a 0x00 after the 0xFF in order to ensure that a marker does not occur within an entropy-coded segment.

The position of the different markers are in the figure 10

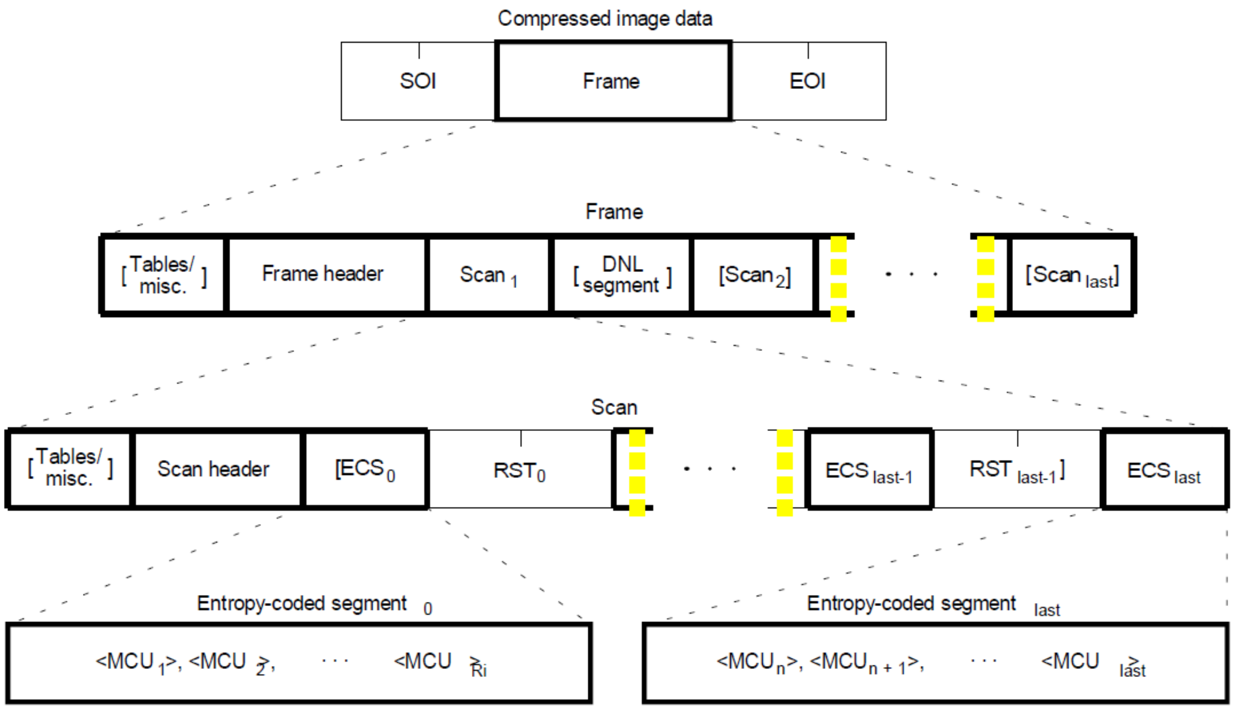


Figure 10: Markers in an image

The marquers obligatory are :

- SOI: Start of image marker – Marks the start of a compressed image represented in the interchange format or abbreviated format, first information in the JPEG file. For the Baseline DCT : SOI = xFF D8

- EOI: End of image marker – Marks the end of a compressed image represented in the interchange format or abbreviated format, last information in the JPEG file.. For the Baseline DCT : EOI = xFF D9

For most of the markers, there also some informations to add like the length indicators, ordering, optional indicators…

The other markers to add are:

QUANTIZATION TABLE-SPECIFICATION

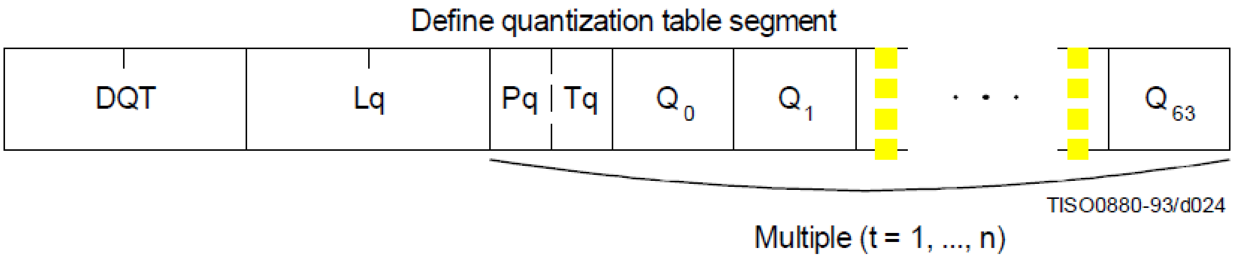


Figure 11 : Quantization marker

Parameter	Size (bits)	Values		
		Sequential DCT		Progressive DCT
		Baseline	Extended	
Lq	16	$2 + \sum_{t=1}^{n} (65 + 64 \times Pq(t))$		
Pq	4	0	0, 1	0, 1
Tq	4	0-3		
Qk	8, 16	1-255, 1-65 535		

Figure 12 : parameters for the DQT marker

DQT: Define quantization table marker – Marks the beginning of quantization table-specification parameters. xFF DB

Lq: Quantization table definition length – Specifies the length of all quantization table parameters shown in figure 12

Pq: Quantization table element precision – Specifies the precision of the Qk values. Value 0 indicates 8-bit Qk values; value 1 indicates 16-bit Qk values.

Tq: Quantization table destination identifier – Specifies one of four possible destinations at the decoder into which the quantization table shall be installed.

Qk: Quantization table element – Specifies the 64 elements. The quantization elements shall be specified in zig-zag scan order.

START OF FRAME MARKERS FOR BASELINE

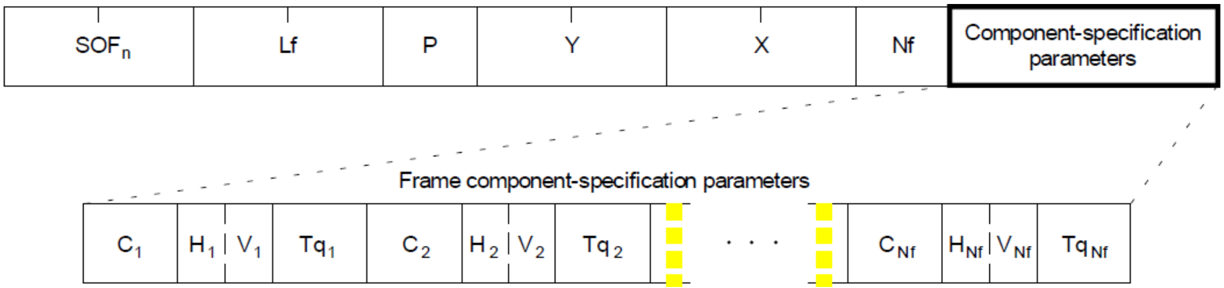


Figure 14 : Frame header

Parameter	Size (bits)	Values			
		Sequential DCT		Progressive DCT	Lossless
		Baseline	Extended		
Lf	16	$8 + 3 \times \text{Nf}$			
P	8	8	8, 12	8, 12	2-16
Y	16	0-65 535			
X	16	1-65 535			
Nf	8	1-255	1-255	1-4	1-255
C_i	8	0-255			
H_i	4	1-4			
V_i	4	1-4			
Tq_i	8	0-3	0-3	0-3	0

Figure 13 : Parameters for the frame header

SOF0: Start of frame marker – Marks the beginning of the frame parameters for baseline DCT

Lf: Frame header length – Specifies the length of the frame header.

P: Sample precision – Specifies the precision in bits for the samples of the components in the frame.

Y: Number of lines – Specifies the maximum number of lines in the source image.

X: Number of samples per line – Specifies the maximum number of samples per line in the source image.

Nf: Number of image components in frame – Specifies the number of source image components in the frame.

Ci: Component identifier – Assigns a unique label to the i^{th} component in the sequence of frame component specification parameters.

Hi: Horizontal sampling factor – Specifies the relationship between the component horizontal dimension and maximum image dimension X.

Vi: Vertical sampling factor – Specifies the relationship between the component vertical dimension and maximum image dimension Y.

Tqi: Quantization table destination selector – Specifies one of four possible quantization table destinations from which the quantization table to use for dequantization of DCT coefficients of component Ci is retrieved.

HUFFMAN TABLE MARKER

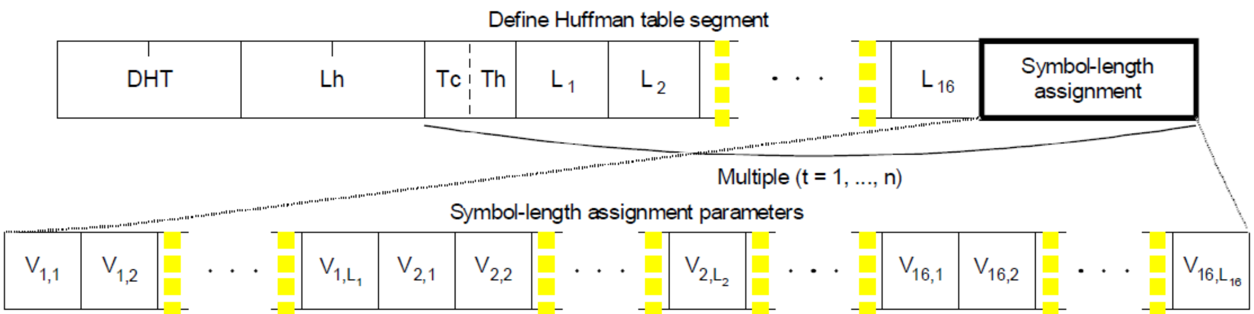


Figure 16 : Huffman table marker

Parameter	Size (bits)	Values			
		Sequential DCT		Progressive DCT	Lossless
		Baseline	Extended		
Lh	16	$2 + \sum_{t=1}^{n} (17 + m_t)$			
Tc	4	0, 1			0
Th	4	0, 1	0-3		
L_i	8	0-255			
$V_{i,j}$	8	0-255			

Figure 15 : Huffman table parameters

DHT: Define Huffman table marker – Marks the beginning of Huffman table definition parameters.

Lh: Huffman table definition length – Specifies the length of all Huffman table parameters.

Tc: Table class – 0 = DC table or lossless table, 1 = AC table.

Th: Huffman table destination identifier – Specifies one of four possible destinations at the decoder into which the Huffman table shall be installed.

L_i: Number of Huffman codes of length i – Specifies the number of Huffman codes for each of the 16 possible lengths allowed by this Specification. L_i's are the elements of the list BITS.

$V_{i,j}$: Value associated with each Huffman code – Specifies, for each i, the value associated with each Huffman code of length i.

The JPEG standard provide markers for the DC luminance (Annex figure 19), AC luminance (Annex figure 22), DC chrominance (Annex figure 20), AC chrominance (Annex figure 23)

SCAN HEADER

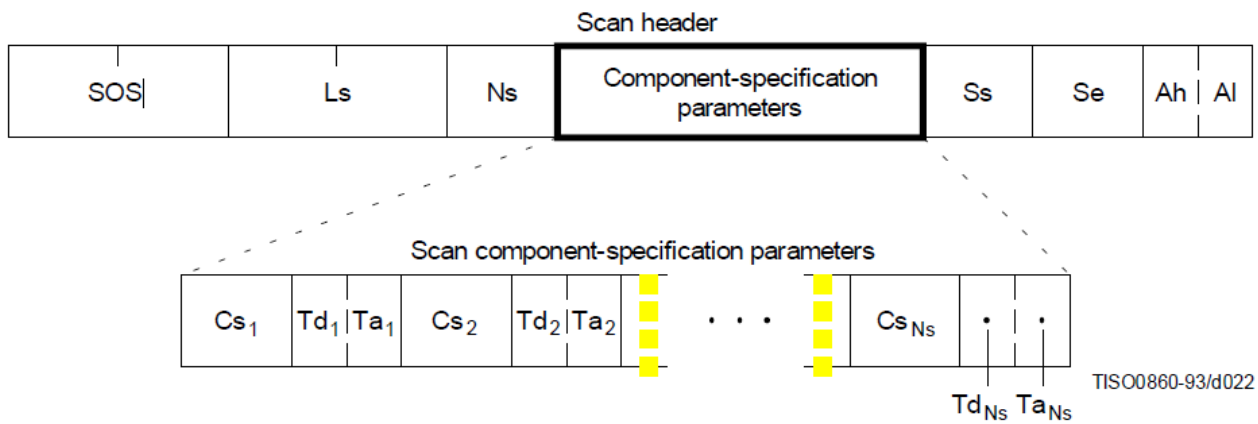


Figure 18 : Scan Header marker

Parameter	Size (bits)	Values			
		Sequential DCT		Progressive DCT	Lossless
		Baseline	Extended		
Ls	16	$6 + 2 \times Ns$			
Ns	8	1-4			
Cs_j	8	0-255 a)			
Td_j	4	0-1	0-3	0-3	0-3
Ta_j	4	0-1	0-3	0-3	0
Ss	8	0	0	0-63	1-7 b)
Se	8	63	63	Ss-63 c)	0
Ah	4	0	0	0-13	0
Al	4	0	0	0-13	0-15

a) Cs_j shall be a member of the set of C_i specified in the frame header.
b) 0 for lossless differential frames in the hierarchical mode (see B.3).
c) 0 if Ss equals zero.

Figure 17 : Scan header parameters

SOS: Start of scan marker – Marks the beginning of the scan parameters.

Ls: Scan header length – Specifies the length of the scan header.

Ns: Number of image components in scan – Specifies the number of source image components in the scan. The value of Ns shall be equal to the number of sets of scan component specification parameters (Csj, Tdj, and Taj) present in the scan header.

Csj: Scan component selector – Selects which of the Nf image components specified in the frame parameters shall be the jth component in the scan.

Tdj: DC entropy coding table destination selector – Specifies one of four possible DC entropy coding table destinations from which the entropy table needed for decoding of the DC coefficients of component Csj is retrieve

Category	Code length	Code word
0	2	00
1	3	010
2	3	011
3	3	100
4	3	101
5	3	110
6	4	1110
7	5	11110
8	6	111110
9	7	1111110
10	8	11111110
11	9	111111110

Figure 19 : Table for luminance DC coefficient differences

For figure 19 (for luminance DC coefficients), the 16 bytes which specify the list of code lengths for the table are:

X’00 01 05 01 01 01 01 01 01 00 00 00 00 00 00 00 00 01 02 03 04 05 06 07 08 09 0A 0B’

Category	Code length	Code word
0	2	00
1	2	01
2	2	10
3	3	110
4	4	1110
5	5	11110
6	6	111110
7	7	1111110
8	8	11111110
9	9	111111110
10	10	1111111110
11	11	11111111110

Figure 21 : Table for chrominance DC coefficient differences

For figure 20 (for chrominance DC coefficients), the 16 bytes which specify the list of code lengths for the table are:

X’00 03 01 01 01 01 01 01 01 01 01 00 00 00 00 00 01 02 03 04 05 06 07 08 09 0A 0B’

Run/Size	Code length	Code word
0/0 (EOB)	4	1010
0/1	2	00
0/2	2	01
0/3	3	100
0/4	4	1011
0/5	5	11010
0/6	7	1111000
0/7	8	11111000
0/8	10	1111110110
0/9	16	1111111110000010
0/A	16	1111111110000011
1/1	4	1100
1/2	5	11011
1/3	7	1111001
1/4	9	111110110
1/5	11	11111110110
1/6	16	1111111110000100
1/7	16	1111111110000101
1/8	16	1111111110000110
1/9	16	1111111110000111
1/A	16	1111111110001000
2/1	5	11100
2/2	8	11111001
2/3	10	1111110111
2/4	12	111111110100
2/5	16	1111111110001001
2/6	16	1111111110001010
2/7	16	1111111110001011
2/8	16	1111111110001100
2/9	16	1111111110001101
2/A	16	1111111110001110
3/1	6	111010
3/2	9	111110111
3/3	12	111111110101
3/4	16	1111111110001111
3/5	16	1111111110010000
3/6	16	1111111110010001
3/7	16	1111111110010010
3/8	16	1111111110010011
3/9	16	1111111110010100
3/A	16	1111111110010101

Figure 22 : Table for luminance AC coefficients (sheet 1 of 4)

Run/Size	Code length	Code word
4/1	6	111011
4/2	10	1111111000
4/3	16	1111111110010110
4/4	16	1111111110010111
4/5	16	1111111110011000
4/6	16	1111111110011001
4/7	16	1111111110011010
4/8	16	1111111110011011
4/9	16	1111111110011100
4/A	16	1111111110011101
5/1	7	1111010
5/2	11	11111110111
5/3	16	1111111110011110
5/4	16	1111111110011111
5/5	16	1111111110100000
5/6	16	1111111110100001
5/7	16	1111111110100010
5/8	16	1111111110100011
5/9	16	1111111110100100
5/A	16	1111111110100101
6/1	7	1111011
6/2	12	111111110110
6/3	16	1111111110100110
6/4	16	1111111110100111
6/5	16	1111111110101000
6/6	16	1111111110101001
6/7	16	1111111110101010
6/8	16	1111111110101011
6/9	16	1111111110101100
6/A	16	1111111110101101
7/1	8	11111010
7/2	12	111111110111
7/3	16	1111111110101110
7/4	16	1111111110101111
7/5	16	1111111110110000
7/6	16	1111111110110001
7/7	16	1111111110110010
7/8	16	1111111110110011
7/9	16	1111111110110100
7/A	16	1111111110110101
8/1	9	111111000
8/2	15	111111111000000

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Run/Size	Code length	Code word
8/3	16	1111111110110110
8/4	16	1111111110110111
8/5	16	1111111110111000
8/6	16	1111111110111001
8/7	16	1111111110111010
8/8	16	1111111110111011
8/9	16	1111111110111100
8/A	16	1111111110111101
9/1	9	111111001
9/2	16	1111111110111110
9/3	16	1111111110111111
9/4	16	1111111111000000
9/5	16	1111111111000001
9/6	16	1111111111000010
9/7	16	1111111111000011
9/8	16	1111111111000100
9/9	16	1111111111000101
9/A	16	1111111111000110
A/1	9	111111010
A/2	16	1111111111000111
A/3	16	1111111111001000
A/4	16	1111111111001001
A/5	16	1111111111001010
A/6	16	1111111111001011
A/7	16	1111111111001100
A/8	16	1111111111001101
A/9	16	1111111111001110
A/A	16	1111111111001111
B/1	10	1111111001
B/2	16	1111111111010000
B/3	16	1111111111010001
B/4	16	1111111111010010
B/5	16	1111111111010011
B/6	16	1111111111010100
B/7	16	1111111111010101
B/8	16	1111111111010110
B/9	16	1111111111010111
B/A	16	1111111111011000
C/1	10	1111111010
C/2	16	1111111111011001
C/3	16	1111111111011010
C/4	16	1111111111011011

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Run/Size	Code length	Code word
C/5	16	1111111111011100
C/6	16	1111111111011101
C/7	16	1111111111011110
C/8	16	1111111111011111
C/9	16	1111111111100000
C/A	16	1111111111100001
D/1	11	11111111000
D/2	16	1111111111100010
D/3	16	1111111111100011
D/4	16	1111111111100100
D/5	16	1111111111100101
D/6	16	1111111111100110
D/7	16	1111111111100111
D/8	16	1111111111101000
D/9	16	1111111111101001
D/A	16	1111111111101010
E/1	16	1111111111101011
E/2	16	1111111111101100
E/3	16	1111111111101101
E/4	16	1111111111101110
E/5	16	1111111111101111
E/6	16	1111111111110000
E/7	16	1111111111110001
E/8	16	1111111111110010
E/9	16	1111111111110011
E/A	16	1111111111110100
F/0 (ZRL)	11	11111111001
F/1	16	1111111111110101
F/2	16	1111111111110110
F/3	16	1111111111110111
F/4	16	1111111111111000
F/5	16	1111111111111001
F/6	16	1111111111111010
F/7	16	1111111111111011
F/8	16	1111111111111100
F/9	16	1111111111111101
F/A	16	1111111111111110

Sheet 4 of 4

For figure 22 (for luminance AC coefficients), the 16 bytes which specify the list of code lengths for the table are:

X’00 02 01 03 03 02 04 03 05 05 04 04 00 00 01 7D’

The set of values which follows this list is

X’01 02 03 00 04 11 05 12 21 31 41 06 13 51 61 07
22 71 14 32 81 91 A1 08 23 42 B1 C1 15 52 D1 F0
24 33 62 72 82 09 0A 16 17 18 19 1A 25 26 27 28
29 2A 34 35 36 37 38 39 3A 43 44 45 46 47 48 49
4A 53 54 55 56 57 58 59 5A 63 64 65 66 67 68 69
6A 73 74 75 76 77 78 79 7A 83 84 85 86 87 88 89
8A 92 93 94 95 96 97 98 99 9A A2 A3 A4 A5 A6 A7
A8 A9 AA B2 B3 B4 B5 B6 B7 B8 B9 BA C2 C3 C4 C5
C6 C7 C8 C9 CA D2 D3 D4 D5 D6 D7 D8 D9 DA E1 E2
E3 E4 E5 E6 E7 E8 E9 EA F1 F2 F3 F4 F5 F6 F7 F8
F9 FA’

Run/Size	Code length	Code word
0/0 (EOB)	2	00
0/1	2	01
0/2	3	100
0/3	4	1010
0/4	5	11000
0/5	5	11001
0/6	6	111000
0/7	7	1111000
0/8	9	111110100
0/9	10	1111110110
0/A	12	111111110100
1/1	4	1011
1/2	6	111001
1/3	8	11110110
1/4	9	111110101
1/5	11	11111110110
1/6	12	111111110101
1/7	16	1111111110001000
1/8	16	1111111110001001
1/9	16	1111111110001010
1/A	16	1111111110001011
2/1	5	11010
2/2	8	11110111
2/3	10	1111110111
2/4	12	111111110110
2/5	15	111111111000010
2/6	16	1111111110001100
2/7	16	1111111110001101
2/8	16	1111111110001110
2/9	16	1111111110001111
2/A	16	1111111110010000
3/1	5	11011
3/2	8	11111000
3/3	10	1111111000
3/4	12	111111110111
3/5	16	1111111110010001
3/6	16	1111111110010010
3/7	16	1111111110010011
3/8	16	1111111110010100
3/9	16	1111111110010101
3/A	16	1111111110010110
4/1	6	111010

Figure 23 : Table for Chrominance AC coefficients (sheet 1 of 4)

Run/Size	Code length	Code word
4/2	9	111110110
4/3	16	1111111110010111
4/4	16	1111111110011000
4/5	16	1111111110011001
4/6	16	1111111110011010
4/7	16	1111111110011011
4/8	16	1111111110011100
4/9	16	1111111110011101
4/A	16	1111111110011110
5/1	6	111011
5/2	10	1111111001
5/3	16	1111111110011111
5/4	16	1111111110100000
5/5	16	1111111110100001
5/6	16	1111111110100010
5/7	16	1111111110100011
5/8	16	1111111110100100
5/9	16	1111111110100101
5/A	16	1111111110100110
6/1	7	1111001
6/2	11	11111110111
6/3	16	1111111110100111
6/4	16	1111111110101000
6/5	16	1111111110101001
6/6	16	1111111110101010
6/7	16	1111111110101011
6/8	16	1111111110101100
6/9	16	1111111110101101
6/A	16	1111111110101110
7/1	7	1111010
7/2	11	11111111000
7/3	16	1111111110101111
7/4	16	1111111110110000
7/5	16	1111111110110001
7/6	16	1111111110110010
7/7	16	1111111110110011
7/8	16	1111111110110100
7/9	16	1111111110110101
7/A	16	1111111110110110
8/1	8	11111001
8/2	16	1111111110110111
8/3	16	1111111110111000

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Run/Size	Code length	Code word
8/4	16	1111111110111001
8/5	16	1111111110111010
8/6	16	1111111110111011
8/7	16	1111111110111100
8/8	16	1111111110111101
8/9	16	1111111110111110
8/A	16	1111111110111111
9/1	9	111110111
9/2	16	1111111111000000
9/3	16	1111111111000001
9/4	16	1111111111000010
9/5	16	1111111111000011
9/6	16	1111111111000100
9/7	16	1111111111000101
9/8	16	1111111111000110
9/9	16	1111111111000111
9/A	16	1111111111001000
A/1	9	111111000
A/2	16	1111111111001001
A/3	16	1111111111001010
A/4	16	1111111111001011
A/5	16	1111111111001100
A/6	16	1111111111001101
A/7	16	1111111111001110
A/8	16	1111111111001111
A/9	16	1111111111010000
A/A	16	1111111111010001
B/1	9	111111001
B/2	16	1111111111010010
B/3	16	1111111111010011
B/4	16	1111111111010100
B/5	16	1111111111010101
B/6	16	1111111111010110
B/7	16	1111111111010111
B/8	16	1111111111011000
B/9	16	1111111111011001
B/A	16	1111111111011010
C/1	9	111111010
C/2	16	1111111111011011
C/3	16	1111111111011100
C/4	16	1111111111011101
C/5	16	1111111111011110

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Run/Size	Code length	Code word
C/6	16	1111111111011111
C/7	16	1111111111100000
C/8	16	1111111111100001
C/9	16	1111111111100010
C/A	16	1111111111100011
D/1	11	11111111001
D/2	16	1111111111100100
D/3	16	1111111111100101
D/4	16	1111111111100110
D/5	16	1111111111100111
D/6	16	1111111111101000
D/7	16	1111111111101001
D/8	16	1111111111101010
D/9	16	1111111111101011
D/A	16	1111111111101100
E/1	14	11111111100000
E/2	16	1111111111101101
E/3	16	1111111111101110
E/4	16	1111111111101111
E/5	16	1111111111110000
E/6	16	1111111111110001
E/7	16	1111111111110010
E/8	16	1111111111110011
E/9	16	1111111111110100
E/A	16	1111111111110101
F/0 (ZRL)	10	1111111010
F/1	15	111111111000011
F/2	16	1111111111110110
F/3	16	1111111111110111
F/4	16	1111111111111000
F/5	16	1111111111111001
F/6	16	1111111111111010
F/7	16	1111111111111011
F/8	16	1111111111111100
F/9	16	1111111111111101
F/A	16	1111111111111110

Sheet 4 of 4

For figure 23 (for chrominance AC coefficients), the 16 bytes which specify the list of code lengths for the table are

X’00 02 01 02 04 04 03 04 07 05 04 04 00 01 02 77’

The set of values which follows this list is:

X’00 01 02 03 11 04 05 21 31 06 12 41 51 07 61 71
13 22 32 81 08 14 42 91 A1 B1 C1 09 23 33 52 F0
15 62 72 D1 0A 16 24 34 E1 25 F1 17 18 19 1A 26
27 28 29 2A 35 36 37 38 39 3A 43 44 45 46 47 48
49 4A 53 54 55 56 57 58 59 5A 63 64 65 66 67 68
69 6A 73 74 75 76 77 78 79 7A 82 83 84 85 86 87
88 89 8A 92 93 94 95 96 97 98 99 9A A2 A3 A4 A5
A6 A7 A8 A9 AA B2 B3 B4 B5 B6 B7 B8 B9 BA C2 C3
C4 C5 C6 C7 C8 C9 CA D2 D3 D4 D5 D6 D7 D8 D9 DA
E2 E3 E4 E5 E6 E7 E8 E9 EA F2 F3 F4 F5 F6 F7 F8
F9 FA’

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