CSE 834 Low Pass Filter

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1 Introduction

Low pass filters are used in many applications from noise filtering to RF modulation. Low pass filters are well understood, and include logically simple components: registers, adders, and multipliers. In this project, we will design a low power low pass filter using VHDL and the Cadence hardware designer. We will include optimizations for power such as reducing components and reducing transitions.

In section 2, we will discuss our design philosophy and design decisions. In section 3 we will describe how we constructed the components and connected them. Finally, in section 4, we will discuss problems we experienced in our design and the tools we used.

2 Design

2.1 Q15 Format

For our filter design, fixed format number format called Q is used. Unlike floating point numbers, Q-format numbers require only a standard integer Arithmetic Logic Unit (ALU) to perform rational number calculations. This means that we do not need to add an Floating Point Unit (FPU) to our design, which requires additional power.

Q format numbers are represented using the Q notation which is written as Qm, n where m is the number of bits set aside to designate the two's complement integer portion of the number, and n is the number of bits used to designate the fractional portion of the number.

In our case, we use simplified notation Qn since we assume that the numbers are normalized into the range of $[-1, 1)$. Notice that this assumption does not affect the generality of the filter, but it simplifies the multiplication operation because the multiplication result never exceeds the range of $[-1, 1)$.

Figure 6 shows the comparison between two's complement integer and Q7 numbers. The only difference between the two is the weight assigned for each bit.

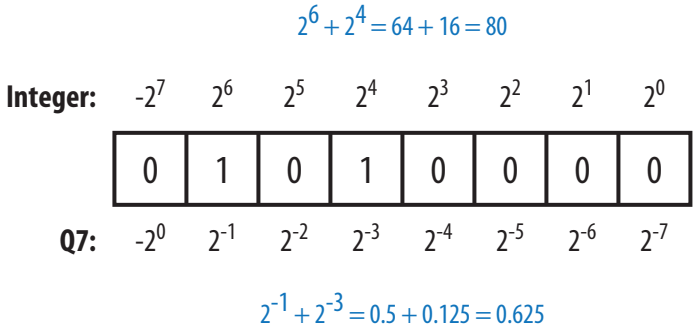

Figure 1: Comparison between integer and Q7 format.

2.2 Filter Characteristics

Coeffiecient	Value	Q15
C_0	-0.022663985459552	1111110100011010
C_1	1.04697822237622e-17	0000000000000000
C_2	0.273977082565524	0010001100010001
C_3	0.497373805788057	0011111110101001
C_4	0.273977082565524	0010001100010001
C_5	1.04697822237622e-17	0000000000000000
C_6	-0.022663985459552	1111110100011010

Table 1: Coefficient values.

The coefficients for the filter is shown in Table 1. These values were computed using Filter Design & Analysis Tool (Figure 2) in Matlab Signal Processing Toolbox which is one of the most widely used filter design tools in the industry. We have chosen a 8^{th} order FIR filter with a Hamming window. This filter is also one of the most widely used in the industry and has straight-forward characteristic.

2.3 Input & Output

The input and output of our design are shown in Table 2. The external clock will allow us to connect to arbitrary clocked external input, as long as it meets the timing requirements of our design. The 16 bit input and output are in the Q15 format described in Section 2.1. The Q15 format is an industry standard, hence we expect that these required input formats are reasonable.

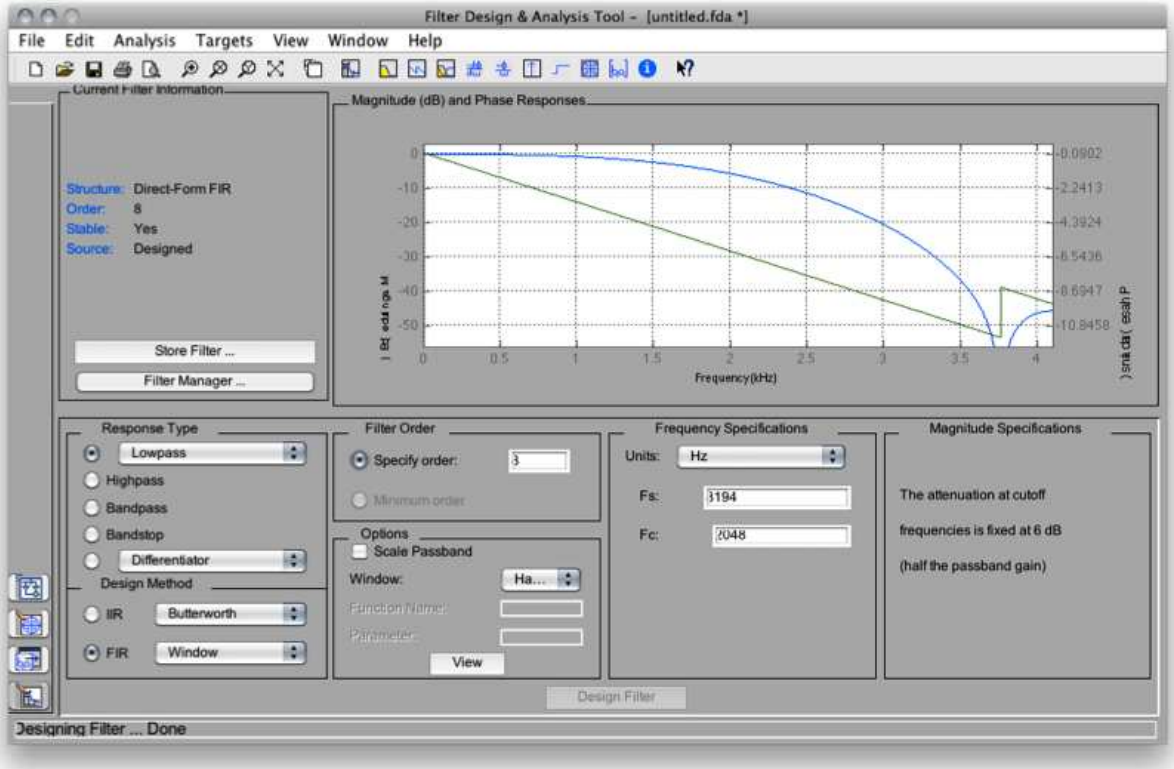

Figure 2: Matlab Filter Design & Analysis Tool.

Input/Output	Description	Bits
Input	Clock	1
Input	Data In	16
Output	Convolution	16

Table 2: Description of input and output to the filter.

2.4 Power Optimization

We will optimize power by removing duplicate multipliers. These duplicate multipliers are created because the filter is symmetric, therefore an adder can be used remove an adder. In the naive filter, shown in Figure 3, the constant is multiplied against each register value. Since the constants are symmetric, ie $C0$ is the same as $C6$, this can be optimized using the associative rule. In Figure 4, you can see that we have removed 3 of the multipliers. Instead, we add the values in the registers before multiplying the constants. This eliminates 3 large and power draining multipliers. It also simplifies the final adder from 7 input to 4.

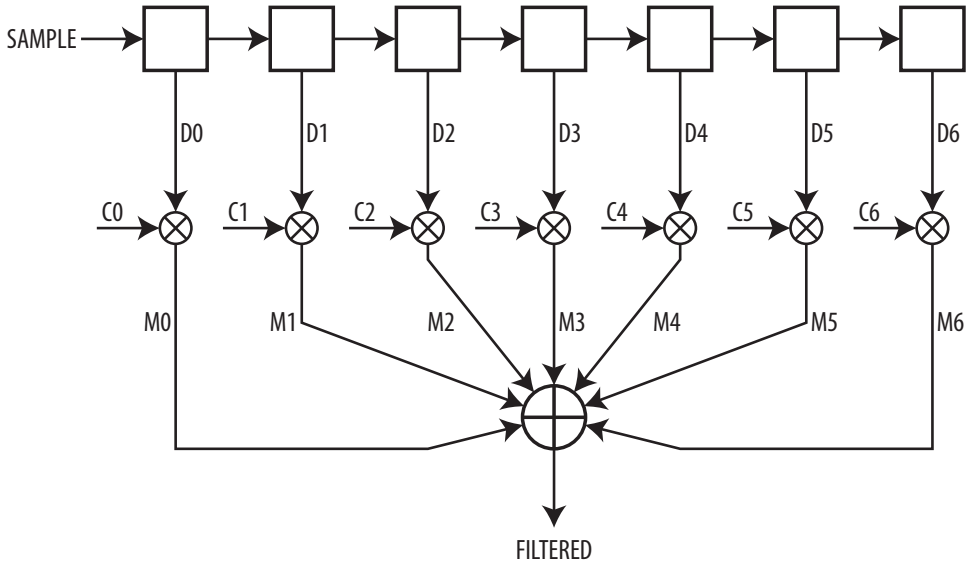

Figure 3: Naive filter implementation.

The adders shown at the bottom of Figure 4 are frequently changing as the final value is stabilized through the convolution hardware above. Therefore, it is important that this hardware is optimized for power. With reducing the number of transistors as our goal, we designed ripple-carry adders to do the final addition. The ripple-carry adders have less hardware than the optimized version that VHDL synthesized when doing a '+'. Also, the ripple carry adders will localize any transition to only the nodes that require it.

Compare the ripple carry to propagate/carry (PG) adders that are designed to optimize latency. The PG adders have significantly more hardware since it has to pre-calculate propagates and carries.

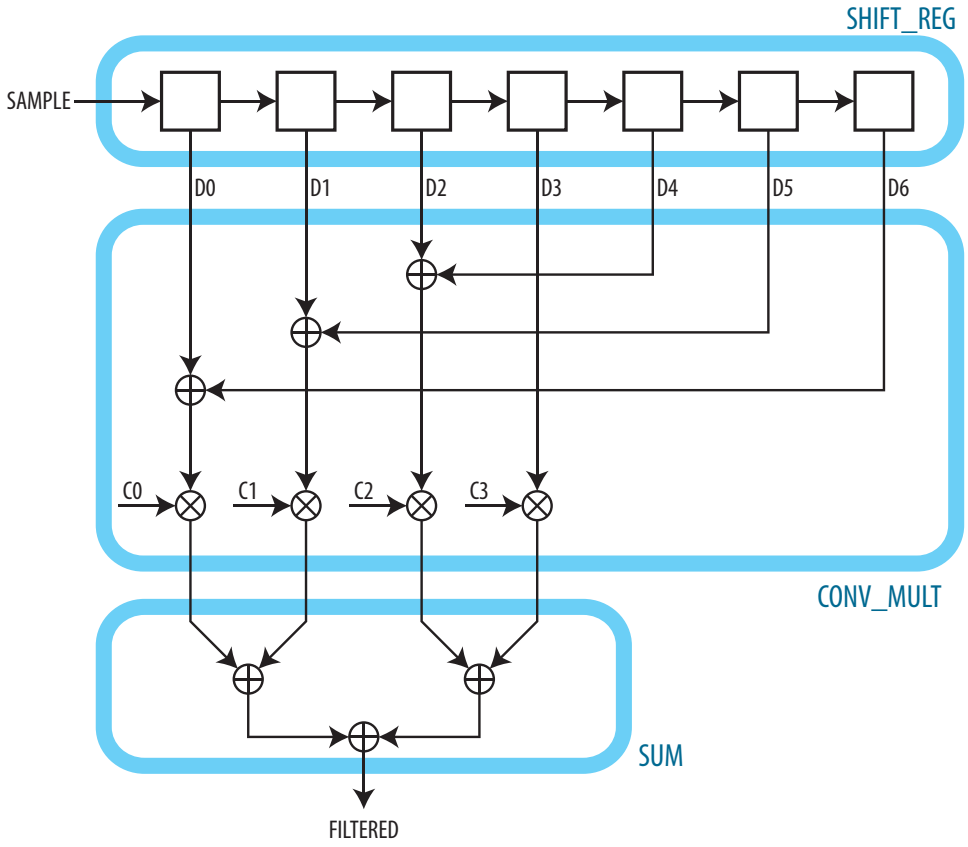

Figure 4: Optimized filter implementation.

We also attempted to use a clock-gated D flip flop seen in Figure 5. While doing simulations of the VHDL, we discovered that this design was flawed. When the clock was high, Q stabilized to the value of D. This is because the XOR gate with the clock and the D input would cause the 'clock' input to the flip flop to change, therefore causing it to save the input. The clock-gated D flip-flop acted as a latch. We did not use this optimization in the final design.

3 Implementation

3.1 Dataflow

In this section I will describe the dataflow shown in Figure 4. The figure outlines the top level components that are described later in section 3.2.

We designed the filster to have 7 16-bit registers. Each of the 7 registers' data is connected to the next register. At each clock pulse, the registers' data is shifted to the next register. The input is placed at $D0$ and the value stored in $D6$ is not saved.

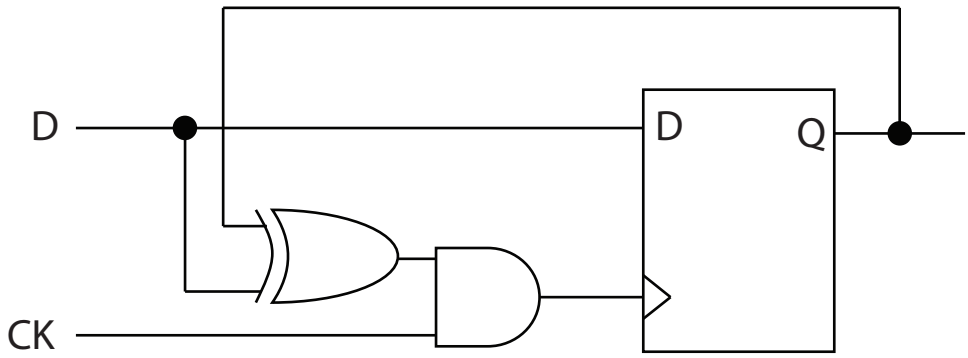

Figure 5: Clock gating low power flip-flop (Credit: Sharad Seth).

For $D0$ through $D2$, the registers' output is also connected to an adder. Because the filter is symmetric, we are able to add two register values together before multiplying by the constants $C0$ through $C2$. After the addition, the values are multiplied by the constants specified in Table 1. The products are then summed using three ripple-carry adders.

3.2 VHDL Design

We decided to design our filter using as much HDL as possible. Therefore, every component is written in VHDL, and are synthesized for the final design. The VHDL is separated into components listed below. These components are then synthesized using the `rc` and Encounter cadence synthesizer.

Separate components:

- `SHIFT_REG`: Shift Register (Appendix A.2.1)
  - `D_FF`: D-Flip Flop (Appendix A.2.2)
- `CONV_MULT`: Convolution (Appendix A.3.1)
- `SUM`: Summation (Appendix A.4.1)
  - `ADD16`: 16-Bit Adder (Appendix A.4.2)
    - `FULL_ADDER`: Full Adder (Appendix A.4.3)

The source of the VHDL components are included in the appendix.

During early synthesis, we found that the standard libraries did not have a flip-flop available. We needed a flip-flop in order to create our registers. Therefore, we created a D Flip Flop using the structural specification.

3.3 Functional Verification

To verify the correctness of the VHDL design files, we have written a C++ program that generates test cases. This program first generates test input with random noise. Then it computes the output using the equivalent filter algorithm in Q15 format. The result is stored in a text file (Appendix B.2) which can be read by a VHDL testbench `filter_tb.vhd` (Appendix A.1.1).

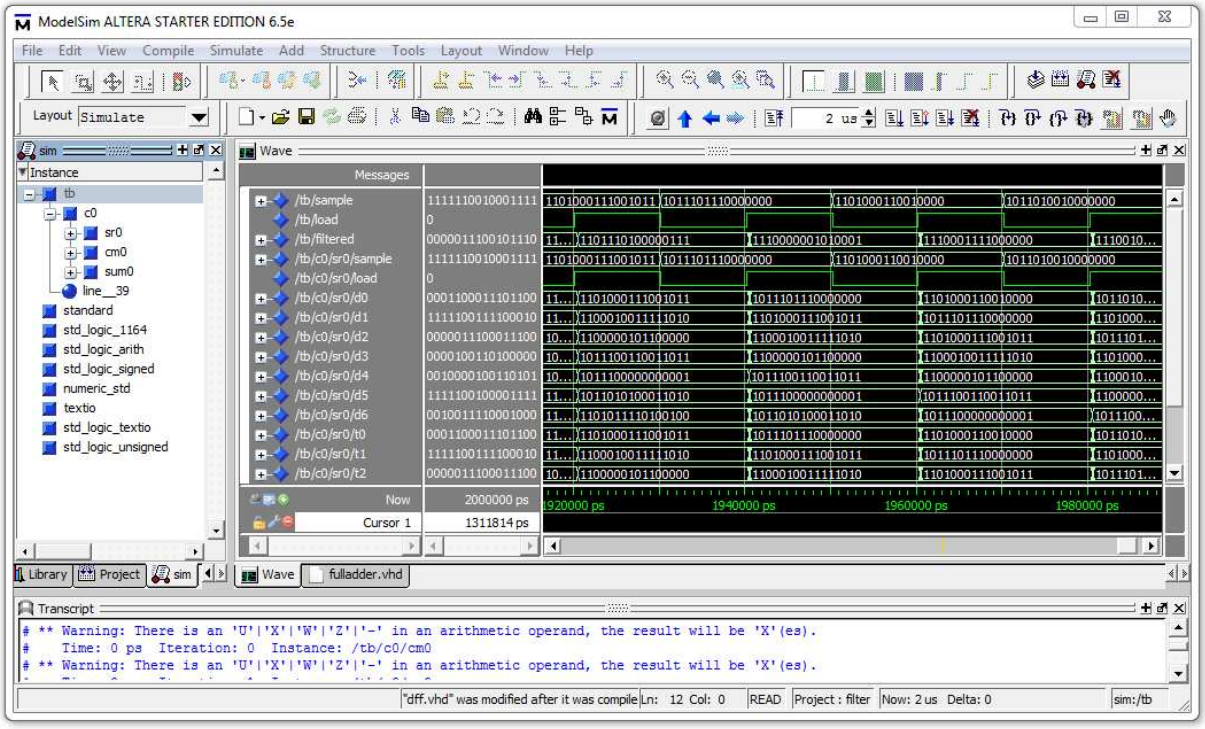

Figure 6: ModelSim from Mentor Graphics was used for VHDL simulation.

For VHDL simulation, we used ModelSim from Mentor Graphics. This tool loads and compiles all VHDL files including the test bench, then shows the waveform and output to the window. Our testbench file follows the VHDL standard and prints the results into a text file, so it should work on other environments other than ModelSim.

We verified that the every bit of the C++ program output and VHDL testbench output matched, therefore the VHDL should be correct with high probability.

3.4 Synthesis

Synthesis was done using rc cadence synthesizer and the Encounter tool. For the encounter tool, we followed the instructions listed in lab 3. The Encounter routing and placement

on the `CONV_MULT` component took 45 minutes to complete while the FullAdder was near instant. See Figure 7 for the synthesized convolution hardware.

3.5 Final Layout & Routing

Since each component was designed in a separate VHDL file, they had to be connected at a high level. See Figure 8 for the schematic of the connected high level components. This logical layout closely resembles the layout shown in Figure 4.

After creating the schematic, we used the Cadence router to route between the top level components. The chip size needed to be increased to 2500x2500 microns in order to accommodate the components. The convolution chip alone is 1500x1500 microns. The routing completes in about an hour with no un-routable endpoints. See Figure 9 for the routed final layout.

4 Conclusion

In this project, we created a power optimized low pass filter. We avoid using a floating point unit by utilizing the Q15 format. The filter is symmetric, allowing for optimizations. The input and output is kept simple. The power optimizations where done at design time using the algorithmic level. The components where developed in VHDL. The design was verified both at the functional level with a C++ program, and using the VHDL through a simulator. The components where synthesized using the Cadence tools. Finally, the layout was done using the autorouter in Cadence.

Both the DRC and LVS for the final layout failed. During autorouting, the router introduced DRC errors. LVS fails due to a cadence configuration error that I was unable to correct. Although both DRC and LVS fail, the VHDL simulates correctly and is functionally correct.

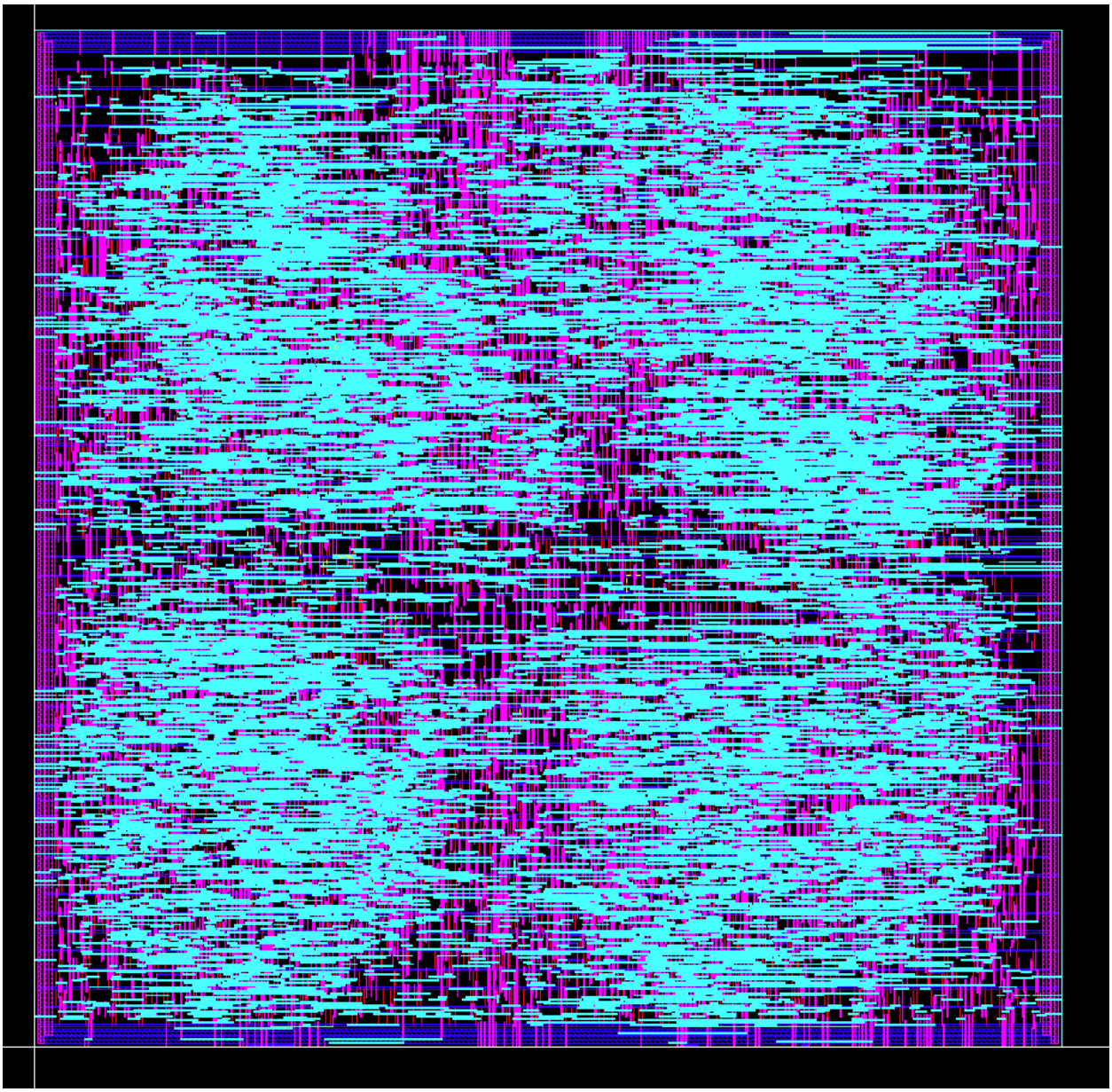

Figure 7: Convolution hardware after synthesis.

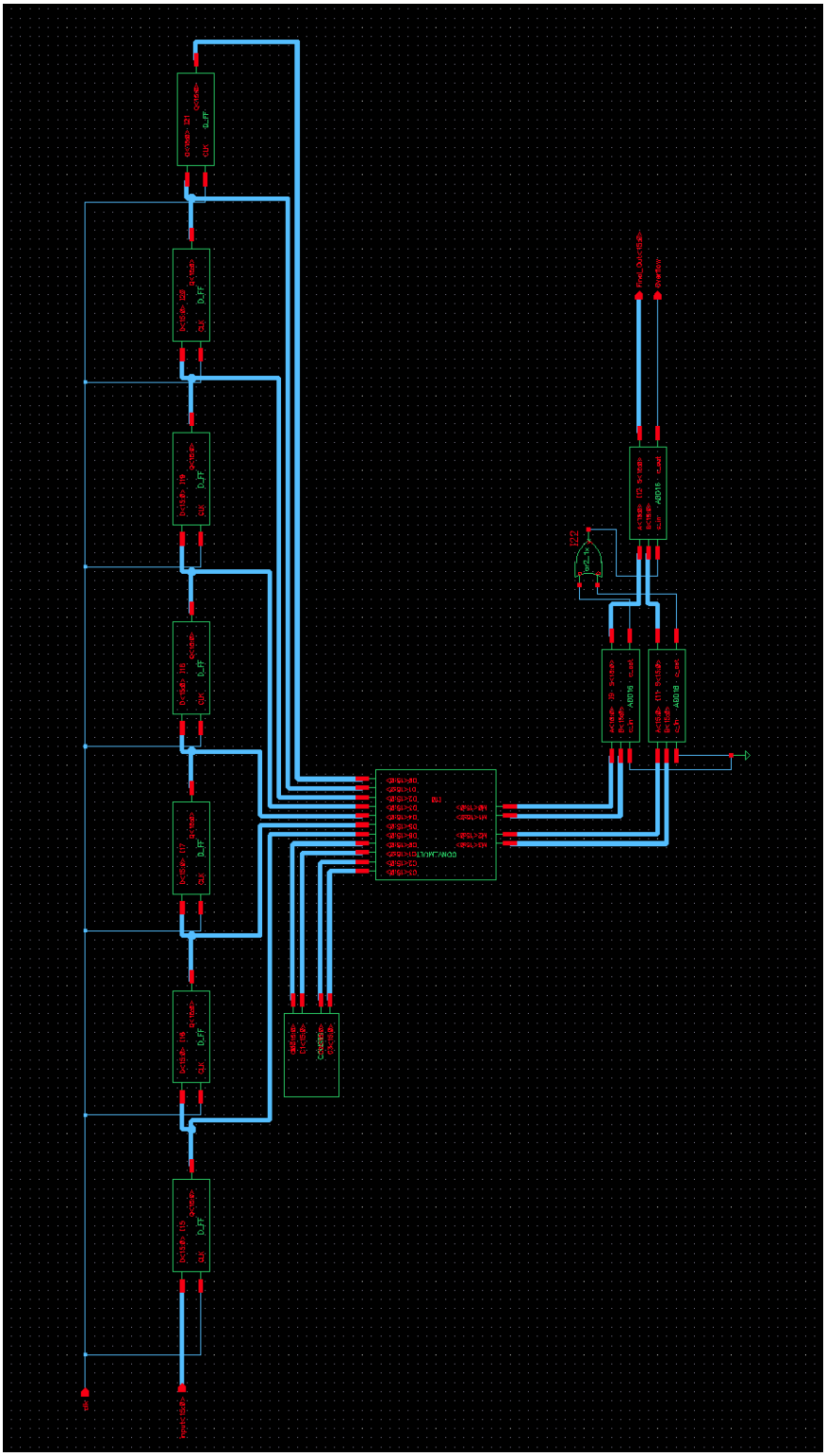

Figure 8: Filter Schematic.

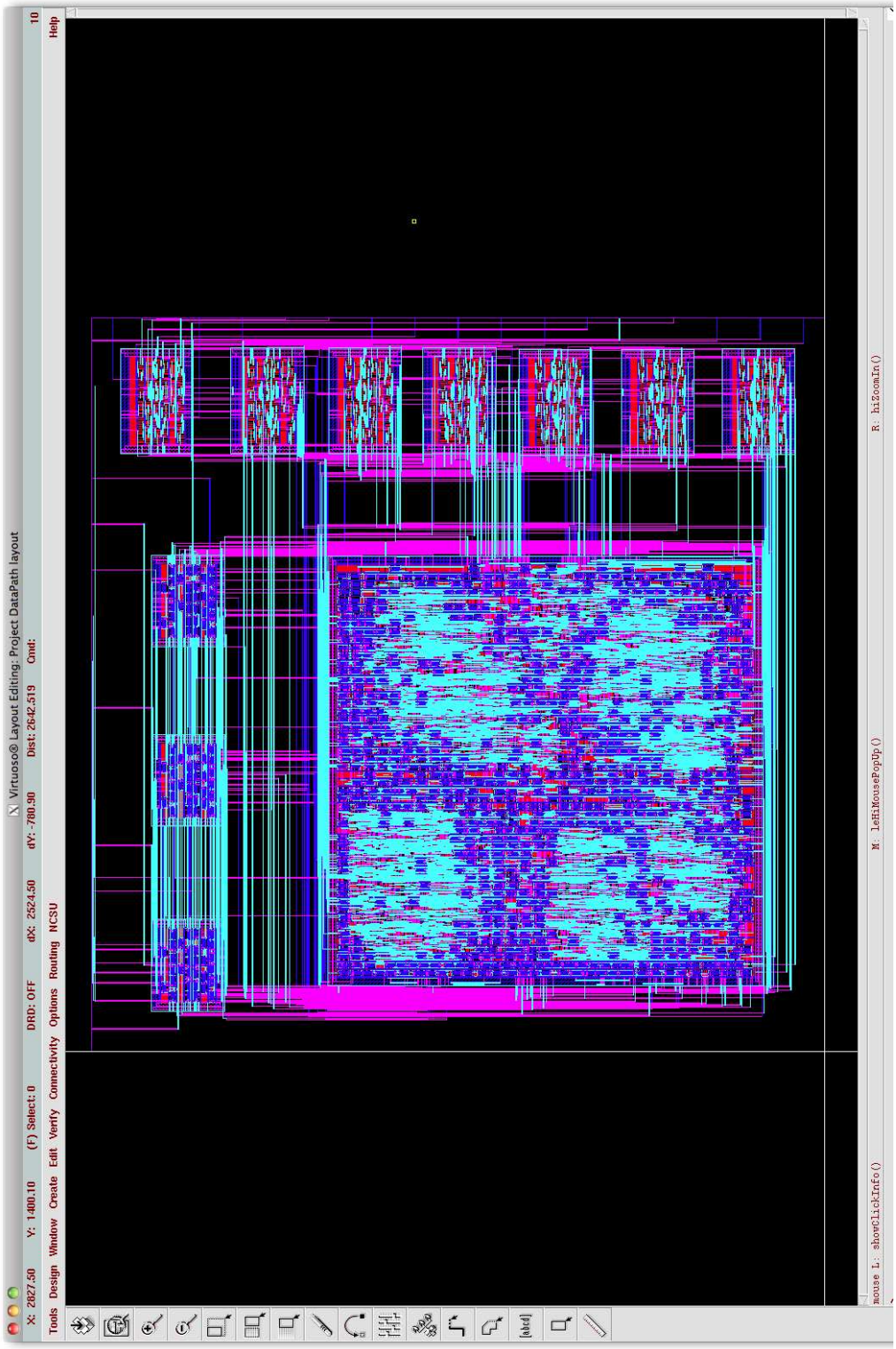

Figure 9: Filter Routed.

A VHDL Design Files

A.1 Top Level

A.1.1 Test Bench (`filter_tb.vhd`)

```
1  library IEEE;
2  use IEEE.std_logic_1164.all;
3  use IEEE.std_logic_signed.all;
4  use IEEE.numeric_std.all;
5  use IEEE.std_logic_textio.all;
6  library STD;
7  use STD.textio.all;
8
9  entity TB is
10 end TB;
11
12 architecture FILTER_TEST of TB is
13
14     -- Inputs.
15     signal sample: std_logic_vector(15 downto 0);
16     signal load: std_logic;
17
18     -- Output.
19     signal filtered: std_logic_vector(15 downto 0);
20
21     component FILTER is
22         port (
23             sample: in std_logic_vector(15 downto 0);
24             load: in std_logic;
25             filtered: out std_logic_vector(15 downto 0)
26         );
27     end component;
28
29     --type TEXTFILE is file of String;
30     file INFILE: TEXT open READ_MODE is "input.txt";
31     file OUTFILE: TEXT open WRITE_MODE is "output.txt";
32
33     for C0: FILTER use entity work.FILTER(BEHAVIORAL);
34 begin
35
36     C0: FILTER port map (sample, load, filtered);
37
38     process
39         variable v_ln: line;
```

```
40          variable v_sample: std_logic_vector(15 downto 0);
41      begin
42          sample <= "0000000000000000";
43          for I in 0 to 50 loop
44              load <= '0';
45              wait for 100 ps;
46              load <= '1';
47              wait for 100 ps;
48          end loop;
49
50          load <= '0';
51          for I in 0 to 100 loop
52              readline(INFILE, v_ln);
53              read(v_ln, v_sample);
54              sample <= v_sample;
55              load <= '0';
56              write(v_ln, filtered);
57              writeline(OUTFILE, v_ln);
58              wait for 10 ns;
59              load <= '1';
60              wait for 10 ns;
61          end loop;
62          wait;
63      end process;
64
65  end FILTER_TEST;
```

A.1.2 Top Level Component (`filter.vhd`)

```
1   library IEEE;
2   use IEEE.std_logic_1164.all;
3   use IEEE.std_logic_unsigned.all;
4   use IEEE.numeric_std.all;
5
6   entity FILTER is
7       port (
8           sample: in std_logic_vector(15 downto 0);
9           load: in std_logic;
10          filtered: out std_logic_vector(15 downto 0)
11      );
12  end FILTER;
13
14  architecture BEHAVIORAL of FILTER is
```

```
15      signal D0, D1, D2, D3, D4, D5, D6: std_logic_vector(15 downto
            0);
16      signal M0, M1, M2, M3: std_logic_vector(15 downto 0);
17      signal c_out: std_logic;
18
19      component SHIFT_REG is
20          port (
21              sample: in std_logic_vector(15 downto 0);
22              load: in std_logic;
23              D0, D1, D2, D3, D4, D5, D6: out std_logic_vector(15
                    downto 0)
24          );
25      end component;
26
27      component SUM16 is
28          port (
29              M0, M1, M2, M3: in std_logic_vector(15 downto 0);
30              S: out std_logic_vector(15 downto 0);
31              c_out: out std_logic
32          );
33      end component;
34
35      component CONV_MULT is
36          port (
37              D0, D1, D2, D3, D4, D5, D6: in std_logic_vector(15
                    downto 0);
38              C0, C1, C2, C3: in std_logic_vector(15 downto 0);
39              M0, M1, M2, M3: out std_logic_vector(15 downto 0)
40          );
41      end component;
42
43      for SR0: SHIFT_REG use entity work.SHIFT_REG(BEHAVIORAL);
44      for CM0: CONV_MULT use entity work.CONV_MULT(BEHAVIORAL);
45      for SUM0: SUM16 use entity work.SUM16(BEHAVIORAL);
46
47  begin
48
49      SR0: SHIFT_REG port map (sample, load, D0, D1, D2, D3, D4, D5
            , D6);
50
51      CM0: CONV_MULT port map (D0, D1, D2, D3, D4, D5, D6,
52              "1111110100011010", "0000000000000000",
53              "0010001100010001", "0011111110101001",
54              M0, M1, M2, M3);
55      SUM0: SUM16 port map (M0, M1, M2, M3, filtered, c_out);
```

```
56
57 end BEHAVIORAL;
```

A.2 Shift Register

A.2.1 Shift Register (`shiftreg.vhd`)

```
1  library IEEE;
2  use IEEE.std_logic_1164.all;
3  use IEEE.std_logic_signed.all;
4  use IEEE.numeric_std.all;
5
6  entity SHIFT_REG is
7      port (
8          sample: in std_logic_vector(15 downto 0);
9          load: in std_logic;
10         D0, D1, D2, D3, D4, D5, D6: out std_logic_vector(15
               downto 0)
11     );
12 end SHIFT_REG;
13
14 architecture BEHAVIORAL of SHIFT_REG is
15
16     signal T0, T1, T2, T3, T4, T5, T6: std_logic_vector(15 downto
           0);
17
18     component D_FF is
19         port(
20             D: in std_logic_vector(15 downto 0);
21             CLK: in std_logic;
22             Q: out std_logic_vector(15 downto 0)
23         );
24     end component;
25
26     for C0: D_FF use entity work.D_FF(BEHAVIORAL);
27     for C1: D_FF use entity work.D_FF(BEHAVIORAL);
28     for C2: D_FF use entity work.D_FF(BEHAVIORAL);
29     for C3: D_FF use entity work.D_FF(BEHAVIORAL);
30     for C4: D_FF use entity work.D_FF(BEHAVIORAL);
31     for C5: D_FF use entity work.D_FF(BEHAVIORAL);
32     for C6: D_FF use entity work.D_FF(BEHAVIORAL);
33
34 begin
```

```
35
36      C0: D_FF port map (sample, load, T0);
37      C1: D_FF port map (T0, load, T1);
38      C2: D_FF port map (T1, load, T2);
39      C3: D_FF port map (T2, load, T3);
40      C4: D_FF port map (T3, load, T4);
41      C5: D_FF port map (T4, load, T5);
42      C6: D_FF port map (T5, load, T6);
43
44      D0 <= T0;
45      D1 <= T1;
46      D2 <= T2;
47      D3 <= T3;
48      D4 <= T4;
49      D5 <= T5;
50      D6 <= T6;
51
52  end BEHAVIORAL;
```

A.2.2 D-Flip Flop (`dff.vhd`)

```
1  library ieee;
2  use ieee.std_logic_1164.all;
3
4  entity D_FF is
5      port(
6          D: in std_logic_vector(15 downto 0);
7          CLK: in std_logic;
8          Q: out std_logic_vector(15 downto 0)
9      );
10 end D_FF;
11
12 architecture BEHAVIORAL of D_FF is
13
14    signal a, b, c, e, f, g, h, lclk: std_logic_vector(15 downto
        0) := "0000000000000000";
15
16 begin
17
18      a <= not (D and g) after 100 ps;
19      b <= not (a and c) after 100 ps;
20      c <= not (b and lclk) after 100 ps;
21      e <= not (c and f) after 100 ps;
22      f <= not (g and e) after 100 ps;
```

```
23      g <= not (c and lclk and a) after 100 ps;
24      h <= e xor D after 100 ps;
25      --lclk <= h and (15 downto 0 => CLK) after 100 ps;
26      lclk <= (15 downto 0 => CLK) after 100 ps;
27
28      Q <= e;
29
30  end BEHAVIORAL;
```

A.3 Convolution

A.3.1 Convolution (convmult.vhd)

```
1   library IEEE;
2   use IEEE.std_logic_1164.all;
3   use IEEE.std_logic_signed.all;
4   use IEEE.numeric_std.all;
5
6   entity CONV_MULT is
7       port (
8           D0, D1, D2, D3, D4, D5, D6: in std_logic_vector(15 downto
                0);
9           C0, C1, C2, C3: in std_logic_vector(15 downto 0);
10          M0, M1, M2, M3: out std_logic_vector(15 downto 0)
11      );
12  end CONV_MULT;
13
14  architecture BEHAVIORAL of CONV_MULT is
15      signal A0, A1, A2, A3: std_logic_vector(16 downto 0);
16      signal B0, B1, B2, B3: std_logic_vector(32 downto 0);
17  begin
18
19      -- Addition for taking advantage of the filter symmetricity.
20      -- Result is in Q1.15.
21      A0 <= (D0(15) & D0) + (D6(15) & D6);
22      A1 <= (D1(15) & D1) + (D5(15) & D5);
23      A2 <= (D2(15) & D2) + (D4(15) & D4);
24      A3 <= (D3(15) & D3);
25
26      -- Multiply by coeffs.
27      B0 <= A0 * C0;
28      B1 <= A1 * C1;
29      B2 <= A2 * C2;
```

```
30      B3 <= A3 * C3;
31
32      -- Convert from Q1.31 to Q15.
33      M0 <= B0(31 downto 16);
34      M1 <= B1(31 downto 16);
35      M2 <= B2(31 downto 16);
36      M3 <= B3(31 downto 16);
37
38  end BEHAVIORAL;
```

A.4 Summation

A.4.1 Sum (`sum.vhd`)

```
1   library IEEE;
2   use IEEE.std_logic_1164.all;
3   use IEEE.std_logic_signed.all;
4   use IEEE.numeric_std.all;
5
6   entity SUM16 is
7       port (
8           M0, M1, M2, M3: in std_logic_vector(15 downto 0);
9           S: out std_logic_vector(15 downto 0);
10          c_out: out std_logic
11      );
12  end SUM16;
13
14  architecture BEHAVIORAL of SUM16 is
15      signal S01, S23, S0123: std_logic_vector(15 downto 0);
16      signal C01, C23, C0123: std_logic;
17
18      component ADD16 is
19          port(
20              A, B: in std_logic_vector(15 downto 0);
21              c_in: in std_logic;
22              S: out std_logic_vector(15 downto 0);
23              c_out: out std_logic
24          );
25      end component;
26
27      for c0: ADD16 use entity work.ADD16(BEHAVIORAL);
28      for c1: ADD16 use entity work.ADD16(BEHAVIORAL);
29      for c: ADD16 use entity work.ADD16(BEHAVIORAL);
```

```
30 begin
31
32     c0: ADD16 port map (M0, M1, '0', S01, C01);
33     c1: ADD16 port map (M2, M3, '0', S23, C23);
34     c: ADD16 port map (S01, S23, '0', S0123, C0123);
35
36     c_out <= C01 or C23 or C0123;
37     S <= S0123;
38
39     --S <= M0 + M1 + M2 + M3;
40     --c_out <= '0';
41
42 end BEHAVIORAL;
```

A.4.2 16-Bit Adder (`add16.vhd`)

```
1  library IEEE;
2  use IEEE.std_logic_1164.all;
3  use IEEE.std_logic_signed.all;
4  use IEEE.numeric_std.all;
5
6  entity ADD16 is
7      port (
8          A, B: in std_logic_vector(15 downto 0);
9          c_in: in std_logic;
10         S: out std_logic_vector(15 downto 0);
11         c_out: out std_logic
12     );
13 end ADD16;
14
15 architecture BEHAVIORAL of ADD16 is
16     signal im: std_logic_vector(14 downto 0);
17
18     component FULL_ADDER is
19         port(
20             a      : in std_logic;
21             b      : in std_logic;
22             c_in   : in std_logic;
23             sum    : out std_logic;
24             c_out  : out std_logic
25         );
26     end component;
27 begin
28
```

```
29      c0: FULL_ADDER port map(A(0), B(0), c_in, S(0), im(0));
30
31      c: for i in 1 to 14 generate
32          c1to14: FULL_ADDER port map (A(i), B(i), im(i-1), S(i),
                im(i));
33      end generate;
34
35      c15: FULL_ADDER port map(A(15), B(15), im(14), S(15), c_out);
36
37  end BEHAVIORAL;
```

A.4.3 Full Adder (`fulladder.vhd`)

```
1   library IEEE;
2   use IEEE.std_logic_1164.all;
3   use IEEE.std_logic_signed.all;
4   use IEEE.numeric_std.all;
5
6   entity FULL_ADDER is
7       port(
8           a      : in std_logic;
9           b      : in std_logic;
10          c_in   : in std_logic;
11          sum    : out std_logic;
12          c_out  : out std_logic
13      );
14  end FULL_ADDER;
15
16  architecture BEHAVIORAL of FULL_ADDER is
17  begin
18
19      sum <= a xor b xor c_in;
20      c_out <= (a and b) or (c_in and (a or b));
21
22  end BEHAVIORAL;
```

B C++ Files for Verification

B.1 C++ Source Code (`filter.cpp`)

```
1  #include <iostream>
2  #include <iomanip>
3  #include <cmath>
4
5  typedef short Q15;
6
7  inline Q15 double_to_q15(double x)
8  {
9      return x * 32768.0;
10 }
11
12 inline double q15_to_double(Q15 x)
13 {
14     return x / 32768.0;
15 }
16
17 void print_q15(Q15 x)
18 {
19     for (int i = 15; i >= 0; i--) {
20         std::cout << ((x >> i) & 0x01);
21     }
22 }
23
24 Q15 lpf(Q15 *history, const Q15 *coeffs, Q15 data)
25 {
26     Q15 result = 0;
27
28     for (int i = 5; i >= 0; i--) {
29         history[i + 1] = history[i];
30     }
31     history[0] = data;
32
33     Q15 m0 = (coeffs[0] * (history[0] + history[6])) >> 16;
34     Q15 m1 = (coeffs[1] * (history[1] + history[5])) >> 16;
35     Q15 m2 = (coeffs[2] * (history[2] + history[4])) >> 16;
36     Q15 m3 = (coeffs[3] * (history[3])) >> 16;
37
38     return m0 + m1 + m2 + m3;
39 }
40
41 int main(void)
42 {
43     static const Q15 coeffs[] = {
44             double_to_q15(-0.022663985459552),
45             double_to_q15(0.0),
```

```
46              double_to_q15(0.273977082565524),
47              double_to_q15(0.497373805788057)
48      };
49
50      // Generate input data.
51      static const int DATA_LEN = 128;
52      double data_double[DATA_LEN];
53      Q15 data[DATA_LEN];
54      for (int i = 0; i < DATA_LEN; i++) {
55          double theta = 360 * i / 180.0 * 3.1415 / DATA_LEN;
56          data_double[i] = std::sin(theta) * 0.5;
57          data_double[i] += 0.2 * ((2.0 * rand() / RAND_MAX) - 1.0)
                ;
58          data[i] = double_to_q15(data_double[i]);
59      }
60
61      // Print coeffs.
62      std::cout << "Coeffs:\n";
63      for (int i = 0; i < 4; i++) {
64          std::cout << "c" << i << " = ";
65          print_q15(coeffs[i]);
66          std::cout << "\n";
67      }
68
69      // Print input data.
70      std::cout << "Input:\n";
71      for (int i = 0; i < DATA_LEN; i++) {
72  #if 0
73          std::printf("%16.8f", data_double[i]);
74          std::cout << "\t";
75  #else
76          print_q15(data[i]);
77  #endif
78          std::cout << "\n";
79      }
80
81      // Print output data.
82      std::cout << "Output:\n";
83      Q15 history[] = {0, 0, 0, 0, 0, 0, 0};
84      for (int i = 0; i < DATA_LEN; i++) {
85          Q15 result = lpf(history, coeffs, data[i]);
86  #if 0
87          std::printf("%16.8f", q15_to_double(result) );
88          std::cout << "\t";
89  #else
```

```
90          print_q15(result);
91 #endif
92          std::cout << '\n';
93      }
94
95      return 0;
96 }
```

B.2 Test Case (testcase.txt)

```
1  Coeffs:
2  c0 = 1111110100011010
3  c1 = 0000000000000000
4  c2 = 0010001100010001
5  c3 = 0011111110101001
6  Input:
7  1110011001100111
8  1111000001000111
9  0001001101011100
10 0000011101000101
11 0000111000101001
12 0000000100101001
13 1111101101100011
14 0001111010110111
15 0010000110101011
16 0011000110011110
17 0001100000110100
18 0010000111100101
19 0011010010000000
20 0000111001001011
21 0001000110111100
22 0010110001111111
23 0011011000000100
24 0001011000110110
25 0010101110000000
26 0001110100111001
27 0011000011111101
28 0100000001110100
29 0011110011111111
30 0100111111100100
31 0100110011011001
32 0011110110100011
33 0010100001011010
```

34 0100010111110110
35 0011101001111000
36 0100100110011011
37 0101010010110011
38 0100110101011000
39 0011001111010110
40 0010100011000000
41 0100101111000111
42 0011011010000011
43 0100010110001111
44 0100101100110110
45 0101011001100010
46 0011010101011101
47 0010111000101101
48 0101001010010000
49 0100001111011000
50 0100001111011110
51 0011110011111001
52 0001110110000111
53 0011100000110111
54 0100001100011110
55 0010000110011110
56 0010011110111010
57 0011011000111111
58 0010010011111101
59 0001011000100010
60 0001010101100001
61 0001011011110111
62 0000101001001011
63 0001011111001110
64 0010100111101101
65 0010011110001000
66 1111100100001111
67 0010000100110101
68 0000100110100000
69 0000011100011100
70 1111100111100010
71 0001100011101100
72 1111110010001111
73 1110110111000011
74 1110000110101010
75 0000101001110010
76 1101101010100010
77 1110110101110111
78 1110010010000100

79 1101110000011010
80 1111100111010101
81 1110001101011101
82 1101110101001001
83 1111001100001000
84 1100001011011001
85 1110010011001100
86 1110001011011101
87 1110001110001001
88 1011110101101000
89 1011010110111111
90 1101011001000000
91 1101110110100101
92 1100111110111110
93 1101001110101000
94 1101000110110001
95 1101111001110011
96 1101011110100100
97 1011010100011010
98 1011100000000001
99 1011100110011011
100 1100000101100000
101 1100010011111010
102 1101000111001011
103 1011101110000000
104 1101000110010000
105 1011010010000000
106 1011110001011101
107 1100001100100100
108 1100000001000110
109 1011011111011100
110 1011001101000101
111 1011001100100100
112 1100100111010000
113 1101011100001010
114 1011000100110010
115 1100110010001100
116 1100110010000011
117 1110010111010110
118 1101110101001001
119 1101010110001001
120 1110100100000101
121 1101110111001001
122 1110101101100010
123 1100101100000100

```
1101000001100010
1110110011010001
1101000110110101
1101001010001111
1101111011100100
1101001111110111
1110110000001101
1101101101001000
0000000101010111
0001000000100010
1110111110001001
Output:
0000000001001010
0000000000101101
1111110001000101
1111011101100100
1111101100010010
0000001110100011
0000011010111100
0000010010000000
0000000011111101
0000001010010010
0000101100101101
0001001011111001
0001001110111000
0001000011110001
0001001001011001
0001001010010110
0000110001001000
0000101111010010
0001001111001101
0001011000010010
0001001000011110
0001000010100000
0001001010100001
0001011111011010
0001110110111010
0010000111101000
0010010110111011
0010010011111000
0001111000000101
0001101001010001
0001110100011001
0010000010100001
0010010011011101
```

169 0010100001111011
170 0010010001101000
171 0001101110011100
172 0001100111011100
173 0001111000101000
174 0001111111100101
175 0010000111111111
176 0010011010101101
177 0010010110001001
178 0001110111011110
179 0001110001111010
180 0010001001111001
181 0010010010001000
182 0010000101011100
183 0001101011001110
184 0001011000111101
185 0001100111111110
186 0001101110110000
187 0001011000111101
188 0001010100000101
189 0001011011111110
190 0001001100000100
191 0000110011101101
192 0000101010011010
193 0000100100100110
194 0000100001000100
195 0000110011101000
196 0001001001110110
197 0000111001100100
198 0000011111100010
199 0000100000110111
200 0000011100101110
201 0000001001011101
202 0000001010110001
203 0000010100011110
204 1111111111011011
205 1111011101010011
206 1111011101001111
207 1111100110101010
208 1111011000110101
209 1111001011101010
210 1111000111101001
211 1111001101000101
212 1111010111111010
213 1111010001000110

214 1111001001100001
215 1111000000001010
216 1110101111101111
217 1110111000000010
218 1111001000011100
219 1110110011111000
220 1110001000010000
221 1101111110010000
222 1110011110010000
223 1110110001100110
224 1110101001101111
225 1110100011110001
226 1110101100001011
227 1110110100100100
228 1110100001100111
229 1101111100110110
230 1101101100111101
231 1101110100000111
232 1110000001010001
233 1110001111000000
234 1110010010110000
235 1110001110111111
236 1110001000010100
237 1101111011010110
238 1101111000010111
239 1110000001000010
240 1101111110101000
241 1101110000110010
242 1101100110101001
243 1101110010010001
244 1110001111001000
245 1110010100001011
246 1110000011101000
247 1110001001011100
248 1110100110000001
249 1110111011010110
250 1110111011101111
251 1110111001011000
252 1111000010101101
253 1111001001110010
254 1110111110011111
255 1110101001000010
256 1110101100101011
257 1110111011110111
258 1110110010111010

```
1110101010010101
1110110000100100
1110111001001001
1111000001001110
1111010011100000
```