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| *Title:* | **Non-CE10: Core Transform Design for HEVC** | | |
| *Status:* | Input Document to JCT-VC | | |
| *Purpose:* | Proposal | | |
| *Author(s) or Contact(s):* | Jie Dong  Yan Ye  9710 Scranton Road, Suite 250,  San Diego, CA 92121, USA | Tel:  Email: | +1 858 210 4809  jie.dong@interdigital.com yan.ye@interdigital.com |
| *Source:* | InterDigital Communication LLC | | |

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# Abstract

This contribution presents the core transform design for HEVC, including 4×4, 8×8, 16×16 and 32×32 forward/inverse transforms. The design has these features: (1) 16 bit data representation before and after each transform stage, (2) transforms can be implemented by full factorization, partial butterfly, or matrix multiplication, (3) 4×4 and 8×8 transforms are orthogonal, and 16×16 and 32×32 transforms are nearly orthogonal, (4) *N×N* transform matrix is reused as the even part of the *2N×2N* transform matrix, (5) no need for correction of different norms of basis vectors during quantization/dequantization. This design was integrated into HM4.0, using both full factorization and partial butterfly. It is reported full factorization for 32*×*32 transform achieves 6X reduction in the number of multiplications, compared with partial butterfly. The R-D performance was tested under the common test conditions specified in JCTVC-F900. The average BD-rate increase is 0.1% to 0.2% for all intra coding, 0.1% for random access coding, and 0.0% to 0.1% for low delay coding.

# Definitions of Transform Matrices

The transform matrices of the 4×4, 8×8, and 16×16 transforms are given as in (1), (2), and (3), respectively. The transform matrix of the 32×32 transform is appended at the end of this document.

(1)

*T4*=[

128 128 128 128

167 70 -70 -167

128 -128 -128 128

70 -167 167 -70

]

(2)

*T8*=[

256 256 256 256 256 256 256 256

360 297 198 72 -72 -198 -297 -360

334 140 -140 -334 -334 -140 140 334

297 -72 -360 -198 198 360 72 -297

256 -256 -256 256 256 -256 -256 256

198 -360 72 297 -297 -72 360 -198

140 -334 334 -140 -140 334 -334 140

72 -198 297 -360 360 -297 198 -72

]

# 

*T16*=[

1024 1024 1024 1024 1024 1024 1024 1024 1024 1024 1024 1024 1024 1024 1024 1024

1445 1377 1275 1105 935 663 425 119 -119 -425 -663 -935 -1105 -1275 -1377 -1445

1440 1188 792 288 -288 -792 -1188 -1440 -1440 -1188 -792 -288 288 792 1188 1440

1402 886 174 -710 -1270 -1434 -1146 -398 398 1146 1434 1270 710 -174 -886 -1402

1336 560 -560 -1336 -1336 -560 560 1336 1336 560 -560 -1336 -1336 -560 560 1336

1318 86 -1074 -1370 -490 966 1446 622 -622 -1446 -966 490 1370 1074 -86 -1318

1188 -288 -1440 -792 792 1440 288 -1188 -1188 288 1440 792 -792 -1440 -288 1188

1104 -672 -1368 120 1440 432 -1272 -936 936 1272 -432 -1440 -120 1368 672 -1104

1024 -1024 -1024 1024 1024 -1024 -1024 1024 1024 -1024 -1024 1024 1024 -1024 -1024 1024

936 -1272 -432 1440 -120 -1368 672 1104 -1104 -672 1368 120 -1440 432 1272 -936

792 -1440 288 1188 -1188 -288 1440 -792 -792 1440 -288 -1188 1188 288 -1440 792

622 -1446 966 490 -1370 1074 86 -1318 1318 -86 -1074 1370 -490 -966 1446 -622

560 -1336 1336 -560 -560 1336 -1336 560 560 -1336 1336 -560 -560 1336 -1336 560

398 -1146 1434 -1270 710 174 -886 1402 -1402 886 -174 -710 1270 -1434 1146 -398

288 -792 1188 -1440 1440 -1188 792 -288 -288 792 -1188 1440 -1440 1188 -792 288

119 -425 663 -935 1105 -1275 1377 -1445 1445 -1377 1275 -1105 935 -663 425 -119

]

(3)

# Forward Transform, Quantization, Dequantization, and Inverse Transform

Denote the bit-depth of the input to transform as *BD*, and denote (*BD*-9) as *ΔBD*. The block input to transform has the size *M*×*N*. When NSQT is enabled, *M* might be different from *N*.

## Forward Transform

The input to forward transform is a prediction residual block, denoted as *XM*×*N*. To perform a 2-D forward transform on *XM*×*N*, the *M* rows and *N* columns in *XM*×*N* are transformed in each dimension sequentially.

1. ***M* is equal to *N* or *M* is smaller than *N.***

The horizontal transform is performed first, as in (4), followed by right shifting with a proper number of bits to store intermediate result in 16-bit.

*UM*×*N* = ( *XM*×*N* × *TNT* + *f* ) >> ( log2(*N*) + log2(*TN*(0,0)) + *ΔBD* - 7 ) (4)

After the horizontal transform, vertical forward transform is performed on the intermediate block *UM*×*N*, as shown in (5).

*YM*×*N* = (*TM*× *UM*×*N* + *f* ) >> (log2(*M*)+ log2( *TM*(0,0) ) ) (5)

1. ***M* is greater than *N.***

The vertical transform is performed first, as in (6).

*UM*×*N* =( *TM* × *XM*×*N* + *f* ) >> ( log2(*M*) + log2(*TM*(0,0)) + *ΔBD* – 7 ) (6)

After the vertical transform, horizontal transform is performed on the intermediate block *UM*×*N*, as shown in (7).

*YM*×*N* =(*UM*×*N* × *TNT* + *f* ) >> ( log2(*N*) +log2(*TN*(0,0) ) ) (7)

## Inverse Transform

The input to inverse transform is a dequantized block *YM*×*N*. To perform a 2-D inverse transform on *YM*×*N*, the *M* rows and *N* columns in *YM*×*N* are transformed in a sequential manner.

1. ***M* is equal to *N* or *M* is greater than *N.***

The horizontal transform is performed first, as in (8).

*VM*×*N* = ( *YM*×*N* × *TN* + *f* ) >> ( log2( *TN*(0,0) ) + 1 ) (8)

After the horizontal transform, vertical inverse transform is performed on the intermediate block *VM*×*N*, as shown in (9).

*XM*×*N* = ( *TMT* × *VM*×*N* + *f* ) >> (log2( *TM*(0,0) ) + 6 - *ΔBD*) (9)



1. ***M* is smaller than *N.***

The vertical transform is performed first, as in (10).

*VM*×*N* =( *TMT* × *YM*×*N* + *f* ) >> ( log2( *TM*(0,0) ) + 1) (10)



After the vertical transform, horizontal transform is performed on the intermediate block *VM*×*N*, as shown in (11).

*XM*×*N* =( *VM*×*N* × *TN* + *f* ) >> (log2( *TN*(0,0) ) + 6 – *ΔBD* ) (11)

## Quantization and Dequantization

Quantization and dequantization in this proposal are the same as in HM4.0 [1].

# Simulation Results

This design was integrated into HM4.0 [1] and its R-D performance was tested under the common test conditions specified in . The average BD-rate increases are 0.1% to 0.2% for all intra coding, 0.1% for random access coding, and 0.0% to 0.1% for low delay coding.

**TABLE 1 R-D performance based on all intra settings (measured by BD-rate)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **All Intra HE** | | | **All Intra LC** | | |
|  | Y | U | V | Y | U | V |
| Class A | 0.4% | 0.3% | 0.1% | 0.7% | 0.2% | -0.1% |
| Class B | 0.1% | 0.1% | 0.1% | 0.2% | 0.1% | 0.1% |
| Class C | 0.1% | 0.1% | 0.1% | 0.1% | 0.0% | 0.0% |
| Class D | 0.0% | 0.0% | 0.0% | 0.0% | 0.1% | 0.0% |
| Class E | 0.1% | 0.2% | 0.2% | 0.2% | 0.0% | 0.1% |
| **Overall** | 0.1% | 0.1% | 0.1% | 0.2% | 0.1% | 0.0% |
|  | 0.1% | 0.1% | 0.1% | 0.2% | 0.1% | 0.0% |

TABLE 2 R-D performance based on random access settings (measured by BD-rate)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Random Access HE** | | | **Random Access LC** | | |
|  | Y | U | V | Y | U | V |
| Class A | 0.2% | -0.1% | 0.0% | 0.3% | 0.4% | -0.1% |
| Class B | 0.1% | 0.1% | 0.0% | 0.1% | 0.0% | 0.1% |
| Class C | 0.1% | 0.0% | 0.2% | 0.1% | 0.0% | 0.1% |
| Class D | 0.1% | 0.0% | -0.2% | 0.0% | 0.0% | 0.3% |
| Class E |  |  |  |  |  |  |
| **Overall** | 0.1% | 0.0% | 0.0% | 0.1% | 0.1% | 0.1% |
|  | 0.1% | 0.0% | 0.0% | 0.1% | 0.1% | 0.1% |

TABLE 3 R-D performance based on low delay B settings (measured by BD-rate)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Low delay B HE** | | | **Low delay B LC** | | |
|  | Y | U | V | Y | U | V |
| Class A |  |  |  |  |  |  |
| Class B | 0.1% | 0.0% | -0.4% | 0.1% | 0.1% | 0.3% |
| Class C | 0.1% | 0.1% | 0.0% | 0.0% | 0.1% | 0.0% |
| Class D | 0.1% | -0.1% | -0.2% | 0.0% | 0.1% | 0.1% |
| Class E | 0.1% | -0.9% | 1.1% | 0.0% | 0.4% | -0.4% |
| **Overall** | 0.1% | -0.2% | 0.0% | 0.0% | 0.1% | 0.0% |
|  | 0.1% | -0.1% | 0.0% | 0.0% | 0.1% | 0.0% |

TABLE 4 R-D performance based on low delay P settings (measured by BD-rate)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Low delay P HE** | | | **Low delay P LC** | | |
|  | Y | U | V | Y | U | V |
| Class A |  |  |  |  |  |  |
| Class B | 0.1% | 0.3% | -0.1% | 0.1% | 0.1% | 0.1% |
| Class C | 0.1% | 0.2% | 0.2% | 0.0% | 0.0% | 0.2% |
| Class D | 0.2% | 0.2% | 0.0% | 0.0% | 0.1% | -0.1% |
| Class E | 0.1% | -0.1% | 0.0% | 0.1% | -0.4% | -0.3% |
| **Overall** | 0.1% | 0.1% | 0.0% | 0.1% | 0.0% | 0.0% |
|  | 0.1% | 0.1% | 0.0% | 0.1% | 0.0% | 0.0% |

# Implementation

The proposed core transform design is realized by both full factorization and partial butterfly. In the enclosed software “JCTVC-G272-software.zip”, the modifications on HM4.0 are indicated by two macros: G272\_TRANSFORM and G272\_TRANSFORM\_FULL\_FACTORIZATION. Enabling only G272\_TRANSFORM, one makes the proposed forward and inverse transforms performed by partial butterfly; enabling both macros, one makes the proposed transforms performed by full factorization. TABLE 5 reports the numbers of multiplications and additions for *N*-point 1-D transform ( *N* = 4, 8, 16, or 32 ), according to the full factorization implementation of the enclosed software, and compares them to matrix multiplication, partial butterfly, and the full factorization implementations from the other two contributions [3] [4] of this meeting.

TABLE Numbers of additions and multiplications for *N*-point 1-D transform ( *N* = 4, 8, 16, or 32 )

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | | Matrix Multiplication | Partial Butterfly | Factorization in  JCTVC-G579 | Factorization in JCTVC-G737 | Proposed Factorization |
| 4-point | Addition | 12 | 8 | 9 | 9 | 9 |
| Multiplication | 16 | 6 | 3 | 3 | 3 |
| 8-point | Addition | 56 | 28 | 26 | 29 | 31 |
| Multiplication | 64 | 22 | 12 | 11 | 11 |
| 16-point | Addition | 240 | 100 | 72 | 81 | 93 |
| Multiplication | 256 | 86 | 36 | 31 | 21 |
| 32-point | Addition | 992 | 372 | 186 | 229 | 279 |
| Multiplication | 1024 | 342 | 92 | 87 | 56 |

# Conclusion

This contribution presents the core transform design for HEVC, including 4×4, 8×8, 16×16 and 32×32 forward/inverse transforms. The design has these features: (1) 16 bit data representation before and after each transform stage, (2) transforms can be implemented by full factorization, partial butterfly, or matrix multiplication, (3) 4×4 and 8×8 transforms are orthogonal, and 16×16 and 32×32 transforms are nearly orthogonal, (4) *N×N* transform matrix is reused as the even part of the *2N×2N* transform matrix, (5) no need for correction of different norms of basis vectors during quantization/dequantization. This design was integrated into HM4.0, using both full factorization and partial butterfly. It is reported full factorization for 32*×*32 transform achieves 6X reduction in the number of multiplications, compared with partial butterfly. The R-D performance was tested under the common test conditions specified in JCTVC-F900. The average BD-rate increases are 0.1% to 0.2% for all intra coding, 0.1% for random access coding, and 0.0% to 0.1% for low delay coding. We suggest putting this design into the core experiment for further investigation.

# Reference

1. <https://hevc.hhi.fraunhofer.de/svn/svn_HEVCSoftware/tags/HM-4.0/>
2. F. Bossen, “Common test conditions and software reference configurations”, JCTVC-F900, Jul. 2011.
3. R. Joshi *et al*., “CE10: Scaled integer transforms supporting recursive factorization structure”, JCTVC-G579, Nov. 2011.
4. E. Alshina *et al*., “CE10: Full Factorization Core Transforms for HEVC”, JCTVC-G737, Nov. 2011.

# Patent rights declaration(s)

**InterDigital Communications LLC may have current or pending patent rights relating to the technology described in this contribution and, conditioned on reciprocity, is prepared to grant licenses under reasonable and non-discriminatory terms as necessary for implementation of the resulting ITU-T Recommendation | ISO/IEC International Standard (per box 2 of the ITU-T/ITU-R/ISO/IEC patent statement and licensing declaration form).**



Fig. Full factorization of 32×32 forward transform, which contains the full factorizations of 16×16, 8×8, and 4×4 forward transforms

 

 

Fig. Operations in the four blocks in Fig. 1

 

 

Fig. Operations in the four blocks in Fig. 4



Fig. Full factorization of 32×32 inverse transform, which contains the full factorizations of 16×16, 8×8, and 4×4 inverse transforms

*T32* = [

2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048 2048

2912 2821 2779 2723 2685 2460 2340 2145 2015 1690 1510 1205 1036 665 455 91 -91 -455 -665 -1036 -1205 -1510 -1690 -2015 -2145 -2340 -2460 -2685 -2723 -2779 -2821 -2912

2890 2754 2550 2210 1870 1326 850 238 -238 -850 -1326 -1870 -2210 -2550 -2754 -2890 -2890 -2754 -2550 -2210 -1870 -1326 -850 -238 238 850 1326 1870 2210 2550 2754 2890

2821 2639 2107 1505 660 -90 -1040 -1690 -2340 -2730 -2920 -2810 -2429 -1981 -1183 -455 455 1183 1981 2429 2810 2920 2730 2340 1690 1040 90 -660 -1505 -2107 -2639 -2821

2880 2376 1584 576 -576 -1584 -2376 -2880 -2880 -2376 -1584 -576 576 1584 2376 2880 2880 2376 1584 576 -576 -1584 -2376 -2880 -2880 -2376 -1584 -576 576 1584 2376 2880

2821 2093 959 -413 -1765 -2590 -2860 -2535 -1495 -130 1220 2355 2884 2667 1911 728 -728 -1911 -2667 -2884 -2355 -1220 130 1495 2535 2860 2590 1765 413 -959 -2093 -2821

2804 1772 348 -1420 -2540 -2868 -2292 -796 796 2292 2868 2540 1420 -348 -1772 -2804 -2804 -1772 -348 1420 2540 2868 2292 796 -796 -2292 -2868 -2540 -1420 348 1772 2804

2730 1456 -399 -2135 -2935 -2305 -715 1235 2665 2795 1735 -115 -1974 -2828 -2457 -1001 1001 2457 2828 1974 115 -1735 -2795 -2665 -1235 715 2305 2935 2135 399 -1456 -2730

2672 1120 -1120 -2672 -2672 -1120 1120 2672 2672 1120 -1120 -2672 -2672 -1120 1120 2672 2672 1120 -1120 -2672 -2672 -1120 1120 2672 2672 1120 -1120 -2672 -2672 -1120 1120 2672

2548 728 -1757 -2807 -1925 405 2535 2665 975 -1495 -2915 -2085 112 2324 2821 1183 -1183 -2821 -2324 -112 2085 2915 1495 -975 -2665 -2535 -405 1925 2807 1757 -728 -2548

2636 172 -2148 -2740 -980 1932 2892 1244 -1244 -2892 -1932 980 2740 2148 -172 -2636 -2636 -172 2148 2740 980 -1932 -2892 -1244 1244 2892 1932 -980 -2740 -2148 172 2636

2457 -182 -2618 -2289 415 2790 2210 -715 -2795 -1950 950 2855 1708 -1288 -2912 -1456 1456 2912 1288 -1708 -2855 -950 1950 2795 715 -2210 -2790 -415 2289 2618 182 -2457

2376 -576 -2880 -1584 1584 2880 576 -2376 -2376 576 2880 1584 -1584 -2880 -576 2376 2376 -576 -2880 -1584 1584 2880 576 -2376 -2376 576 2880 1584 -1584 -2880 -576 2376

2275 -910 -2870 -721 2490 2200 -1300 -2860 -390 2600 1900 -1460 -2765 -210 2730 1729 -1729 -2730 210 2765 1460 -1900 -2600 390 2860 1300 -2200 -2490 721 2870 910 -2275

2208 -1344 -2736 240 2880 864 -2544 -1872 1872 2544 -864 -2880 -240 2736 1344 -2208 -2208 1344 2736 -240 -2880 -864 2544 1872 -1872 -2544 864 2880 240 -2736 -1344 2208

2093 -1729 -2506 1197 2690 -705 -2925 130 2860 455 -2875 -980 2569 1519 -2366 -1911 1911 2366 -1519 -2569 980 2875 -455 -2860 -130 2925 705 -2690 -1197 2506 1729 -2093

2048 -2048 -2048 2048 2048 -2048 -2048 2048 2048 -2048 -2048 2048 2048 -2048 -2048 2048 2048 -2048 -2048 2048 2048 -2048 -2048 2048 2048 -2048 -2048 2048 2048 -2048 -2048 2048

1911 -2366 -1519 2569 980 -2875 -455 2860 -130 -2925 705 2690 -1197 -2506 1729 2093 -2093 -1729 2506 1197 -2690 -705 2925 130 -2860 455 2875 -980 -2569 1519 2366 -1911

1872 -2544 -864 2880 -240 -2736 1344 2208 -2208 -1344 2736 240 -2880 864 2544 -1872 -1872 2544 864 -2880 240 2736 -1344 -2208 2208 1344 -2736 -240 2880 -864 -2544 1872

1729 -2730 -210 2765 -1460 -1900 2600 390 -2860 1300 2200 -2490 -721 2870 -910 -2275 2275 910 -2870 721 2490 -2200 -1300 2860 -390 -2600 1900 1460 -2765 210 2730 -1729

1584 -2880 576 2376 -2376 -576 2880 -1584 -1584 2880 -576 -2376 2376 576 -2880 1584 1584 -2880 576 2376 -2376 -576 2880 -1584 -1584 2880 -576 -2376 2376 576 -2880 1584

1456 -2912 1288 1708 -2855 950 1950 -2795 715 2210 -2790 415 2289 -2618 182 2457 -2457 -182 2618 -2289 -415 2790 -2210 -715 2795 -1950 -950 2855 -1708 -1288 2912 -1456

1244 -2892 1932 980 -2740 2148 172 -2636 2636 -172 -2148 2740 -980 -1932 2892 -1244 -1244 2892 -1932 -980 2740 -2148 -172 2636 -2636 172 2148 -2740 980 1932 -2892 1244

1183 -2821 2324 -112 -2085 2915 -1495 -975 2665 -2535 405 1925 -2807 1757 728 -2548 2548 -728 -1757 2807 -1925 -405 2535 -2665 975 1495 -2915 2085 112 -2324 2821 -1183

1120 -2672 2672 -1120 -1120 2672 -2672 1120 1120 -2672 2672 -1120 -1120 2672 -2672 1120 1120 -2672 2672 -1120 -1120 2672 -2672 1120 1120 -2672 2672 -1120 -1120 2672 -2672 1120

1001 -2457 2828 -1974 115 1735 -2795 2665 -1235 -715 2305 -2935 2135 -399 -1456 2730 -2730 1456 399 -2135 2935 -2305 715 1235 -2665 2795 -1735 -115 1974 -2828 2457 -1001

796 -2292 2868 -2540 1420 348 -1772 2804 -2804 1772 -348 -1420 2540 -2868 2292 -796 -796 2292 -2868 2540 -1420 -348 1772 -2804 2804 -1772 348 1420 -2540 2868 -2292 796

728 -1911 2667 -2884 2355 -1220 -130 1495 -2535 2860 -2590 1765 -413 -959 2093 -2821 2821 -2093 959 413 -1765 2590 -2860 2535 -1495 130 1220 -2355 2884 -2667 1911 -728

576 -1584 2376 -2880 2880 -2376 1584 -576 -576 1584 -2376 2880 -2880 2376 -1584 576 576 -1584 2376 -2880 2880 -2376 1584 -576 -576 1584 -2376 2880 -2880 2376 -1584 576

455 -1183 1981 -2429 2810 -2920 2730 -2340 1690 -1040 90 660 -1505 2107 -2639 2821 -2821 2639 -2107 1505 -660 -90 1040 -1690 2340 -2730 2920 -2810 2429 -1981 1183 -455

238 -850 1326 -1870 2210 -2550 2754 -2890 2890 -2754 2550 -2210 1870 -1326 850 -238 -238 850 -1326 1870 -2210 2550 -2754 2890 -2890 2754 -2550 2210 -1870 1326 -850 238

91 -455 665 -1036 1205 -1510 1690 -2015 2145 -2340 2460 -2685 2723 -2779 2821 -2912 2912 -2821 2779 -2723 2685 -2460 2340 -2145 2015 -1690 1510 -1205 1036 -665 455 -91

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