Fast multiple *run_before* decoding method for efficient implementation of an H.264/advanced video coding context-adaptive variable length coding decoder

Dae Wook Ki
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Dae Wook Ki
Jae Ho Kim
Pusan National University
Department of Electronics Engineering
San 30, Jangjeon-Dong
Kumjeong-Gu, Pusan, 609-735 Republic of Korea
E-mail: jhkim@pusan.ac.kr

Abstract. We propose a fast new multiple *run_before* decoding method in context-adaptive variable length coding (CAVLC). The transform coefficients are coded using CAVLC, in which the *run_before* symbols are generated for a 4×4 block input. To speed up the CAVLC decoding, the *run_before* symbols need to be decoded in parallel. We implemented a new CAVLC table for simultaneous decoding of up to three *run_befores*. The simulation results show a *Total Speed-up Factor* of $205\% \sim 144\%$ over various resolutions and quantization steps. [DOI: 10.1117/1.OE.52.7.071502]

Subject terms: *run_before*; context-adaptive variable length coding; H.264/advanced video coding; multiple decoding.

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1 Introduction

Efficient decoding of H.264/advanced video coding (AVC) is quite important in personal computer (PC)-based decoding as well as for application specific integrated circuit (ASIC) implementation. Low power implementations are more important for mobile devices such as smart phones and digital multimedia broadcasting.

H.264/AVC uses context-adaptive variable length coding (CAVLC) for encoding the transformed coefficients of 4×4 blocks. The method is composed of five syntax elements: *TotalCoef (coeff_token)*, *TrailingOnes (coeff_token)* and *trailing_ones_sign_flag*, *level*, *total_zeros*, and *run_before*. For *TrailingOnes* (or T1s), the *trailing_ones_sign_flag* is assigned to 0 or 1 to represent the "+" or "−" sign of the trailing ones, respectively. For this syntax element, there is no need for decoding in the calculation or table access. There is only one value of *TotalCoef(coeff_token)*, *T1 (coeff_token)*, and *total_zeros* for one 4×4 block. But in many cases there may be more than one "level" and "run_before" value for the block.

Moon[1] proposed a method to reduce the large number of memory access operations in the decoding process for *coeff_token*. He used new variable-length decoding (VLD)s for *coeff_token* and a state machine instead of the *run_before* decoding table. This method reduced 95% of the memory access, which is quite a good improvement for a low power hardware implementation. Kim et al.[2] used conventional digital signal processor (DSP) or general purpose processor (GPP) instructions for CAVLC decoding. As shown in Fig. 1, the *run_before* table is divided into five groups and their decoding algorithms are proposed separately. They removed most of the table accesses. This has advantages for DSP- or GPP-based systems; however, the hardware implementation is complex as the equation uses complicated calculation logic.

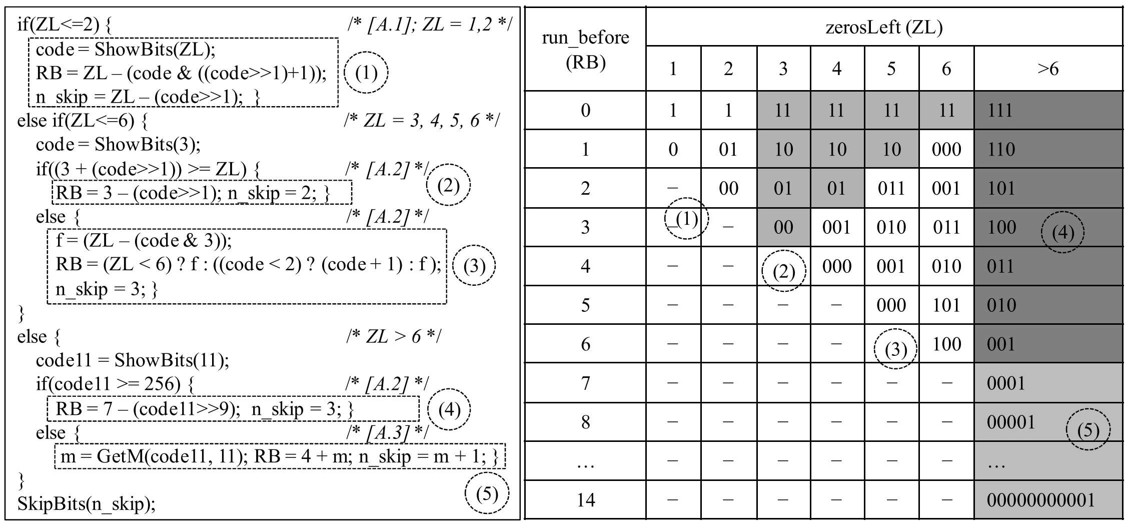
For implementing the 1~5 groups of Fig. 1, hardware blocks such as shifters, adders, and multiplexers are needed. For the outer "if then else" statements, the condition calculation logics and multiplexers are needed.

Many researchers have contributed different methods to the efficient decoding of CAVLC in H.264/AVC.[3–10] Key to these methods is noting the bottleneck that inhibits decoding speed. The authors propose to increase the speed of *run_before* decoding since in many cases there are multiple *run_befores* for one 4×4 block. This is also the case for the *levels* in CAVLC; however, as the multiple parallel decoding of *levels* is quite complex, this paper only focuses on the multiple parallel decoding of *run_before*.

Wen[3] earlier proposed parallel multiple *run_befores*, using parallel multiple hardware decoders. It is shown in Fig. 2. A total of six decoding units were used in the actual design of the hardware. Each decoding unit had a different starting position for the input bit stream, and they produced decoding results or failures according to each bit stream input. Therefore, each decoder needed its own variable-length coding (VLC) table. The hardware complexity was quite high, as was the power consumption since the units ran in parallel. This did not improve the decoding algorithm and it also increased the degree of hardware complexity.

The method of Nikara[5] is an MPEG2 version of Wen[3] using multiple decoders. Each decoder has a complete decoding logics and a code detector (CD) table. Their starting bit positions in the input bit stream are different. They are trying to decode their own bit streams simultaneously. Some result in *success_flags*, the decoded bits, and the code lengths. Others result in failures. This method is used to speed up the hardware decoding process. Before this is proposed, a simple decoding is iterated many times. Compared to that, this method reduces the overall hardware decoding time. But there is no algorithmic improvement in Nikara[5] and the required hardware size is increasing as the multiple decoding logics are used in parallel.

As an alternative, the authors propose fast multiple *run_befores* decoding with reduced memory access. The main



```
if(ZL<=2) {                                       /* [A.1]; ZL = 1,2 */
  code = ShowBits(ZL);
  RB = ZL – (code & ((code>>1)+1));               (1)
  n_skip = ZL – (code>>1); }
else if(ZL<=6) {                                  /* ZL = 3, 4, 5, 6 */
  code = ShowBits(3);
  if((3 + (code>>1)) >= ZL) {                     /* [A.2] */
    RB = 3 – (code>>1); n_skip = 2; }             (2)
  else {                                          /* [A.2] */
    f = (ZL – (code & 3));
    RB = (ZL < 6) ? f : ((code < 2) ? (code + 1) : f);   (3)
    n_skip = 3; }
}
else {                                            /* ZL > 6 */
  code11 = ShowBits(11);
  if(code11 >= 256) {                             /* [A.2] */
    RB = 7 – (code11>>9);  n_skip = 3; }          (4)
  else {                                          /* [A.3] */
    m = GetM(code11, 11); RB = 4 + m; n_skip = m + 1; }
}
SkipBits(n_skip);                                 (5)
```

run_before (RB)	zerosLeft (ZL)						
	1	2	3	4	5	6	>6
0	1	1	11	11	11	11	111
1	0	01	10	10	10	000	110
2	–	00	01	01	011	001	101
3	(1)	–	00	001	010	011	100 (4)
4	–	–	(2)	000	001	010	011
5	–	–	–	–	000	101	010
6	–	–	–	–	(3)	100	001
7	–	–	–	–	–	–	0001
8	–	–	–	–	–	–	00001 (5)
...	–	–	–	–	–	–	...
14	–	–	–	–	–	–	00000000001

Fig. 1 The single *run-before* decoding method of Kim.[2]

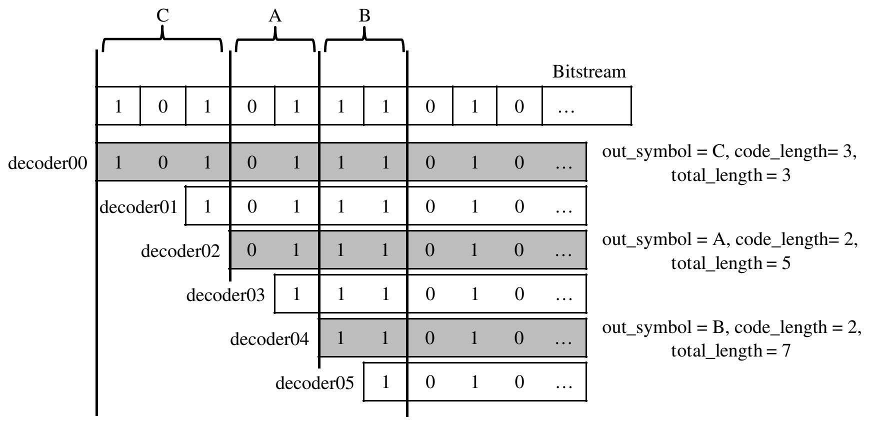

C
A
B
Bitstream
1 0 1 0 1 1 1 0 1 0 ...
decoder00
decoder01
decoder02
decoder03
decoder04
decoder05
out_symbol = C, code_length= 3, total_length = 3
out_symbol = A, code_length= 2, total_length = 5
out_symbol = B, code_length = 2, total_length = 7

Fig. 2 An example of multiple symbol decoding.[3]

idea is that there is a higher probability of *run_befores* with shorter coded bits. During our research, we found many cases in which three *run_before* codes can be decoded using only one 8-bit table access. In those cases, one table access can produce three decoded values of *run_before*. This has the benefit of a low power implementation due to fewer table accesses. This is a big achievement for implementation compared to Nikara.[5] There is no need for many decoders running in parallel in the proposed idea.

This paper is organized as follows. Section 2 reviews the general CAVLC algorithm and briefly describes the contributions from earlier papers. Section 3 explains the proposed method, and Sec. 4 analyzes the experimental results. Section 5 provides the conclusions regarding proposed algorithm.

2 H.264/AVC CAVLC

CAVLC decoding is the inverse of encoding and operates on coded information from the compressed bit stream.

In the encoding side, zigzag scanning is applied after quantization of the transformed coefficients, and then CAVLC is used to encode the transformed coefficients. The following syntax elements are used for coding efficiency:

1. *The total number of coefficients* (*TotalCoef* or *Tc*): *Tc* for the neighborhood blocks are used in selecting the current VLC look-up table.
2. *TrailingOnes (T1s)*: After quantization, most of the nonzero coefficients are $+1$ or -1. They are called *T1s*. Note that their signs are coded separately as *trailing_ones_sign_flag. If there are more than three T1s, they are regarded as level.*
3. *level*: Coefficient values above 1 are coded as *level*. Note that the value "1" after counting three "1"s is also regarded as *level*. For coding these *levels*, the VLC look-up table is selected adaptively using information from the most recently coded *level*.
4. *total_zeros*: Encodes the total number of zeros occurring after the first nonzero coefficient.
5. *run_before*: The quantized block typically has many zero coefficients. CAVLC uses *run_before* for the efficient coding of zeros.

Figure 3 shows the five decoding process for the five syntaxes of CAVLC.[1] The quantized 4×4 coefficients are reordered by zigzag scanning and encoded by the CALVC encoder. When the encoded bit stream is provided to the

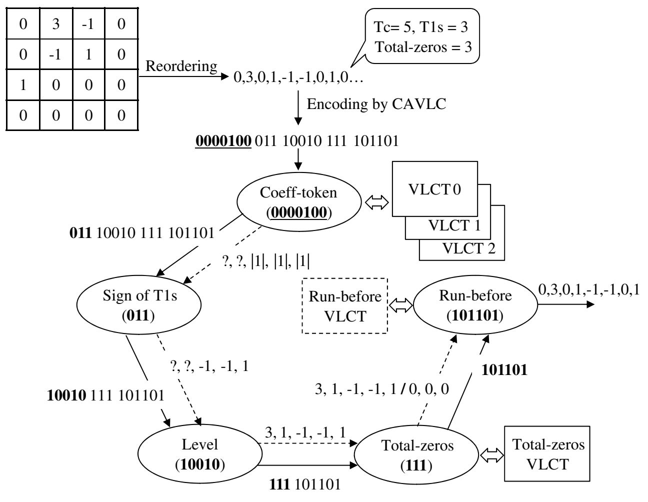


Fig. 3 CAVLC decoding processes[1] and syntax examples.

decoder, *coeff_token*, *signs of T1s*, *level*, *total_zero*, and *run_before* are decoded sequentially.

3 Proposed Multiple *run_before* Decoding Algorithm

In the proposed method, up to three *run_befores* can be decoded simultaneously. The number "*zerosLeft*" indicates how many "0"s are not yet decoded. The code length of *run_before* is a maximum 3 bits if *zerosLeft* is between 1 and 6. In the entropy coding, a shorter code length means a higher occurrence probability of the code.

Figure 4 shows the *run_before* decoding table. The codes in region (1) provide the target where multiple decoding is possible. The codes in region (2) are decoded by the normal decoding method because they are less likely. If *zerosLeft* is not greater than 6, the proposed multiple decoding is applied. For various test sequences, we found that the average probability of regions (1) and (2) are 87.3% and 12.7%, respectively.

run_before	zerosLeft						
	1	2	3	4	5	6	>6
0	1	1	11	11	11	11	111
1	0	01	10	10	10	000	110
2	-	00	01	01	011	001	101
3	-	-	00	001	010	011	100
4	- (1)	-	-	000	001	010	011
5	-	-	-	-	000	101	010
6	-	-	-	-	-	100	001 (2)
7	-	-	-	-	-	-	0001
8	-	-	-	-	-	-	00001
9	-	-	-	-	-	-	000001
10	-	-	-	-	-	-	0000001
11	-	-	-	-	-	-	00000001
12	-	-	-	-	-	-	000000001
13	-	-	-	-	-	-	0000000001
14	-	-	-	-	-	-	00000000001

Fig. 4 The *run_before* decoding table. In region (1), the authors propose multiple parallel decoding. In region (2), conventional single decoding is used.

3.1 *Proposed Multiple Decoding Table*

Region (1) in the *run_before* table needs to be reorganized for multiple decoding. The revised table is shown in Fig. 5(a). The 8-bit buffer holding the input bit stream is used for the column address of the table, and *zerosLeft* is used for the row address. The memory output of the table shows three *run_before* values and the corresponding *run_before* code bits consumed.

An example illustrates the usage of the new table, shown in Fig. 5(b). The zigzag scanned coefficients arrive from right to left. The relationship of *zerosLeft* and *run_before* is depicted in Fig. 5(b), which shows that *zerosLeft* is reduced by the value of a decoded *run_before.* Assume that an encoded bit stream is "10011." This means that *run_before* and *zerosLeft* are (1,2,0,1) and (4,3,1,1) in the coding process, respectively. Of course, this is unknown until they are subsequently decoded correctly.

Total_zeros is decoded as "4" just before the *run_before* decoding starts. The coded bit stream "10011xxx" is stored in the input bit buffer of the decoder, and *zerosLeft* is initialized with *total_zeros* at the start of *run_before* decoding. The bit data of the input buffer and *zerosLeft* are used for the column and row addresses of the table. Then "001 010 000 101" is the output of the table. The first three 4-bit numbers represent the *run_before* value 1, 2, and 0, respectively. The last 4-bit number shows the consumed number of bits, which is used to shift the buffer for the next decoding process. Because three *run_befores* are decoded, the next starting *zerosLeft* becomes 1.

If there are more than three *run_befores*, then additional iterations of this process are needed. The *run_before* decoding table size in Fig. 5(a) is 6 (row size) × 256 (column size) × 12 bits (output bits size), i.e., 18,432 bits. Our aim is to

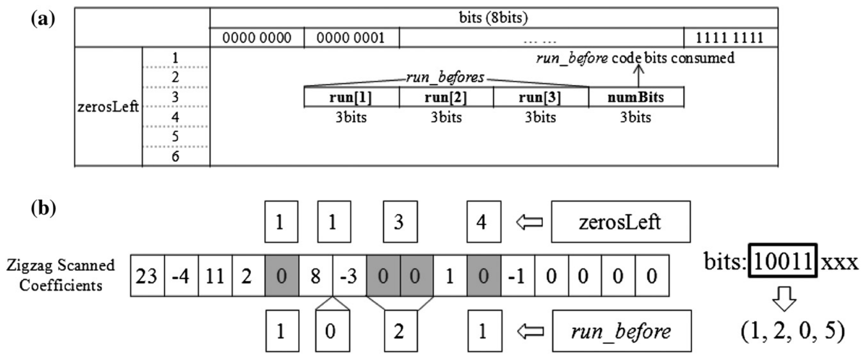


Fig. 5 (a) The proposed multiple *run_before* decoding table which provides up to three decoded values of *run_before* and the consumed number of bits. "10011xxx" is the input bit stream for multiple decoding, and (1,2,0,5) is the output of the table access. (b) An illustration for the decoding of the zigzag scanned coefficients.

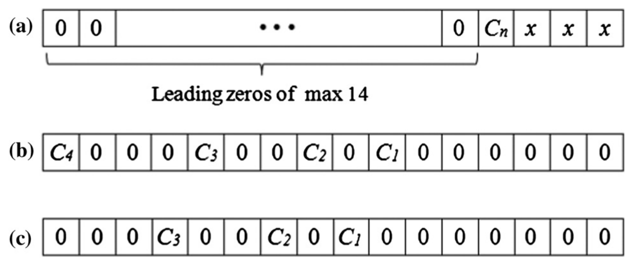

(a)
0 0 • • • 0 C_n x x x
Leading zeros of max 14
(b)
C_4 0 0 0 C_3 0 0 C_2 0 C_1 0 0 0 0 0 0
(c)
0 0 0 C_3 0 0 C_2 0 C_1 0 0 0 0 0 0 0

Fig. 6 (a) Leading zeros before C_n. Note that *x* means *don't care*. (b) An example of no leading zeros, starting with C_4. (c) Another example of leading zeros. Note the pattern is the same as (b) except C_4.

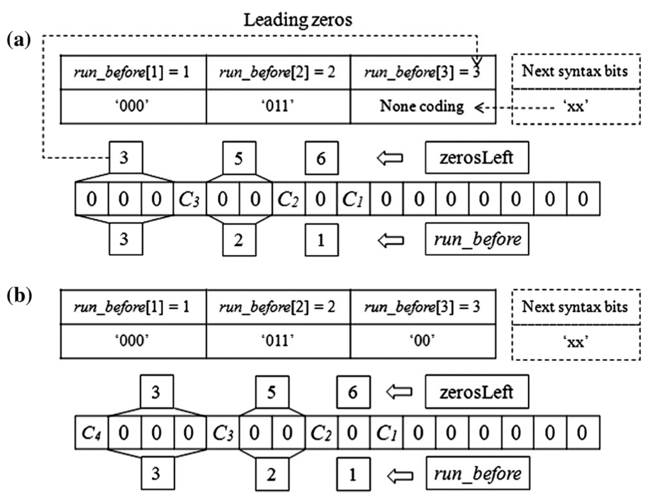


Fig. 7 The encoding process of Fig. 6(a) and 6(b).

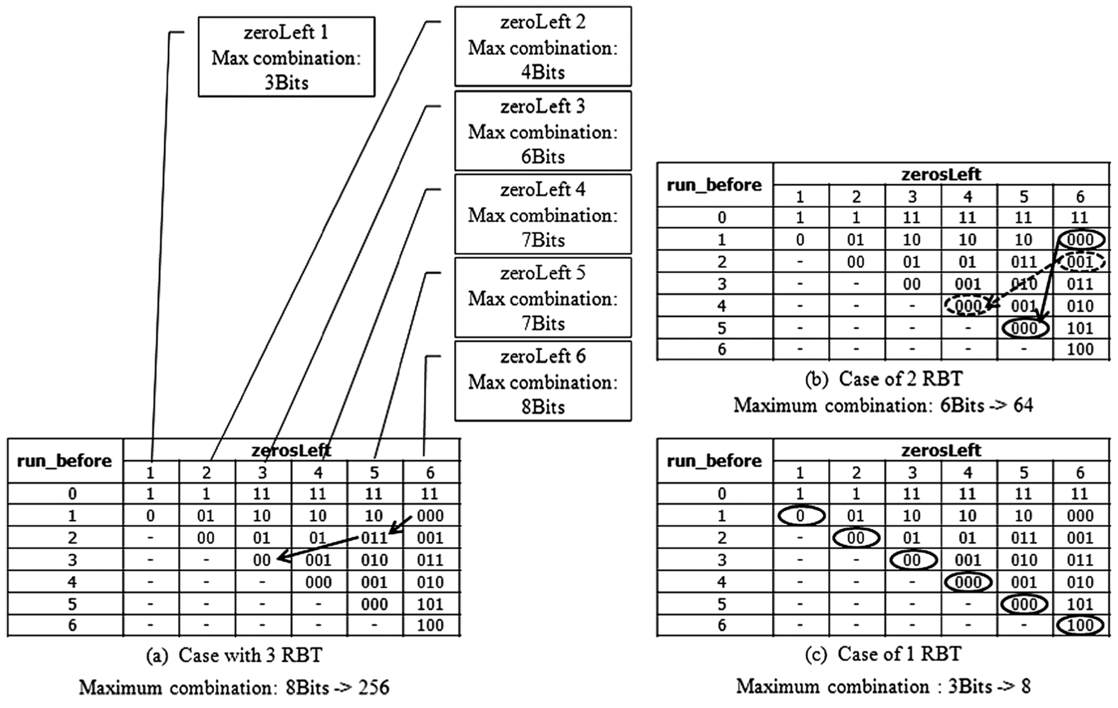
decode a maximum of three *run_befores* at once. We need three tables to support either one, two, or three *run_befores* (see the following section). Therefore, the required table size is $18,432$ bits $\times 3 = 55,296$ bits. This is too large for a hardware implementation.

3.2 *Reducing the Multiple Decoding Table*

Figure 6(a) shows the special case in which the coefficients before C_n are all "0," called the leading zero case (LZC). Note that C_n is a nonzero coefficient. In LZC, after decoding C_n, the decoder knows that all nonzero coefficients are decoded and that the remaining coefficients are all zeros. The encoder does not assign any bits for the *run_before* of the leading zeros. In the leading zero case, the multiple *run_befores* decoding table needs to be separated; an explanation follows.

Figure 6(b) and 6(c) shows how the decoding is performed regardless of whether there are leading zeros.

In the encoding process, *zerosLeft* is set to 6 for both Fig. 7(a) and 7(b). Consider the *run_before* values for Fig. 7(a). The first (before C_1), second (before C_2), and third (before C_3) *run_befores* are 1, 2, and 3, respectively. But the third *run_before* is not coded because it is the leading zeros. Therefore, the *run_before* stream for (a) is "000011." The next syntax element (xx) will be concatenated, so that "000011xx" will be the encoded stream. On the other hand, in the case of Fig. 7(b), the first, second, and third *run_befores* are 1, 2, and 3, respectively, and the *run_before* stream is "00001100." On the decoding side, when "00001100" arrives we cannot distinguish between the Fig. 7(b) case "00001100" or the Fig. 7(a) case "000011xx" with the following syntax element $xx =$ ″00″. The number of consumed bits for Fig. 7(a) and 7(b) are 6 and 8, respectively.


zeroLeft 1 Max combination: 3Bits
zeroLeft 2 Max combination: 4Bits
zeroLeft 3 Max combination: 6Bits
zeroLeft 4 Max combination: 7Bits
zeroLeft 5 Max combination: 7Bits
zeroLeft 6 Max combination: 8Bits

run_before	zerosLeft 1	2	3	4	5	6
0	1	1	11	11	11	11
1	0	01	10	10	10	000
2	-	00	01	01	011	001
3	-	-	00	001	010	011
4	-	-	-	000	001	010
5	-	-	-	-	000	101
6	-	-	-	-	-	100

(a) Case with 3 RBT
Maximum combination: 8Bits -> 256

run_before	zerosLeft 1	2	3	4	5	6
0	1	1	11	11	11	11
1	0	01	10	10	10	000
2	-	00	01	01	011	001
3	-	-	00	001	010	011
4	-	-	-	000	001	010
5	-	-	-	-	000	101
6	-	-	-	-	-	100

(b) Case of 2 RBT
Maximum combination: 6Bits -> 64

run_before	zerosLeft 1	2	3	4	5	6
0	1	1	11	11	11	11
1	0	01	10	10	10	000
2	-	00	01	01	011	001
3	-	-	00	001	010	011
4	-	-	-	000	001	010
5	-	-	-	-	000	101
6	-	-	-	-	-	100

(c) Case of 1 RBT
Maximum combination : 3Bits -> 8

Fig. 8 Reduction table size for decoding multiple *run_befores*.

In other words, the same bit stream "00001100" should produce different table outputs according to whether there is a leading zero case, and we need to separate the table. Considering how many *run_befores* are decoded at once, the above two examples Fig. 7(a) and 7(b) can be decoded with the tables having two and three *run_befores*. These tables are called *run_before*-table (RBT)3 and RBT2. For the same reason, it is quite easy to understand that we need another table having only one *run_before*, called RBT1.

Table 1 The required table sizes for *zerosLeft* equals 1 ~ 6 and 1 ~ 3 *run_befores*.

	RBT1	RBT2	RBT3
1 *zerosLeft*	8	4	8
2 *zerosLeft*	8	8	16
3 *zerosLeft*	8	16	64
4 *zerosLeft*	8	32	128
5 *zerosLeft*	8	32	128
6 *zerosLeft*	8	64	256
Total		804	

Table 2 Conditions of the simulation.

Version of joint model		JM11.0
Profile		Baseline
Frame rate		30 Hz
Test sequences (frames)	CIF	Foreman(300), Mobile(300), Paris(300), Tempete(260)
	4CIF	City(300), Crew(300), Harbour(300), Soccer(300)
	HD	Pedest(300), Rushhour(300)
QP (Quantization parameter)		22, 27, 32, 37
Hadamard transform		Used
Search range		16
Number of reference frames 2 frames		2 frames
Sequence type		IPPP . . .
Motion vector resolution		1/4 pel
RD-optimized mode decision		Used
Fast motion estimation		Used

In the multiple *run_before* process, loop_count is initialized as Total coefficient − 1. This loop_count indicates how many coefficients have not yet been decoded. The number of decoded *run_befores* (# *run_before*) is the same as the number of decoded coefficients. In the next iteration loop_count is decreased by # *run_before*. If loop_count is greater than or equal to 3, equals 2, or equals 1, then RBT3, RBT2, or RBT1 will be selected, respectively.

The maximum coded bit length for various combinations of multiple *run_befores* varies, and it is also a function of *zerosLeft*. In other words, the maximum coded bit length determines the table size. Figure 8 shows how the table size can be reduced.

The following discussion explains how the size of the tables can be reduced for decoding multiple *run_befores* (please refer to Fig. 8).

1. This is an example of decoding the "00001100" *run_before* bit stream when *zerosLeft* is 6. With table access the 8-bit input can be decoded to have a

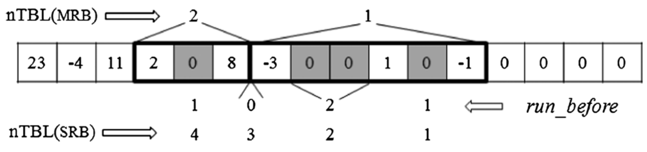


Fig. 9 Illustration of the number of table accesses for MRB and SRB. In this example, nTBL(MRB) = 2 and nTBL(SRB) = 4.

Table 3 The *Gain* for all cases of one 4 × 4 block.

nTBL(SRB)	nTBL(MRB)	Gain
1	1	1
2		2
3		3
4	2	2
5		2.5
6		3
7	3	2.33
8		2.67
9		3
10	4	2.5
11		2.75
12		3
13	5	2.6
14		2.8
15		3

Table 4 The probability of the *Gain* appearing for various sequences. QP 22 is used.

Gain	Foreman CIF (%)	Mobile CIF (%)	Paris CIF (%)	Tempete CIF (%)	City 4CIF (%)	Crew 4CIF (%)	Harbour 4CIF (%)	Soccer 4CIF (%)	Pedest HD (%)	Rushhour HD (%)
3	14.362	23.619	24.103	23.451	17.185	17.471	23.177	18.937	12.636	16.020
2.8	0.000	0.013	0.022	0.006	0.000	0.000	0.000	0.000	0.000	0.000
2.75	0.084	0.807	1.175	0.374	0.010	0.014	0.002	0.031	0.037	0.000
2.67	0.834	4.922	5.625	3.661	0.502	0.392	0.123	0.690	0.353	0.100
2.6	0.007	0.092	0.149	0.037	0.000	0.001	0.000	0.001	0.005	0.000
2.5	5.586	10.820	10.637	9.497	6.232	4.714	4.614	6.180	2.583	2.979
2.33	1.062	5.749	6.618	5.306	0.981	0.808	0.417	1.354	0.657	0.547
2	22.316	22.409	21.109	24.429	25.901	30.650	40.348	28.237	26.540	26.849
1	55.751	31.568	30.562	33.239	49.190	45.949	31.320	44.570	57.190	53.506

Table 5 *Total Speed-Up Factor* for various sequences and QPs.

	Total speed-up factor									
QP	Foreman CIF (%)	Mobile CIF (%)	Paris CIF (%)	Tempete CIF (%)	City 4CIF (%)	Crew 4CIF (%)	Harbour 4CIF (%)	Soccer 4CIF (%)	Pedest HD (%)	Rushhour HD (%)
22	162.38	203.33	205.80	199.48	171.78	174.42	194.39	178.39	157.22	164.25
27	151.71	183.98	186.72	179.76	156.76	164.32	158.54	173.68	163.92	148.07
32	151.48	176.10	178.90	171.33	152.92	159.13	131.56	163.34	172.76	151.34
37	154.05	175.78	170.19	155.78	144.93	156.01	125.91	152.26	167.86	166.13

sequence of 1, 2, and 3 *run_befores*. We need to use RBT3 to simultaneously decode three *run_befores*. After analyzing all RBT3 cases, the authors found that the maximum bit stream is 8, so the table size can be 256.

2. This is two examples of decoding “000000” and “001000” when *zerosLeft* is 6. They are decoded to have a sequence of (1,5) and (2,4) *run_befores*, respectively. In these cases, RBT3 is needed to simultaneously decode two *run_befores*. After analyzing all RBT2 cases, it is found that the maximum bit stream is 6. This means the table size can be 64.
3. This shows the case of RBT1, for which the maximum bit stream is 3. This means the table size can be 8.

We further reduced the table for the case of Fig. 8(a). As in the above example, we only considered *zerosLeft* equals 6. If the *zerosLefts* are 5, 4, 3, 2, and 1, the maximum bit streams become 8, 7, 7, 6, 4, and 3 bits, respectively. This tells us the table size can be reduced further.

Similarly, we can summarize the necessary memory table sizes for various cases as shown in Table 1.

4 Simulation Results

Simulations are used to compare the proposed multiple *run_befores* decoding and conventional single decoding. The gain is calculated for various test sequences and quantization parameter (QP)s. Simulation conditions are shown in Table 2.

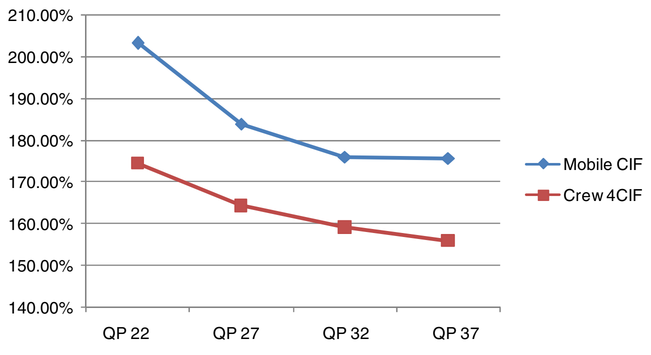


Fig. 10 The trend of the *total speed-up factor* (*TSF*) according to QPs for two typical video sequences.

Table 6 The FPGA synthesis results and the execution time of the proposed method are compared with Wen.[3]

	Wen[3]	The proposed method
Design platform (Device)	Xilinx Virtex II FPGA (XC2V4000-6BF957)	
Maximum frequency/Maximum period	24.993 MHz/40.012 ns	144.928 MHz/6.9 ns
CLB count	654	374
Synthesized ROM size	10112 Bits	10248 Bits
Test sequence	Foreman CIF	
Required decoding cycles	163192	243050
Total decoding time	6529.638 us	1677.045 us

4.1 *Comparison of the Number of Table Accesses*

We define the proposed decoding method as multiple *run_-befores* (MRB) and the conventional decoding method as single *run_before* (SRB). The number of table accesses for MRB and SRB is defined as nTBL(MRB) and nTBL (SRB), as illustrated in Fig. 9. In the case of MRB, two decoding steps are needed as shown in the bold line boxes. Here, *run_before* 1, 2, 0 can be decoded in the first decoding and *run_before* 1 can be decoded in the second decoding. In the case of SRB, *run_before* 1, 2, 0 and 1 are decoded with four iterations.

The processing *gain* of the proposed MRB compared to SRB can be defined as

$$\text{Gain} = \frac{\text{nTBL(SRB)}}{\text{nTBL(MRB)}}. \tag{1}$$

Table 3 shows the *gain* for all possible cases of one 4×4 block.

4.2 *Ideal Speed-Up Gain of the Proposed Method*

Simulations using the baseline profile for the common intermediate format (CIF), 4CIF, and high definition (HD) sequences are performed. In MRB, there are nine distinct cases of *gain* in the decoding. Table 4 presents the simulation results and the probability of the *gain*.

We applied several QPs, such as 22, 27, 32, and 37. To simplify the presentation, only one experimental result of QP 22 is summarized in Table 3. In this result, *gain* 3 appears more frequent with less moving or in lower resolution (CIF) video sequences.

This paper is proposing a new novel algorithm of the multiple *run_before* decoding for hardware implementation. Therefore, note that comparing with the software implementation efficiency is not necessary.

We define the *total speed-up factor* as the sum of the product of the *gain* and the probability of the case. This reflects the proposed algorithmic efficiency compared to the single *run_before* decoding. Simulation is performed for entire video frames, and the results are summarized in Table 5. This table shows the experimental results of QP 22, 27, 32, and 37.

From Table 4 it can be seen that the proposed method shows higher *total speed-up factor* (*TSF*) in lower resolutions or with smaller QP. Figure 10 shows that *TSF* changes according to the QP. For the mobile and Paris CIF sequences, the proposed algorithm produces more than twice the *TSF* at QP22.

4.3 *Comparison of the Implementation with Wen*

For the implementation point of view, it is necessary to compare the hardware size and the operating frequency of the design. Wen's[3] method is compared because it uses H.264 and proposes efficient decoding of *run_before*. Both are coded in Verilog HDL and synthesized for a field programmable gate array (FPGA, Xilinx Virtex II XC2V4000BF957). The results of synthesis and comparison are shown in Table 6. The proposed method has achieved 6.9 ns maximum period. The critical path delay of the proposed design is about 5.8 times smaller than Wen.[3] The number of required configurable logic block (CLB) in Wen[3] is 654, but we use only 374. The total execution time is equal to the maximum period multiplied by the required decoding cycles. The proposed method's total execution time gain is about 3.89 compared to Wen.[3]

Fewer table accesses means lower power consumption in implemented digital systems. The proposed method is useful for mobile devices such as cell phones, personal digital assistants, and smart phones.

5 Conclusions

CAVLC is used for *run_before* coding of the quantized residual coefficients in H.264/AVC. The elements of the CAVLC stream are *TotalCoef (coeff_token), TrailingOnes (coeff_token), trailing_ones_sign_flag, level, total_zeros, and run_-before*. Efficient implementation of CAVLC is important for mobile devices.

Prior research has been performed to improve the decoding of CAVLC.[1–8] *Coeff_token* decoding has been improved by using new *coeff_token* VLD,[1] and *total_zeros* decoding has been improved and memory access reduced by 80~90%.[4] *Trailing_ones_sign_flag* is simply assigned as "0" or "1." Thus, the remaining targets for improving CAVLC decoding are *level* and *run_before*. As the *level* decoding is quite complex, the authors leave this topic for future research.

Here, our target of research is to improve the *run_before* decoding. Note that *Coeff_token* and *Total _zeros* appear only once for a 4×4 block. But *run_before* usually appears many times for one 4×4 block; therefore, it is quite important to improve this run-before decoding for overall efficiency of the CAVLC decoding. Previous research on *run_before* decoding used an arithmetic operation to reduce the table accesses.[2] But this is efficient when GPP or DSP is used. Our aim is to develop a new algorithm for improving *run_before* decoding for hardware implementation. In this paper, we applied simultaneous decoding of up to three *run_befores*. In the simulation results, the *Total Speed-up Factor* is 144.9% ~ 205.8% for various sequences and QPs.

For the implementation point of view, Wen[3] is selected because it proposes multiple *run_before* decoding for H.264 CAVLC. Verilog HDL is used for hardware coding and synthesized for an FPGA (Xilinx Virtex II XC2V4000BF957). The proposed method is using only about 57% of Wen[3] for CLB count, about 5.79 times faster for the critical delay. Total decoding time gain of the proposed method is about 3.89 times faster for decoding the Foreman video sequence. The proposed method has less memory access and smaller hardware size. It means less power consumption and is good for mobile device application.

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Dae Wook Ki received his MS degree from the Department of Electronics Engineering at Pusan National University in 2005. He is currently a candidate for a PhD at Pusan National University. His research interests include video coding standard, very large scale integration design and multimedia systems.

Jae Ho Kim received his MS and PhD degrees from the Department of Electronics Engineering at the Korea Advanced Institute of Science and Technology in 1982 and 1990, respectively. He worked in the Laboratory of Visual Communication at Samsung Electronics from 1988 to 1992. He is currently a professor in the Department of Electronics Engineering at Pusan National University. His research interests include video coding standard, high-resolution image processing, and animation automation.