Using MMX™ Technology Instructions to Implement a 2/3T Equalizer

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CONTENTS

1.0. INTRODUCTION
2.0. THE 2/3T SPACED EQUALIZER ALGORITHM
3.0. CODE PARTITIONING AND DATA STORAGE FORMAT
4.0. THE FILTER OPERATION (STEP 1 OF LOOP B)
5.0. ADAPTATION/UPDATE OF FILTER COEFFICIENTS (STEP 3 OF LOOP B)
6.0. SCALAR CODE SEGMENT (STEP 2 OF LOOP B)
APPENDIX A
APPENDIX B
APPENDIX C
1.0. INTRODUCTION

The Intel Architecture media extensions include single-instruction, multi-data (SIMD) instructions. This application note presents example code that implements a 2/3T Spaced Equalizer algorithm on complex arithmetic data using the media extensions. First, a brief description of the 2/3T Spaced Equalizer algorithm is given below. Next, the C language implementation of the 2/3T Spaced Equalizer algorithm is analyzed and partitioned from a performance efficiency viewpoint. Subsequently, its implementation and optimization using MMX technology instructions are discussed. The improved performance is achieved by using instruction pairing and MMX technology features such as data packing, performing four word multiplies and two double word adds in three cycles.

2.0. THE 2/3T SPACED EQUALIZER ALGORITHM

This algorithm is an example of an adaptive filter. It primarily consists of three loops, which perform the following operations (refer to the C code given in Appendix A for details):

Loop A: (Loop over input sequence length)
- Tempreal[k] = Inputreal[i];
- Tempimag[k] = Inputimag[i];
  where k = (a constant) * 2 + i; i = 0, 1, ..N-1

Loop B: (Loop over one-third the input sequence length)
- This loop consists of two inner loops with a scalar code segment between these two inner loops. The primary functionality performed during each pass of this loop can be categorized into the following three basic operations:
  
  Step 1. Filters the input data (loop over filter coefficient length).
  This operation involves a complex multiplication (four multiply and two add operations), and a complex summation (two add operations).
  \[
  \begin{align*}
  \text{Sumreal} &= (\text{Inputreal}(k) \times \text{Coeffreal}(i) - \text{Inputimag}(k) \times \text{Coeffimag}(i)) \\
  \text{Sumimag} &= (\text{Inputimag}(k) \times \text{Coeffreal}(i) + \text{Inputreal}(k) \times \text{Coeffimag}(i))
  \end{align*}
  \]
  where i = 0, 1, 2......N-1 and k = (a constant) + 2 * i
  N denotes the number of filter coefficients.

  Step 2. Stores the output and estimates the error (scalar code segment).
  This involves conditional assignments, four add and four shift operations. This is a scalar segment of code and no loops are involved.
  \[
  \begin{align*}
  \text{Outputreal}[k] &= (\text{Sumreal}+0x4000)\gg14; \\
  \text{Outputimag}[k] &= (\text{Sumimag}+0x4000)\gg14; \\
  \text{if} \ (\text{Outputreal}[k] \gggeq 0) \\
  &\quad \text{Errorreal} = (\text{constanta} - \text{outputreal}[k])\gg4 \\
  \text{else} \\
  &\quad \text{Errorimag} = (\text{constantb} - \text{outputimag}[k])\gg4 \\
  \end{align*}
  \]

  Step 3. Adapts/updates the filter coefficients based on the estimated error (loop over filter coefficient length).
  This requires a complex multiplication (four multiply and two add operations), four addition and two shift operations. The result is finally saturated to a 16-bit fixed-point representation.
Temp = Errorreal * Inputreal(k) + Errorimag * Inputimag(k)
Coeffreal(i) = \[(\text{Temp} + 0x4000) >> 15\] + Coeffreal(i)
Temp = Errorimag * Inputreal(k) - Errorreal * Inputimag(k)
Coeffimag(i) = \[(\text{Temp} + 0x4000) >> 15\] + Coeffimag(i)
where i = 0, 1, 2...N-1 and k = (a constant) + 2*i
denotes the number of filter coefficients.

Loop C: (Loop over twice the filter coefficient length)
  Tempreal[i] = Tempreal[k];
  Tempimag[i] = Tempimag[k];
  where k = (a constant) + i; i = 0, 1, 2..N-1

are represented as complex 16 bit fixed point quantities.
3.0. CODE PARTITIONING AND DATA STORAGE FORMAT

In order to create an MMX technology implementation of the compute-intensive segments in the code, it was decided to retain loops A and C (mentioned above) as part of the C code and implement only loop B as part of the MMX technology code (see Appendix B).

Note that in loop B, to perform the filtering operation (step 2), we require the real and imaginary components of the filter coefficients \( h_I \) and \( h_Q \), respectively) as well as of the input data \( s_I \) and \( s_Q \). Since all these are word (16-bit) quantities, we could exploit the PMADDWD instruction to perform the entire complex multiplication in three cycles. This can be accomplished only if the data quantities are stored in the right format and can be fetched as quadwords (64-bit). The subtraction operation involved in the computation of the real component requires that data be not only properly formatted, but also properly modified. The two options available for storing these information (as quadwords) to perform the computation of step 1 are:\n
\[
\begin{array}{c|c|c|c|c|c|c|c}
63 & 31 & 0 & 63 & 31 & 0 \\
\hline
h_I & h_Q & h_I & h_Q & OR & h_I & h_Q & h_I \\
\hline
s_I & s_Q & s_Q & s_I & s_I & s_Q & s_I & s_Q \\
\end{array}
\]

In the option on the left, we need a negative \( s_Q \). In the option on the right, we need a negative \( h_Q \). Note that if we chose to implement the second compute option (the one where negative \( h_Q \) is stored, during adaptation (step 3), it would be difficult to update and store the updated values of \( h_I \) and \( h_Q \) in the same format \( (h_I, -h_Q, h_Q, h_I) \). On the other hand, \( s_I \) and \( s_Q \) are not modified by the code. Hence, it would be easier to store \( (s_I, s_Q) \) in the modified form \( (s_I, -s_Q, s_Q, s_I) \). Consequently, we chose the first compute option for representing \( (h_I, h_Q) \) and \( (s_I, s_Q) \). This also facilitates simultaneous execution of step 1 for the real and imaginary components of the output. After PMADDWD, the upper 32 bits correspond to the real part and the lower 32 bits correspond to the imaginary part. Of course, the (16 bit) real and imaginary components of the output \( (y_I \) and \( y_Q \)) can be packed as one DWORD (32 bit) quantity and stored with one memory store operation.

Note that during adaptation the error term \( (e_I \) and \( e_Q) \) is multiplied with the complex conjugate of \( s_I \) and \( s_Q \). However, to facilitate the filtering operation, \( s_I \) and \( s_Q \) were stored (discussion above) in a format NOT conducive to this multiplication. This complex multiply can still be performed efficiently by properly formatting the error terms. Note that after the execution of the filter operation, the real and imaginary parts of the output are stored in the lower 32 bits of a register. Straightforward processing of this results in the real and imaginary components of the error term also being stored in the same format. This will not facilitate the performance of the complex multiply operation in the adaptation loop because of the format in which \( (s_I, s_Q) \) are stored. Hence, the error term will have to be formatted accordingly. This is not an expensive formatting operation since step 2 is a scalar segment within loop B (unlike steps 1 and 3 which are loops themselves). From the required complex multiplication and the above-mentioned storage scheme for \( (s_I, s_Q) \), we arrive at the following format for the error term:

\[
\begin{array}{c|c|c|c|c}
63 & 31 & 0 & 63 & 31 \\
\hline
h_I & h_Q & h_I & h_Q & OR \\
\hline
s_I & s_Q & s_Q & s_I \\
\end{array}
\]

With these data formats, the complex multiply operations in both steps 1 and 3 can be performed with one PMADDWD instruction (executes in three cycles).
To implement these, the assignment operations in loops A and C should also be properly modified in the C code. The modified C code is shown in Appendix B.

Observe that by storing \((sI, sQ)\) as a 8 byte quantity, the \((sI, sQ)\) index computation in steps 1 and 3 (within loop B) will always result in quad-aligned memory accesses. Likewise, \((hI, hQ)\) and \((yI, yQ)\) fetches and stores, respectively, always result in DWORD-aligned memory accesses.

Penalty:

While all of these data formatting steps have enhanced the performance, the memory requirement for this algorithm has increased. The \((sI, sQ)\) data which originally required four bytes of storage, now needs eight bytes. This, in most cases, is not a serious penalty. The memory requirement for \((hI, hQ)\), however, need not be doubled since it can be easily formatted into the desired form by using the UNPACK instructions available as part of the MMX instruction set:

Final data formats in memory:

<table>
<thead>
<tr>
<th>63</th>
<th>0</th>
<th>31</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>sI</td>
<td>sQ</td>
<td>sQ</td>
<td>sl</td>
</tr>
<tr>
<td>hI</td>
<td>Hq</td>
<td></td>
<td></td>
</tr>
<tr>
<td>yI</td>
<td>yQ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where \((sI, sQ)\) are the input data terms, \((hI, hQ)\) are the filter coefficient terms and \((yI, yQ)\) are the output terms.
4.0. THE FILTER OPERATION (STEP 1 OF LOOP B)

The basic filter operation code is given below. The \((hI, hQ)\) values are stored in memory pointed to by register ebx while the \((sI, sQ)\) values are stored in memory pointed to by register EAX. The partial sum is computed and stored in register MM7. The \((hI, hQ)\) values are unpacked in instruction 2 to prepare for the complex multiplication performed in instruction 3. Please refer to the assembly code in Appendix C during the discussion in this section. Of these four instructions, only instruction 3 is a multi-cycle instruction (three cycles). So each iteration through this loop takes six cycles. Also, none of these instructions can be paired for execution in the same cycle (due to register data dependencies). Hence, for a fully optimized implementation, we have at our disposal, four half cycles that might pair with each of these instructions and two idle cycles between instructions 3 and 4. These provide for a potential of eight additional instructions.

<table>
<thead>
<tr>
<th>Instruction Number</th>
<th>Command</th>
<th>Operands</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MOVD</td>
<td>MM1, [EBX]</td>
</tr>
<tr>
<td>2</td>
<td>PUNPCKLDQ</td>
<td>MM1, MM1</td>
</tr>
<tr>
<td>3</td>
<td>PMADDWD</td>
<td>MM1, [EAX]</td>
</tr>
<tr>
<td>4</td>
<td>PADDD</td>
<td>MM7, MM1</td>
</tr>
</tbody>
</table>

In order to take advantage of these idle cycles, we could fetch and process the \((hI, hQ)\) and \((sI, sQ)\) elements for the next iteration of this loop. Given that each iteration requires four instructions and there is a potential for a total of eight additional instructions, we could process the next two iterations also within this loop. By doing so, we arrive at the resulting code for the optimized loop.

<table>
<thead>
<tr>
<th>Clock Number</th>
<th>Pipe</th>
<th>Data Set</th>
<th>Command</th>
<th>Operands</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>U Pipe</td>
<td>first</td>
<td>MOVD</td>
<td>MM1, [EBX]</td>
</tr>
<tr>
<td>1</td>
<td>V Pipe</td>
<td>second</td>
<td>PADDD</td>
<td>MM7, MM3</td>
</tr>
<tr>
<td>2</td>
<td>U Pipe</td>
<td>second</td>
<td>MOVD</td>
<td>MM3, [4EBX]</td>
</tr>
<tr>
<td>2</td>
<td>V Pipe</td>
<td>first</td>
<td>PUNPCKLDQ</td>
<td>MM1, MM1</td>
</tr>
<tr>
<td>3</td>
<td>U Pipe</td>
<td>first</td>
<td>PMADDWD</td>
<td>MM1, [EAX]</td>
</tr>
<tr>
<td>3</td>
<td>V Pipe</td>
<td>third</td>
<td>PADDD</td>
<td>MM7, MM5</td>
</tr>
<tr>
<td>4</td>
<td>U Pipe</td>
<td>third</td>
<td>MOVD</td>
<td>MM5, [8EBX]</td>
</tr>
<tr>
<td>4</td>
<td>V Pipe</td>
<td>second</td>
<td>PUNPCKLDQ</td>
<td>MM3, MM3</td>
</tr>
<tr>
<td>5</td>
<td>U Pipe</td>
<td>second</td>
<td>PMADDWD</td>
<td>MM3, [16EAX]</td>
</tr>
<tr>
<td>5</td>
<td>V Pipe</td>
<td>third</td>
<td>PUNPCKLDQ</td>
<td>MM5, MM5</td>
</tr>
<tr>
<td>6</td>
<td>U Pipe</td>
<td>third</td>
<td>PMADDWD</td>
<td>MM5, [32EAX]</td>
</tr>
<tr>
<td>6</td>
<td>V Pipe</td>
<td>first</td>
<td>PADDD</td>
<td>MM7, MM1</td>
</tr>
</tbody>
</table>

While ordering these instructions within the loop, attention was paid to the number of cycles each instruction would take before its results would be available for further computation. Another important aspect considered was to ensure that each instruction could be issued to its corresponding U or V pipe in the processor. For example, care was taken to ensure that the memory fetch/store operations would be
issued only to the U pipe. Note that if the length of this loop were not a multiple of three, then one or two sets of elements would have to be computed outside of the loop to take the proper boundary condition into account.

Note that in this case, we did not add any new cycles while attempting to process three elements within each loop. This results in a performance of two cycles per iteration as opposed to the initial implementation which has a performance of six cycles per iteration. This may not always be possible. Based on each application, one will have to evaluate the cycles per iteration. In some cases, it is possible that this number might improve despite the addition of a few cycles to the loop.
5.0. ADAPTATION/UPDATE OF FILTER COEFFICIENTS
(STEP 3 OF LOOP B)

The basic MMX technology version of the adaptation/update operation is given in the table below. Once again, the ebx register points to the memory location where \((hI, hQ)\) are stored and likewise the eax register points to the memory location for \((sI, sQ)\). The complex error term computed earlier is stored in register mm4 while register mm5 contains the rounding constant. Please refer to the assembly code in Appendix C during the discussion in this section.

Instructions 1 and 2 could have been combined into one instruction (PMADDWD MM4, [EAX]). This requires that MM4 be the destination register. But this destroys the error term stored earlier in register MM4. Hence, to retain the error term in register mm4, the memory operand is copied to register mm0 in instruction 1.

Instructions 5, 6 and 7 are used to format the partial result in the desired format so that the complex saturated addition with \((hI, hQ)\) can be executed in one cycle. Refer above to the discussion on the data storage format to observe that the error term is stored in a format different from the format in which \((hI, hQ)\) are stored. These three instructions are the penalty one pays for choosing the above-mentioned storage format. Once again due to data dependencies, most of these instructions cannot be paired. Here again, PMADDWD is the only multi-cycle (three cycles) instruction. Also, like in the filter loop, not much pairing related optimization can be achieved within each iteration due to data dependencies with the loop as given in the following table.

<table>
<thead>
<tr>
<th>Instruction Number</th>
<th>Command</th>
<th>Operands</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MOVQ</td>
<td>MM0, [EAX]</td>
</tr>
<tr>
<td>2</td>
<td>PMADDWD</td>
<td>MM0, MM4</td>
</tr>
<tr>
<td>3</td>
<td>PADD</td>
<td>MM0, MM5</td>
</tr>
<tr>
<td>4</td>
<td>PSRAD</td>
<td>MM0, 15</td>
</tr>
<tr>
<td>5</td>
<td>MOVQ</td>
<td>MM7, MM0</td>
</tr>
<tr>
<td>6</td>
<td>PUNPCKHDQ</td>
<td>MM7, MM7</td>
</tr>
<tr>
<td>7</td>
<td>PUNPCKLWD</td>
<td>MM0, MM7</td>
</tr>
<tr>
<td>8</td>
<td>PADDSW</td>
<td>MM0, [EBX]</td>
</tr>
<tr>
<td>9</td>
<td>MOVD</td>
<td>[EBX], MM0</td>
</tr>
</tbody>
</table>

As in the filter loop, doing a second set of elements within the same iteration of this loop allows much better pairing. It also allows useful work while waiting for the multiplier results. This results in the following table:

<table>
<thead>
<tr>
<th>Instruction Number</th>
<th>Pipe</th>
<th>Data Set</th>
<th>Command</th>
<th>Operands</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>U Pipe</td>
<td>First</td>
<td>MOVQ</td>
<td>MM0, [EAX]</td>
</tr>
<tr>
<td>1</td>
<td>V Pipe</td>
<td>Second</td>
<td>PADD</td>
<td>MM2, MM5</td>
</tr>
<tr>
<td>2</td>
<td>U Pipe</td>
<td>Second</td>
<td>MOVD</td>
<td>MM3, 4[EBX]</td>
</tr>
</tbody>
</table>
Since the number of instructions required to execute in each iteration was greater than the number of idle cycles available in the basic implementation, computation of the second set of elements was initiated prior to entering this loop. This helped ensure optimized execution of the loop with all the instructions being paired except one. Also, by updating the eax register in two steps instead of one, data integrity was ensured during the computation of the two sets of elements within each iteration of the loop. Note that if the loop count were not even, then one set of elements would have to be computed outside of the loop to take the proper boundary condition into account.

Several interesting aspects show up in this table. Note that instruction 6 is not paired. Also, relative to the basic implementation, it seems as if a few more cycles have been added. However, notice that the number of cycles per iteration have been reduced. The optimized version computes one iteration in about 5.5 cycles, whereas the scalar version yields about nine cycles per iteration.
6.0. SCALAR CODE SEGMENT (STEP 2 OF LOOP B)

The scalar section of code between the filter loop and the adaptation loop primarily computes the error term. Relative to the two loops, execution of this code segment has a lower impact on the execution speed performance. The principal code optimization techniques employed here are the elimination of conditional jumps and the re-ordering of instructions to give better pairing of instructions.

The if-then-else statement encountered in step 2 of loop B can be implemented without branches by the following sequence of instructions:

<table>
<thead>
<tr>
<th>Instruction Number</th>
<th>Command</th>
<th>Operands</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PCMPEQW</td>
<td>MM0, MM1</td>
<td>compare if equal to zero</td>
</tr>
<tr>
<td>2</td>
<td>PCMPGTW</td>
<td>MM2, MM1</td>
<td>compare if greater than zero</td>
</tr>
<tr>
<td>3</td>
<td>POR</td>
<td>MM0, MM2</td>
<td>generate boolean pattern for &gt;= zero</td>
</tr>
<tr>
<td>4</td>
<td>PAND</td>
<td>MM3, MM0</td>
<td>place constant if &gt;= zero</td>
</tr>
<tr>
<td>5</td>
<td>PANDN</td>
<td>MM0, MM4</td>
<td>place constant if &lt; zero</td>
</tr>
<tr>
<td>6</td>
<td>POR</td>
<td>MM3, MM0</td>
<td>place constant a or constant b depending on &gt;= zero or &lt; than zero</td>
</tr>
<tr>
<td>7</td>
<td>PSUBW</td>
<td>MM3, MM1</td>
<td>subtract the output term from the corresponding constant term. This result can then be right shifted by four to give the desired error terms.</td>
</tr>
</tbody>
</table>

In the above table, register mm1 contains outputreal in bits 31 to 16 and outputimag in bits 15 to 0. Registers MM0 and MM2 have been initialized to zeros while registers mm3 and mm4 contain constanta and constantb, respectively. The 16 bit quantities, constanta and constantb, will have to be copied onto bits 31 to 16 as well so that they can be used to operate on both outputreal and outputimag terms. This technique allows the real and imaginary parts to be done in parallel, and also eliminates any delays due to branch mispredictions in the traditional implementation of an if-then-else statement.
APPENDIX A

/* The following is the listing of the C code that implements the Equalizer 2/3T algorithm. */
void Equalizer23 (short *sI, short *sQ, short *hI, short *hQ, short *xI, short *xQ, short *yI, short *yQ, short h_Leng, short x_Leng)
{
    Complex v, e;
    short i, j;
    long SumI, SumQ;

    for (i = 0; i < x_Leng; i++) {
        sI[h_Leng*2+i] = xI[i];
        sQ[h_Leng*2+i] = xQ[i];
    }

    for (j = 0; j < x_Leng; j = j+3) {
        for (SumI = 0, SumQ = 0, I = 0; I < h_Leng; i++) {
            SumI = SumI + sI[3+j+2*i] * (long)hI[i] - sQ[3+j+2*i] * (long)hQ[i];
            SumQ = SumQ + sI[3+j+2*i] * (long)hQ[i] + sQ[3+j+2*i] * (long)hI[i];
        }

        yI[j/3] = (SumI+0x4000)>>14;   // with gain 2
        yQ[j/3] = (SumQ+0x4000)>>14;   // with gain 2

        if (yI[j/3] >= 0)  {v.I = 0x0800;} // generate error
        else {v.I = -0x0800;}
        if (yQ[j/3] >= 0)  {v.Q = 0x0800;}
        else {v.Q = -0x0800;}
        e.I = (v.I - yI[j/3])>>4;
        e.Q = (v.Q - yQ[j/3])>>4;

        // adaption
        for (i = 0; i < h_Leng; i++) {
            SumI = e.I*(long)sI[3+j+2*i]+e.Q*(long)sQ[3+j+2*i];
            SumQ = e.Q*(long)sI[3+j+2*i]-e.I*(long)sQ[3+j+2*i];
            SumI = ((SumI+0x4000)>>15)+hI[i];
            SumQ = ((SumQ+0x4000)>>15)+hQ[i];
            hI[i] = SumI;
            hQ[i] = SumQ;
            if (SumI > 0x7fff)  { hI[i] = 0x7fff; } // update initial state
            if (SumI < -0x8000)  { hI[i] = -0x8000; }
            if (SumQ > 0x7fff)  { hQ[i] = 0x7fff; }
            if (SumQ < -0x8000)  { hQ[i] = -0x8000; }
        }
    }

    // update initial state
    for (i = 0; i < 2*h_Leng; i++) {
        sI[i] = sI[x_Leng+i];
        sQ[i] = sQ[x_Leng+i];
    }
}
APPENDIX B

/*
The following is the listing of the modified C code. It is functionally equivalent to the C code given in Appendix A. This version facilitates optimization in the MMX technology based implementation of this function.
*/
#include <stdio.h>
extern void FilAdapAsm(short *sP, short *hP, short *yP, short h_Leng, short x_Leng);

This routine represents the C code of the function that is implemented/optimized in assembly (using MMX technology instructions).

/*
void FilAdapC(short *sP, short *hP, short *yP, short h_Leng, short x_Leng);
void *AlignAlloc(unsigned int nbytes);
void Equalizer23MMx(short *sP, short *hI, short *hQ, short *xI, short *xQ, short *yI, short *yQ, short h_Leng, short x_Leng)
{
    short i, k;
    short *hP, *yP;
    for (i=0; i < x_Leng; i++) {
        k = (h_Leng*2+i)*4;
        sP[k] = xI[i];
        sP[k+1] = xQ[i];
        sP[k+2] = -xQ[i];
        sP[k+3] = xI[i];
        /* sI[h_Leng*2+i] = xI[i]; */
        /* sQ[h_Leng*2+i] = xQ[i]; */
    }
    /* Allocate the space for interleaving hI and hQ. */
    /* The hI/hQ pair will be organized as: Real Imag. */
    /* Unlike the sI/sQ, the hI/hQ pair will not be duplicated. */
    hP = (short *)AlignAlloc(h_Leng*4);
    for (i=0; i < h_Leng; i++) {
        hP[2*i] = hQ[i];
        hP[2*i+1] = hI[i];
    }
    /* Allocate the space for interleaving yI and yQ. */
    /* The yI and yQ output by FilAdapC will be organized as: Real Imag. */
    yP = (short *)AlignAlloc(x_Leng*4);
    FilAdapAsm(sP, hP, yP, h_Leng, x_Leng);
    /*
    FilAdapC(sP, hP, yP, h_Leng, x_Leng);
    */
    /* update initial state */
    for (i=0; i < 2*h_Leng; i++) {
        k = (x_Leng+i)*4;
        sP[4*i] = sP[k];
        sP[4*i+1] = sP[k+1];
        sP[4*i+2] = sP[k+2];
        sP[4*i+3] = sP[k+3];
        /* sI[i] = sI[x_Leng+i]; */
        /* sQ[i] = sQ[x_Leng+i]; */
    }
    /* Update yI and yQ as modified by FilAdapC */
    for (i=0; i < x_Leng; i++) {
        yI[i/3] = yP[((i/3)*2)+1];
    }
}*/
void FilAdapC(short *sP, short *hP, short *yP, short h_Leng, short x_Leng) {
    short vI, vQ, eI, eQ;
    short i, j, k;
    long SumI, SumQ;
    for (j=0; j < x_Leng; j=j+3) {
        for (SumI=0, SumQ=0, i=0; i<h_Leng; i++) {
            k = 3+j+2*i ;
            SumI=SumI+sP[4*k]*(long)hP[2*i+1]-sP[4*k+1]*(long)hP[2*i];
            SumQ=SumQ+sP[4*k]*(long)hP[2*i]+sP[4*k+1]*(long)hP[2*i+1];
        }
        k = (j/3)*2 ;
        yP[k+1]=(SumI+0x4000)>>14;   /* with gain 2   */
        yP[k]=(SumQ+0x4000)>>14;     /* with gain 2   */
        /* generate error   */
        if (yP[k+1]>=0) {vI=0x0800;} else {vI=-0x0800;}
        if (yP[k]>=0) {vQ=0x0800;} else {vQ=-0x0800;}
        eI=(vI-yP[k+1])>>4;
        eQ=(vQ-yP[k])>>4;
        /* adaption   */
        for (i=0; i<h_Leng; i++) {
            k = 3+j+2*i ;
            SumI=eI*(long)sP[4*k]+eQ*(long)sP[4*k+1];
            SumQ=eQ*(long)sP[4*k]-eI*(long)sP[4*k+1];
            SumI = ((SumI+0x4000)>>15)+hP[2*i+1];
            SumQ = ((SumQ+0x4000)>>15)+hP[2*i];
            hP[2*i+1] = SumI ;
            hP[2*i] = SumQ ;
            if (SumI>0x7fff) { hP[2*i+1]=0x7fff; } if (SumI<0x8000) { hP[2*i+1]=-0x8000; }
            if (SumQ>0x7fff) { hP[2*i]=0x7fff; } if (SumQ<-0x8000) { hP[2*i]=-0x8000; }
        }
    }
}

void *AlignAlloc(unsigned int nbytes) {
    char *cptr;
    cptr = (char *)malloc(nbytes+8);
    if (!cptr) {
        perror("malloc: Error allocating memory");
        exit(1);
    }
    cptr = (char *)((unsigned long)cptr & 0xFFFFFFFF8);
    return(cptr);
}
APPENDIX C

; The following is the listing of the optimized (using MMX technology; instructions) assembly code.

INCLUDE iammx.inc
TITLE fil2t3
486P
; INCLUDE listing.inc
.model FLAT

_DATA SEGMENT
; Define all the constants/local variables
; const_rnd: to store the rounding value
; pos_bias: to store the positive bias for clipping
; neg_bias: to store the negative bias for clipping
; err_fmt_one: pattern "ffff0000 0000ffff" used while formatting the error value
; err_fmt_two: pattern "0000ffff ffff0000" used while formatting the error value
const_rnd DWORD 4000H, 4000H
pos_bias DWORD 08000800H
neg_bias DWORD 0f800f800H
err_fmt_one DWORD 0000ffffH, 0ffff0000H
err_fmt_two DWORD 0ffff0000H, 0000ffffH

_DATA ENDS

; ************************** ASSUMPTIONS **************************
; The real(sI) & imag.(sQ) terms of the data input are stored as:
; bits->  63...  ...0
;   sI : -sQ : sQ : sI
; Before the second inner loop(adaption operation), the real(eI)
; and imag.(eQ) components of the error term will be formatted as:
; bits->  63...  ...0
;   eI : -eQ : -eQ : eI
; The real(hI) & imag.(hQ) terms of the filter coeff. are stored as:
; bits->  31...  ...0
;   hQ : hI
; The real(yI) & imag.(yQ) terms of the output are stored as:
; bits->  31...  ...0
;   yQ : yI
; ****************************************************************************

_TEXT SEGMENT
; setup the pointers for sI/sQ, hI/hQ, yI/yQ.
; also set the pointers for storing the input length
; and filter coefficient length.
sPtr$ = 28
_hPtr$ = 32
_yPtr$ = 36
_hLen$ = 40
_xLen$ = 44
PUBLIC _FilAdapAsm
_FilAdapAsm PROC NEAR USES ebx ecx edx ebp esi edi
; store sI/sQ pointer in ecx
; store hI/hQ pointer in edx
; store yI/yQ pointer in ebp
; store the input data length in di
; store the filter coeff length in loop_count
MOV ecx, _sPtr$[esp]
MOV edx, _hPtr$[esp]
MOV ebp, _yPtr$[esp]
MOV di, _xLen$[esp]

; This loop embeds two inner loops. The first inner loop performs
; the filtering operation. The second inner loop performs the adaption
; of the filter coefficients. Between the two inner loops, there is a
; scalar section of code that calculates the output and the error terms.

outerLoop:
  MOV ebx, edx    ; copy hIQ ptr into ebx
  PXOR mm7, mm7   ; initialize mm7 to zeros.
  ; One of the partial sums in
  ; innerloop1 will be stored in
  ; mm7

  MOV si, _hLen$[esp]; copy filter length to si
  ; this will be the loop
  ; counter for innerloop1
  ; Note that this assumes no
  ; stack pushes are done
  ; within this code
  ; If needed, this can easily be
  ; avoided by storing this
  ; value in a local variable

  PXOR mm5, mm5   ; initialize mm5 to zeros
  ; mm5 will be used in
  ; innerloop1
  ; to store one of the partial
  ; results of complex multiply

  ADD ecx, 24 ; initialize ecx to point to
  ; first element of sIQ for
  ; next iteration of innerloop1

  MOV eax, ecx    ; copy sIQ pointer to eax.
  ; eax will be used within
  ; innerloop1 to point to
  ; subsequent elements of sIQ

  PXOR mm3, mm3   ; initialize mm3 to zeros.
  ; One of the partial sums in
  ; innerloop1 will be stored in
  ; mm3. mm1 will also be
  ; used in storing
  ; the partial sum. But it does
  ; not have to be initialized to
  ; zeros since it is used only
  ; towards the end of the
  ; loop(after calculating the
  ; partial product).

  ; This loop performs the filtering operation. It computes the intermediate
  ; sum used in calculating the output terms(real and imaginary).

Inner Loop1:
  MOVD mm1, [ebx] ; fetch first element
  ; of hIQ

  PADD mm7, mm3 ; accumulate 2nd partial
  ; product in mm7

  MOVD mm3, 4[ebx] ; fetch second element of
  ; hIQ

  PUNPCKLDQ mm1, mm1 ; copy 1st hIQ into upper
  ; half of mm1
PMADDWD mm1, [eax] ; complex multiply the first
; set of sIQ and hIq
; elements
PADD mm7, mm5 ; accumulate 3rd partial
; product in mm7
MOV mm5, 8[ebx] ; fetch third element of hIq
PUNPCKLDQ mm3, mm3 ; copy 2nd hIq into upper
; half of mm3
PMADDWD mm3, 16[eax] ; complex multiply the
; second set of sIQ and hIq
; elements
PUNPCKLDQ mm5, mm5 ; copy 3rd hIq into upper
; half of mm5
PMADDWD mm5, 32[eax] ; complex multiply the third
; set of sIQ and hIq
; elements
PADD mm7, mm1 ; accumulate the 1st partial
; product in mm7
ADD eax, 48 ; update eax to point to
; next sIQ
ADD ebx, 12 ; update ebx to point to next
; hIq
SUB si, 3 ; decrement loop count by
; three
JNZ innerLoop1 ; end of inner loop1
MOV mm6, const_rnd ; fetch the rounding constant
PADD mm7, mm3 ; accumulate the partial product
; from the last iteration of innerloop1
MOV mm2, pos_bias ; fetch the positive bias for clipping
PADD mm7, mm5  ; accumulate the partial product
; from the last iteration of innerloop1
MOV mm3, neg_bias ; fetch the negative bias for clipping
PADD mm7, mm6  ; add the rounding constant to sumIQ
PSRAD mm7, 14 ; signed shift right the real and imag.
; terms of sumIQ by 14 bits. The real
; and
; imag. terms of the output are now in
; upper & lower 32 bits of mm7
; respectively
PXOR mm0, mm0 ; initialize mm0 to zeros. used for
; checking the output for zero equality
MOV mm6, mm7 ; copy the output(yIQ) into mm6
PXOR mm1, mm1 ; initialize mm1 to zeros
MOV mm5, err_fmt_one ; fetch 1st constant for formatting
; the error term
PUNPCKHDQ mm6, mm6 ; copy upper half(yI) of mm6 into lower
PUNPCKLMD mm7, mm6 ; pack yIQ into mm7 with bits[15..0]
; specifying the imag. term and
bits[31..16]
MOV mm4, mm7 ; copy yIQ into mm4
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March 1996

```assembly
    ; check the real and imag. terms of output
    PCMPEQW mm0, mm7          ; check the real & imag. terms of output
                             ; for zero equality
    MOVDD [ebp], mm7          ; store the output
    PCMPGTW mm4, mm1          ; check the real & imag. terms of output
                             ; for > zero
    ADD ebp, 4                ; update ebp to point to next output
    POR mm0, mm4              ; create the boolean pattern to check
                             ; the output terms are >= zero
                             ; store positive bias in mm2
    PAND mm2, mm0             ; if yI >= 0 and yQ >= 0
                             ; store negative bias in mm0
                             ; if yI < 0 and yQ < 0
                             ; compute vI and vQ terms, used in calculating the error terms
                             ; initialize mm4 to zeros
                             ; fetch 2nd constant for formatting
                             ; the error term
                             ; compute the diff. between vIQ and yIQ
                             ; copy sIQ pointer to eax. eax will be used within innerloop2 to point to subsequent elements of sIQ
                             ; signed shift right mm0 by 4 bits
                             ; the real & imag. terms of the error are now in bits [31..16] and bits[15..0]
    PSUBW mm0, mm7            ; respectively
    MOVQ mm2, 16[eax]         ; fetch the 2nd sIQ element for complex multiplication in innerloop2. The 1st sIQ element will be fetched within innerloop2. In this case, the 2nd partial product is being computed before the first one for performance reasons
    PUNPCKLDQ mm0, mm0        ; copy real & imag. error terms to upper half...bits[63..32]
    MOV ebx, edx              ; copy hIQ ptr into ebx. will be used within innerloop2 to point to subsequent elements of hIQ
    PSUBW mm4, mm0            ; compute the negative of real & imag. error terms in mm4...(0 - eI/eQ = -eI/-eQ)
    PAND mm0, mm5             ; format real(eI) & imag(eQ) error terms in
                               ; bits[63..48] & bits[15..0]
    PAND mm4, mm1             ; format -eQ and -eI in bits[47..32]
    MOVQ mm5, const_rnd       ; and bits[31..16] respectively
    POR mm4, mm0              ; fetch the rounding constant
    MOV si, _hLen$[esp]       ; get eIQ in the form: eI:-eQ:-eI:eQ
                               ; copy filter length to si
                               ; this will be the loop counter
```
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March 1996

PMADDWD mm2, mm4

; This loop performs the adaption operation. It calculates the new
; filter coefficient terms.
innerLoop2:

    MOVQ    mm0, [eax] ; fetch the 1st sIQ element
    PADD    mm0, mm5 ; add the rounding constant to
                    ; the 2nd complex product
    MOVQ    mm3, 4[ebx] ; fetch the 2nd hIQ element
    PMADDWD mm0, mm4   ; complex multiply 1st sIQ with
                        ; the error term
    MOVD    mm1, [ebx] ; fetch the 1st hIQ element
    PSRAD   mm2, 15 ; signed shift right 2nd partial product by 15 bits
    MOVD    mm6, mm2 ; copy 2nd partial product to mm6
    ADD     eax, 16 ; partially update eax to point to
                    ; next sIQ.
    PADDD   mm0, mm5 ; add the rounding constant to
                    ; the 1st complex product
    PUNPCKHDQ mm6, mm6 ; copy the real term of the 2nd partial product
                     ; and bits[31..16] respectively
    PUNPCKHDQ mm7, mm7 ; copy the real term of the 1st partial product
                     ; to lower 32 bits of mm6
    PADDSW   mm3, mm2 ; perform saturated addition of the 2nd partial
                    ; product with hIQ
    MOVD    4[ebx], mm3 ; store the (2nd)new filter coeffs.
    PUNPCKLWD mm0, mm7 ; format the real & imag. terms of
                       ; 1st partial product in bits[31..16]
                       ; and bits[15..0] respectively
    MOVQ    mm2, 32[eax] ; fetch the 2nd sIQ element
    PADDSW   mm1, mm0 ; perform saturated addition of the 1st partial
                     ; product with hIQ
    MOVD    [ebx], mm1 ; store the (1st)new filter coeffs.
    PMADDWD mm2, mm4 ; complex multiply 2nd sIQ with
                     ; the error term
    ADD     eax, 16 ; partially update eax to point to
                    ; next sIQ.
    ADD     ebx, 8 ; update ebx to point to next hIQ
    SUB      si, 2 ; decrement loop count by two
    JNZ     innerLoop2 ; end of innerLoop2
    SUB      di, 3 ; decrement outerloop count by 3
    JNZ     outerLoop ; end of outerloop
Done:
    ret 0
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March 1996

_FilAdapAsm ENDP
_TEXT ENDS
END