Fixed Point DSP Software Library

USER’S GUIDE
# Table of Contents

Copyright ................................................................. 2  
Revision Information .................................................. 2  

1 Introduction .......................................................... 4  

2 Other Resources ..................................................... 5  

3 Library Structure ................................................... 6  
3.1 Build Options used to build the library .......................... 7  

4 Using the Fixed Point Library ...................................... 9  
4.1 Library Build Configurations .................................... 9  
4.2 Integrating the Library into your Project ....................... 10  
4.3 Choosing a Q representation for the FFT routines .......... 13  

5 Application Programming Interface (Fixed Point Library) .... 14  
5.1 Fixed Point DSP Module Summary ................................. 14  
5.2 Module Description ................................................ 16  
5.2.1 Complex FFT Bit Reverse Function ............................. 16  
5.2.2 Real FFT Bit Reverse Function ................................. 19  
5.2.3 Real Input Point by Point Bit Reverse Function .......... 22  
5.2.4 32 Bit Complex Fast Fourier Transform Module .......... 25  
5.2.5 32 Bit Real Fast Fourier Transform Module .................. 32  
5.2.6 16 Bit FIR Filter Module ....................................... 39  
5.2.7 32 Bit FIR Filter Module ....................................... 51  
5.2.8 16 Bit IIR Filter Module ....................................... 54  
5.2.9 32 Bit IIR Filter Module ....................................... 59  

6 Revision History ..................................................... 64  

A IIR Filter Design Package User’s Guide .......................... 65  
A.1 IIR Filter Specifications ......................................... 65  
A.2 ezIIR Filter Design Script Usage ................................. 67  
A.3 ezIIR IIR Filter Design Examples ................................ 71  
A.3.1 LPF Design ....................................................... 71  
A.3.2 HPF Design ....................................................... 73  
A.3.3 BPF Design ....................................................... 76  
A.3.4 BSF Design ....................................................... 78  
A.4 Test coefficients for IIR filter .................................. 81  

IMPORTANT NOTICE .................................................. 84  

Oct 20, 2014 3
1 Introduction

The Texas Instruments TMS320C28x Fixed Point DSP Library is a collection of highly optimized application functions written for the C28x. These functions enable C/C++ programmers to take full advantage of the performance potential of the C28x. This document provides a description of each function included within the library.

Chapter 2 provides a host of resources on the C28x in general, as well as training material.

Chapter 3 describes the directory structure of the package.

Chapter 4 provides step-by-step instructions on how to integrate the library into a project and use any of the math routines.

Chapter 5 describes the structures and programming interface for this library

Chapter 6 lists the revision history of the library.

Examples have been provided for each library routine. They can be found in the examples_ccsv5 directory. For the current revision, all examples have been written for the F2833x and tested on a controlCard platform. Each example has a script “SetupDebugEnv.js” that can be launched from the Scripting Console in CCS. These scripts will set-up the watch variables for the example. In some examples graphs (.graphProp) are provided; these can be imported into CCS during debug.
2 Other Resources

The user can get answers to F2833x frequently asked questions (FAQ) from the processors wiki page. Links to other references such as training videos will be posted here as well. [http://processors.wiki.ti.com/index.php/Main_Page](http://processors.wiki.ti.com/index.php/Main_Page)

Also check out the TI Delfino page: [http://www.ti.com/delfino](http://www.ti.com/delfino)

And don’t forget the TI community website: [http://e2e.ti.com](http://e2e.ti.com)

In order to build the library and examples you will require **Codecen Tools v6.2.5 or later**. The tools can be obtained either through a CCS update or through this website: [http://processors.wiki.ti.com/index.php/Compiler_Releases](http://processors.wiki.ti.com/index.php/Compiler_Releases)

The examples require **v133** of the **F2833x** device support files in controlSUITE, which may be found here: [http://www.ti.com/tool/controlsuite](http://www.ti.com/tool/controlsuite).
3 Library Structure

As installed, the C28x Fixed Point Library is partitioned into a well-defined directory structure. The library and source code is installed into the controlSUITE directory,

```
C:\TI\controlSUITE\libs\dsp\FixedPointLib\v1_20_00_00
```

Figure. 3.2 shows the directory structure while the subsequent table 3.1 provides a description for each folder.

Figure 3.1: Directory Structure of the Fixed Point DSP Library
Library Structure

<table>
<thead>
<tr>
<th>Folder</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;base&gt;</td>
<td>Base install directory. By default this is C:/TI/controlSUITE/libs/dsp/FixedPointLib/v1_20_00_00. For the rest of this document &lt;base&gt; will be omitted from the directory names.</td>
</tr>
<tr>
<td>&lt;base&gt;/ccs</td>
<td>Project files for the library. Allows the user to reconfigure, modify and re-build the library to suit their particular needs.</td>
</tr>
<tr>
<td>&lt;base&gt;/cmd</td>
<td>Linker command files used in the examples.</td>
</tr>
<tr>
<td>&lt;base&gt;/doc</td>
<td>Documentation for the current revision of the library including revision history.</td>
</tr>
<tr>
<td>&lt;base&gt;/examples_ccsv5</td>
<td>Examples that illustrate the library functions. At the time of writing these examples were built for the F2833x device using the CCS 5.5.0.00077 IDE.</td>
</tr>
<tr>
<td>&lt;base&gt;/include</td>
<td>Header files for the Fixed Point library. These include function prototypes and structure definitions.</td>
</tr>
<tr>
<td>&lt;base&gt;/lib</td>
<td>Pre-built Fixed Point libraries.</td>
</tr>
<tr>
<td>&lt;base&gt;/source</td>
<td>Source files for the library.</td>
</tr>
<tr>
<td>&lt;base&gt;/test</td>
<td>Test framework for the library routines.</td>
</tr>
<tr>
<td>&lt;EXAMPLE&gt;/matlab</td>
<td>MATLAB reference code. These are useful as they provide a standard input/output reference that the user can check against while debugging.</td>
</tr>
</tbody>
</table>

Table 3.1: Fixed Point Library Directory Structure Description

3.1 Build Options used to build the library

The CCS project for the library was built with C28x Codegen Tools v6.2.5 and has two build configurations

1. ISA_C2800, standard build configuration
2. ISA_C28FPU32, this variant of the library must be used in projects that have the fpu32 support turned on. This does not mean that the library routines use floating point numbers, rather, it gives the user the option to use fixed point routines alongside floating point routines.

![Build Configuration](image)

Figure 3.2: Build Configurations for the Fixed Point DSP Library

**Note:** If the fpu32 option is enabled and the user attempts to use the standard library build configuration it will result in a compiler error about mismatching instruction set architectures.
The **ISA_C2800** build configuration was built with the following options:

```
-v28 -mt -ml -g --diag_warning=225
```

while the **ISA_C28FPU32** build configuration was built with these options:

```
-v28 -mt -ml -g --diag_warning=225 --fpu_support=fpu32
```
4 Using the Fixed Point Library

Library Build Configurations ................................................................. 9
Integrating the Library into your Project .................................................. 10
Choosing a Q representation for the FFT routines ...................................... 13

The source code and project for the Fixed Point library are provided. The user may import the project into CCSv5 (or later) and be able to view and modify the source code for all routines and lookup tables (see Fig. 4.1)

![c28x_fixedpoint_dsp_library](Active - ISA_C2800)

- Includes
- ISA_C2800
- ISA_C28FPU32
- CFFT32_brev.asm
- CFFT32_mag.asm
- CFFT32_win.asm
- FFT32_calc.asm
- FFT32_init.asm
- FFT32_izero.asm
- fir16_altasm
- fir16.asm
- fir32_altasm
- fir32.asm
- iir5biq16.asm
- iir5biq32.asm
- RFFT32_brev_RT.asm
- RFFT32_brevasm
- RFFT32_mag.asm
- RFFT32_split.asm
- RFFT32_win.asm
- sel_q.asm

Figure 4.1: Fixed Point Library Project View

4.1 Library Build Configurations

The current version of the library has two build configurations (Fig. 4.2): ISA_C2800, henceforth referred to as the standard build or standard library, and ISA_C28FPU32, the alternate build or alternate library. The ISA_C28FPU32 configuration is built with the --float_support=fpu32 run-time support option set to fpu32, allowing you to integrate this library into a project where hardware floating point support is enabled. This does not mean that the library routines use floating point numbers, rather, it gives the user the option to use Fixed point routines along-side floating point routines. Running a build on the ISA_C2800 configuration will generate the c28x_fixedpoint_dsp_library.lib while the ISA_C28FPU32 configuration will generate the c28x_fixedpoint_dsp_library_fpu32.lib; both libraries (.lib) will be output to the “lib” folder.
**NOTE:** ATTEMPTING TO LINK IN THE _fpu32 LIBRARY INTO A PROJECT THAT DOES NOT HAVE THE FLOAT_SUPPORT ENABLED WILL RESULT IN A COMPILER ERROR ABOUT MISMATCHING INSTRUCTION SET ARCHITECTURES. THE SAME IS TRUE WHEN LINKING THE STANDARD BUILD INTO A PROJECT WITH FLOATING POINT SUPPORT TURNED ON.

Figure 4.2: Library Build Configurations

### 4.2 Integrating the Library into your Project

To begin integrating the library into your project follow these easy steps:

1. Go to the **Project Properties->Build->Variables(Tab)** and add a new variable (see Fig. 4.3), INSTALLROOT_TO_FIXEDPTLIB, and point it to the root directory of the Fixed Point library in controlsuite, this is usually the version folder.

Figure 4.3: Creating a new build variable
Add the new path, INSTALLROOT_TO_FIXEDPTLIB/include, to the Include Options section of the project properties (Fig. 4.4). This option tells the compiler where to find the library header files.

Figure 4.4: Adding the Library Header Path to the Include Options

2. When using the standard library be sure the –float_support option, in the Runtime Model Options, is disabled. If you intend to use the fixed point library in a project with the –float_support option set to fpu32 (Fig. 4.5), then include the alternate library in your project instead.
Using the Fixed Point Library

Figure 4.5: Runtime Support Options

3. Add the name of the library and its location to the File Search Path as shown in Fig. 4.6. **NOTE:** BE SURE TO USE THE APPROPRIATE LIBRARY, STANDARD OR ALTERNATE, DEPENDING ON THE FLOATING POINT SUPPORT OPTION
4.3 Choosing a Q representation for the FFT routines

The operation and execution time of the FFT routine, FFT32_calc(), is dependent on the Q format selected in the file “sel_q.asm”. The macro TF_QFMAT can be set to either Q30 or Q31; the choice of the Q format decides which twiddle factor table will be used in the calculations.

When changing the value of this macro, TF_QFMAT, the user must rebuild the library for the changes to take effect.
5 Application Programming Interface (Fixed Point Library)

5.1 Fixed Point DSP Module Summary

This release contains the FFT and Filter modules. Other modules may be added in future releases. The functions under the FFT, FIR and IIR categories are member functions of the structure defined for each module and should be invoked through the structure object as opposed to direct function calls. The exception are the bit reversal functions which can only be called directly.

Default macros are provided to aid the user in initializing the module object and assuring the right values are written to each of the object’s elements. This is important, especially in the case of the Complex and Real FFT modules. They both use the complex FFT function, FFT32_calc(), with the difference that an N point real FFT is done by running an N/2 point complex FFT followed by a split operation. The user must, therefore, instantiate an RFFT object with the correct size of the FFT, twiddle factor skip ratio and the number of stages. The use of the initialization macros makes the task straightforward and error free. The following table lists the functions and their prototypes:

<table>
<thead>
<tr>
<th>Description</th>
<th>Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bit Reverse Modules</strong></td>
<td></td>
</tr>
<tr>
<td>CFFT32_brev</td>
<td>void CFFT32_brev(int32 *src, int32 *dst, int16 size );</td>
</tr>
<tr>
<td>RFFT32_brev</td>
<td>void RFFT32_brev(int32 *src, int32 *dst, int16 size );</td>
</tr>
<tr>
<td>RFFT32_brev_RT</td>
<td>void RFFT32_brev_RT(void *);</td>
</tr>
<tr>
<td><strong>FFT Modules</strong></td>
<td></td>
</tr>
<tr>
<td>FFT32_calc</td>
<td>void FFT32_calc(void *);</td>
</tr>
<tr>
<td>FFT32_init</td>
<td>void FFT32_init(void *);</td>
</tr>
<tr>
<td>FFT32_izero</td>
<td>void FFT32_izero(void *);</td>
</tr>
<tr>
<td>CFFT32_mag</td>
<td>void CFFT32_mag(void *);</td>
</tr>
<tr>
<td>CFFT32_win</td>
<td>void CFFT32_win(void *);</td>
</tr>
<tr>
<td>RFFT32_split</td>
<td>void RFFT32_split(void *);</td>
</tr>
<tr>
<td>RFFT32_mag</td>
<td>void RFFT32_mag(void *);</td>
</tr>
<tr>
<td>RFFT32_win</td>
<td>void RFFT32_win(void *);</td>
</tr>
<tr>
<td><strong>FIR Modules</strong></td>
<td></td>
</tr>
<tr>
<td>FIR16_init</td>
<td>void FIR16_init(void *);</td>
</tr>
<tr>
<td>FIR16_calc</td>
<td>void FIR16_calc(void *);</td>
</tr>
<tr>
<td>FIR16_Alt_init</td>
<td>void FIR16_Alt_init(void *);</td>
</tr>
<tr>
<td>FIR16_Alt_calc</td>
<td>void FIR16_Alt_calc(void *);</td>
</tr>
<tr>
<td>FIR32_init</td>
<td>void FIR32_init(void *);</td>
</tr>
<tr>
<td>FIR32_calc</td>
<td>void FIR32_calc(void *);</td>
</tr>
<tr>
<td>FIR32_Alt_init</td>
<td>void FIR32_Alt_init(void *);</td>
</tr>
<tr>
<td>FIR32_Alt_calc</td>
<td>void FIR32_Alt_calc(void *);</td>
</tr>
<tr>
<td><strong>IIR Modules</strong></td>
<td></td>
</tr>
<tr>
<td>IIR5BIQ16_init</td>
<td>void IIR5BIQ16_init(void *);</td>
</tr>
<tr>
<td>IIR5BIQ16_calc</td>
<td>void IIR5BIQ16_calc(void *);</td>
</tr>
<tr>
<td>IIR5BIQ32_init</td>
<td>void IIR5BIQ32_init(void *);</td>
</tr>
<tr>
<td>IIR5BIQ32_calc</td>
<td>void IIR5BIQ32_calc(void *);</td>
</tr>
</tbody>
</table>

Table 5.1: Summary of Library Routines
5.2 Module Description

5.2.1 Complex FFT Bit Reverse Function

Description:
This function reads N-point in-order real data samples, stored in alternate memory locations, and writes it as N-complex data in bit-reversed order, to cater to the bit-reversal requirement of complex FFT. It supports both in-place and off-place bit reversing.

Prototype:
void CFFT32_brev(int16 *src, int16 *dst, int16 size);

Parameters:
- src Pointer to in-order data samples stored in alternate locations.
- dst Pointer to destination array, to store bit revered complex output, the destination array buffer must be aligned to 4N word boundary (16-bit word length) or 2N long words, where N is the size of the complex FFT (a power of 2).
- size Number of real-data samples (N) to be bit reversed in complex form; it should be power of 2.

Header File:
fft.h

Availability:
C-Callable Assembly (CcA)

Usage:
Pointer to the source buffer *src, pointer to the destination buffer *dst and length of the buffer size are passed to the CFFT32_brev function:

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-Values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>src</td>
<td>Input buffer</td>
<td>Pointer to 32-bit integer array</td>
<td>Q31~Q0</td>
<td>Input data</td>
</tr>
<tr>
<td>dst</td>
<td>Output buffer</td>
<td>Pointer to 32-bit integer array</td>
<td>Q31~Q0</td>
<td>Output data. The first call of this function bit-reversed the real part of the input. The second call of this function bit-reversed the imaginary part of the input.</td>
</tr>
<tr>
<td>size</td>
<td>Number of the bit reversing elements</td>
<td>int16</td>
<td>Q0</td>
<td>Must be power of 2</td>
</tr>
</tbody>
</table>

Background Information:
In many real time applications, the data sequences to be processed are real valued. Even though the data is real, the complex-valued DFT algorithm can still be used. One simple approach is to create a complex sequence from the real sequence, that is, real data for the real components and zeros for the imaginary component, the complex FFT can then be applied directly. Moreover, the complex FFT needs the input in bit reversed order so that the output, at the end of computation, will be in natural order.

This function facilitates N point complex FFT computation on the N-point in-order real data sequence stored in alternate memory locations. It reads real input samples and stores it as complex data in bit reversed order to perform complex FFT computation. The real data samples occupy the real part of the complex number and imaginary part will be zeroed before invoking the complex FFT. If the source and destination pointer are the same, then it performs
an in-place bit reversal.

In order to store the N-point real valued sequence (32-bit) in complex form, we need 2N long words. The destination buffer must be aligned to a 4N word boundary (16-bit word length) or 2N long words, where N is the number of acquired samples (should be a power of 2).

Figure 5.1 demonstrates the bit-reversal process for 8 real data samples. The real data samples Re(n) occupy the even locations of the source array (the real part) while the odd locations (the imaginary part), Im(n), are left untouched. In this particular example, the storage buffer must be aligned to 16 longs words in order to bit reverse the 8 real data samples (32-bit) in complex form.

![Figure 5.1: Bit Reversal Process](image)

**Example:**
The following sample code obtains the bit-reversed result of the complex input.

```c
#include <fft.h>
```

Oct 20, 2014
```c
#define N 128
#define FFT_STAGES 7
/* Align the INBUF section to 2*FFT_SIZE */
#pragma DATA_SECTION(ipcb, "FFTipcb");
#pragma DATA_SECTION(ipcbsrc, "FTTipcbsrc");
    long ipcbsrc[2*N];
    long ipcb[2*N];
    long INPUT[2*N]; // Input complex number
main()
{
    ........
    //Input data
    for(i=0; i < (N*2); i=i+2)
    {
        ipcbsrc[i] = (long)(INPUT[i]);
        ipcbsrc[i+1] = (long)(INPUT[i+1]);
    }
    //Clean up buffer
    for(i=0; i < (N*2); i=i+2)
    {
        ipcb[i] = 0;
        ipcb[i+1] = 0;
    }
    ........
    //Real part bit reversing
    CFFT32_brev(ipcbsrc, ipcb, N);
    //Imaginary part bit reversing
    CFFT32_brev(&ipcbsrc[1], &ipcb[1], N);
    ........
}
```

**Benchmark Information:**

All buffers and stack are placed in internal memory (zero-wait states in data space). Note that the CFFT32_brev must be called twice consecutively to first bit-reverse order the real part of the input buffer followed by the imaginary part.

<table>
<thead>
<tr>
<th>Size</th>
<th>C-Callable ASM</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>282 cycles</td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>538 cycles</td>
<td></td>
</tr>
<tr>
<td>128</td>
<td>1050 cycles</td>
<td></td>
</tr>
<tr>
<td>256</td>
<td>2074 cycles</td>
<td></td>
</tr>
<tr>
<td>512</td>
<td>4122 cycles</td>
<td></td>
</tr>
<tr>
<td>1024</td>
<td>8218 cycles</td>
<td></td>
</tr>
</tbody>
</table>

1 Execution cycles for a single invocation of the function
5.2.2 Real FFT Bit Reverse Function

Description:
This function reads N-point in-order real data samples (32-bit) stored in contiguous locations and writes them in bit-reversed order. It supports both in-place and off-place bit reversing.

Prototype:
void RFFT32_brev(int16 *src, int16 *dst, int16 size);

Parameters:
src Pointer to in-order data samples stored in contiguous locations.

dst Pointer to destination array, to store bit reversed complex output, the destination array buffer must be aligned to 2N word boundary (16-bit word length) or N long words, where N is size of the real FFT (a power of 2).

size Number of real-data samples (N) to be bit reversed in complex form, it should be power of 2.

Header File:
fft.h

Availability:
C-Callable Assembly (CcA)

Usage:
Pointer to the source buffer *src, pointer to the destination buffer *dst and length of the buffer size are passed to the RFFT32_brev function:

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-Values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>src</td>
<td>Input buffer</td>
<td>Pointer to 32-bit integer array</td>
<td>Q31~Q0</td>
<td>Input data is stored in contiguous memory locations, i.e., there are no zeros between two data points.</td>
</tr>
<tr>
<td>dst</td>
<td>Output buffer</td>
<td>Pointer to 32-bit integer array</td>
<td>Q31~Q0</td>
<td>Output data. For real input FFT calculation, the output buffer should be cleaned up before calling this function.</td>
</tr>
<tr>
<td>size</td>
<td>Number of the bit reversing elements</td>
<td>int16</td>
<td>Q0</td>
<td>Must be power of 2</td>
</tr>
</tbody>
</table>

Background Information:
In many real applications, the data sequences to be processed are real valued. Even though the data is real, complex-valued DFT algorithm can still be used. One simple approach creates a complex sequence from the real sequence; that is, real data for the real components and zeros for the imaginary components, The complex FFT can then be applied directly. However, this method is not efficient as it consumes $2N$ memory locations (Real Imaginary) for $N$ point sequence.

When input is purely real, their symmetric properties compute DFT very efficiently. One such optimized real FFT algorithm for $N$-point real data sequence is packing algorithm. The original $N$-point sequence is packed as $\frac{N}{2}$-point complex sequence and $\frac{N}{2}$-point complex FFT is performed on the complex sequence. Finally, the resulting $\frac{N}{2}$-point complex output is unpacked into another $\frac{N}{2} + 1$ point complex sequence, which corresponds to spectral bin $[0, \frac{N}{2})$ of $N$-point real input sequence. Spectral bin 0 to $\frac{N}{2}$ is sufficient, as the remaining bins $\frac{N}{2} + 1$ to $N-1$ are complex conjugates of spectral bins $\frac{N}{2} - 1$ to 1. Notice that the bin 0 and $\frac{N}{2}$ do not have a matching point. Real part of bin 0 corresponds to DC offset which is average of all the time domain samples and the imaginary part will always be zero. The real part of bin
number $\frac{N}{2}$ corresponds to nyquist frequency and the imaginary part will always be zero.

The real FFT requires $N+2$ memory locations to compute the FFT for $N$-point real valued sequence, which is highly preferable in contrast to the complex FFT that consumes $2N$ locations for $N$-point real valued sequence.

The figure below demonstrates the concept of packing and how the bit reversal process works.

Example:
The following sample code obtains the bit-reversed result of the real input.

```c
#include <fft.h>
#define N 128 /* FFT_SIZE */
#define FFT_STAGES 7 /* log2(FFT_SIZE) */
/* Align the INBUF section to 2*FFT_SIZE in the linker file */
#pragma DATA_SECTION(ipcb, "FFTipcb");
#pragma DATA_SECTION(ipcbsrc, "FFTipcbsrc");
```

![Figure 5.2: Bit Reversal Process](image-url)
long ipcbsrc[N];
long ipcb[2*N];
long INPUT[N];  // Input complex number
main()
{
    ........
    for(i=0; i < (N); i++)
    {
        ipcbsrc[i] = (long)(INPUT[i]);  // Input data
    }
    // Clean up data buffer
    for(i=0; i < (N+2); i=i+2)
    {
        ipcb[i] = 0;
        ipcb[i+1] = 0;
    }
    ........
    RFFT32_brev(ipcbsrc, ipcb, N);  // Bit reversed
    ........
}

Benchmark Information:
All buffers and stack are placed in internal memory (zero-wait states in data space).

<table>
<thead>
<tr>
<th>Size</th>
<th>C-Callable ASM</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>169 cycles</td>
</tr>
<tr>
<td>64</td>
<td>313 cycles</td>
</tr>
<tr>
<td>128</td>
<td>601 cycles</td>
</tr>
<tr>
<td>256</td>
<td>1177 cycles</td>
</tr>
<tr>
<td>512</td>
<td>2329 cycles</td>
</tr>
<tr>
<td>1024</td>
<td>4633 cycles</td>
</tr>
<tr>
<td>2048</td>
<td>9241 cycles</td>
</tr>
</tbody>
</table>
5.2.3 Real Input Point by Point Bit Reverse Function

**Description:**
This module acquires N real data samples in real time and stores it as \( \frac{N}{2} \) point complex data sequence in bit-reversed order to perform an N point real FFT computation.

**Header File:**
fft.h

**Availability:**
C-Callable Assembly (CcA)

**Object Definition:**
The structure of the RFFT32_ACQ object is as follows

```c
typedef struct {
    int16 acqflag;
    int16 count;
    int32 input;
    int32 *tempptr;
    int32 *buffptr;
    int16 size;
    void (*update)(void *);
} RFFT32_brev_RT_ACQ;
```

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Range (Hex)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>acqflag</td>
<td>Acquisition flag</td>
<td>int16</td>
<td>0 or 1</td>
<td>Acquisition ENABLE flag. Set this flag to start the acquisition and it will be reset when all the samples are acquired</td>
</tr>
<tr>
<td>count</td>
<td>Integer counter</td>
<td>int16</td>
<td>Q0</td>
<td>Counter to keep track of the acquired samples</td>
</tr>
<tr>
<td>input</td>
<td>Data input</td>
<td>int32</td>
<td>Q0~Q31</td>
<td>32 bit integer number</td>
</tr>
<tr>
<td>tempptr</td>
<td>Temporary pointer</td>
<td>Pointer to int16</td>
<td>N/A</td>
<td>Temporary pointer, modified in bit reversed order, to store successive samples</td>
</tr>
<tr>
<td>buffptr</td>
<td>Destination buffer pointer</td>
<td>Pointer to int16</td>
<td>N/A</td>
<td>Pointer to the buffer to store the data samples. The buffer should be aligned to 4N words (16-bit word size) or 2N long words, where N is the no. of samples to be acquired</td>
</tr>
<tr>
<td>size</td>
<td>Number of samples</td>
<td>Integer (Q0)</td>
<td>(2^k (k = 1 : 15))</td>
<td>Number of samples to be acquired, should be power of 2</td>
</tr>
<tr>
<td>update</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>Bit reverse function entry point should be passed to this pointer</td>
</tr>
</tbody>
</table>
Special Constants and Data types:

**RFFT32_brev_RT_ACQ** The module definition is created as a data type. This makes it convenient to instance an interface to the FFT module. To create multiple instances of the module simply declare variables of type RFFT32_brev_RT_ACQ

**RFFT32_brev_RT_ACQ_handle** User defined Data type of pointer to RFFT32_brev_RT_ACQ Module

**RFFT32_brev_RT_ACQ_DEFAULTS** Structure symbolic constant is to initialize RFFT32_brev_RT_ACQ module. This provides the initial values to the terminal variables as well as method pointers.

**Methods:**

```c
void RFFT32_brev_RT(void *);
```

This routine reads N successive real input samples (32-bit) and stores it as $\frac{N}{2}$ point complex data sequence in bit reversed order. The even data samples occupy the real part and odd data samples occupy imaginary part. Real FFTacquisition buffer should be aligned to 2N word (16-bit word size) boundary.

This function starts the acquisition, only if the “acqflag” is set and it resets this flag when samples are acquired. Thus the “acqflag” acts as the trigger for the acquisition module.

---

![Diagram of Bit Reversal Process](image)

**Figure 5.3: Bit Reversal Process**
Example:
In the header file fft.h, a default header structure templates had been defined and ready to be called

```c
#define RFFT32_brev_RT_ACQ_DEFAULTS(
    1,
    0,
    0,
    (int32 *)NULL,
    (int32 *)NULL,
    0,
    (void (*)(void *))RFFT32_brev_RT
}
```

The following sample code shows how to call the point by point bit reversed function.

```c
#include fft.h
#define N 32 // FFT size
// Data buffer alignment
#pragma DATA_SECTION(ipcb, "FFTipcb");
#pragma DATA_SECTION(ipcbsrc, "FFTipcbsrc");
long ipcbsrc[2*N];
long ipcb[2*N];
RFFT32_brev_RT_ACQ acq=RFFT32_brev_RT_ACQ_DEFAULTS;
main()
{
    ........
    //Header structure initialization
    acq.buffptr=ipcb;
    acq.tempptr=ipcb;
    acq.size=N;
    acq.count=N;
    acq.acqflag=1;
    for(i=0; i < N; i++)
    {
        acq.input=ipcbsrc[i]; //Input data
        acq.update(&acq); //One point bit reversed
    }
}
```

**Benchmark Information:**
All buffers and stack are placed in internal memory (zero-wait states in data space).

<table>
<thead>
<tr>
<th>Size</th>
<th>C-Callable ASM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Block</td>
<td>29 cycles</td>
</tr>
</tbody>
</table>
5.2.4 32 Bit Complex Fast Fourier Transform Module

**Description:**
This module computes the FFT of N point Complex FFT sequence.

**Header File:**
fft.h

**Availability:**
C-Callable Assembly (CcA)

**Object Definition:**
The structure of the CFFT32 object is as follows

```c
typedef struct {
    int32 *ipcbptr;
    int32 *tfptr;
    int16 size;
    int16 nrstage;
    int32 *magptr;
    int32 *winptr;
    int32 peakmag;
    int16 peakfrq;
    int16 ratio;
    void (*init)(void *);
    void (*izero)(void *);
    void (*calc)(void *);
    void (*mag)(void *);
    void (*win)(void *);
}CFFT32;
```

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ipcbptr</td>
<td>Input data</td>
<td>Pointer to 32-bit integer array</td>
<td>Q31</td>
<td>Computation buffer pointer, this buffer must be aligned to 2N word (32-bit word size) boundary for N point complex FFT</td>
</tr>
<tr>
<td>tfptr</td>
<td>Twiddle factor pointer</td>
<td>Pointer to 32-bit integer array</td>
<td>Q30 or Q31</td>
<td>Not initialized by user. It will assigned by CFFT32_init function</td>
</tr>
<tr>
<td>size</td>
<td>FFT sample size</td>
<td>Int16</td>
<td>Q0</td>
<td>Must be a power of 2</td>
</tr>
<tr>
<td>nrstage</td>
<td>Number of stages</td>
<td>Int16</td>
<td>Q0</td>
<td>nrstages = log2(size)</td>
</tr>
<tr>
<td>magptr</td>
<td>Magnitude output</td>
<td>Pointer to 32-bit integer array</td>
<td>Q30</td>
<td>Magnitude buffer pointer</td>
</tr>
</tbody>
</table>

Continued on next page
Table 5.2 – continued from previous page

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>winptr</td>
<td>Window input</td>
<td>Pointer to 32-bit integer array</td>
<td>Q31</td>
<td>Window coefficient pointer for windowed FFT, only used for real FFT</td>
</tr>
<tr>
<td>peakmag</td>
<td>Peak magnitude</td>
<td>32-bit integer</td>
<td>Not used</td>
<td>Not used</td>
</tr>
<tr>
<td>ratio</td>
<td>Twiddle factor search step</td>
<td>Int16</td>
<td>Q0</td>
<td>ratio=4096/size</td>
</tr>
<tr>
<td>init</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>Twiddle factor initialization function</td>
</tr>
<tr>
<td>izero</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>Zero imaginary part of specific buffer. Used for CFFT only if want to use CFFT structure to calculate RFFT</td>
</tr>
<tr>
<td>calc</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>FFT calculation function</td>
</tr>
<tr>
<td>mag</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>Magnitude calculation function</td>
</tr>
<tr>
<td>win</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>Windowed input function</td>
</tr>
</tbody>
</table>

Special Constants and Data types:

- **CFFT32** The module definition is created as a data type. This makes it convenient to instance an interface to the FFT module. To create multiple instances of the module simply declare variables of type CFFT32.

- **CFFT32_Handle** User defined Data type of pointer to CFFT32 Module

- **CFFT32_xxxP_DEFAULTS: xxx=8, 16, 32, 64, 128, 256, 512, 1024, 2048** Structure symbolic constant to initialize CFFT32 Module to compute “xxx” point complex FFT. This provides the initial values to the terminal variables as well as method pointers.

- **TF_QFMAT** The Q-format for the twiddle factors is determined by the constant TF_QFMAT which can be found in the source file “sel_q.asm”. The user has the option to set the constant to either Q30 or Q31. By default, the library was built with the constant set to Q30. When altering the value of this constant, the user must rebuild the library for the change to take effect. The FFT32_init function, on the basis of the TF_QFMAT value, will set the object twiddle factor pointer to either the Q31 table (TF_QFMAT = Q31) or the Q30 table (TF_QFMAT = Q30).

Methods:

- `void init(CFFT32_Handle);`
- `void izero(CFFT32_Handle);`
- `void calc(CFFT32_Handle);`
- `void mag(CFFT32_Handle);` (OPTIONAL)
- `void win(CFFT32_Handle);` (OPTIONAL)

- `void init(CFFT32_Handle);` The FFT initialization routine updates the twiddle factor pointer with the address of twiddle factor table. Twiddle factors are assembled into “FFTtf” section and contains 3072 entries (32-bit words) to facilitate complex FFT computation of up to 4096 points. The table has \( \frac{3N}{4} \) entries, where N is the maximum supported FFT. The
entries are as follows:

\[
\begin{align*}
\sin(2 \times \pi \times 0/4096) \\
\sin(2 \times \pi \times 1/4096) \\
\ldots \\
\sin(2 \times \pi \times 1024/4096) \text{ or } \cos(2 \times \pi \times 0/4096) \\
\sin(2 \times \pi \times 1025/4096) \text{ or } \cos(2 \times \pi \times 1/4096) \\
\ldots \\
\sin(2 \times \pi \times 2047/4096) \text{ or } \cos(2 \times \pi \times 1023/4096) \\
\sin(2 \times \pi \times 2048/4096) \text{ or } \cos(2 \times \pi \times 1024/4096) \\
\ldots \\
\sin(2 \times \pi \times 3071/4096) \text{ or } \cos(2 \times \pi \times 2047/4096)
\end{align*}
\]

Therefore, the total space (in words) that needs to be allocated for the twiddle factor table is 6144 or 0x1800.

**void izero(CFFT32_Handle);** This function zeros the imaginary part of the complex input sequence in the computation buffer to obtain the FFT of real valued time domain signal.

**void calc(CFFT32_Handle);** This routine performs radix 2, N point in-place FFT computation on the bit-reversed data sequence (in Q31 format) pointed by the ipcbptr of the FFT module and produce in-order data (in Q31 format) representing frequency domain information. The \( \frac{1}{N} \) scaling of FFT is distributed across the stages. Note that the input and output data are in Q31 format. Size of the computation buffer is 2N long words (Twice the FFT length).

**void win(CFFT32_Handle); (OPTIONAL)** This function applies a window, pointed to by the winptr element of CFFT32 object, to the bit reversed data sequence (in Q31 format) in the computation buffer. The aim is to reduce the spectral leakage that occurs when the sampling rate is not an integer multiple of the constituent frequencies of the input waveform. The window is only applied to the real part of this buffer; the assumption being that the user acquires N real data points from the ADC, stores them at alternate locations (real part) of the input buffer and then zeros out the imaginary part, before running the complex FFT. If, however, the user is sampling complex data, i.e. in-phase and quadrature phase data, and wishes to window both the real and imaginary parts, they can use the CFFT32_win_dual() instead - prior to calling the window function, set the “win” function pointer of the CFFT32 object to point to the CFFT32_win_dual().

```c
   cfft.win = CFFT32_win_dual;
   cfft.win(&cfft);
```

The size of the window coefficient array is \( \frac{N}{2} \) long words (1/2 of the FFT length). Note that the windowing function should be invoked once the input data has been reordered in bit-reversed format. The window coefficients, for 32 to 4096 point FFTs, are provided for the following windows:

1. barthannwin
2. bartlett
3. blackman
4. blackmanharris
5. bohmanwin
6. chebwin
7. flattopwin
8. gausswin
9. hamming
10. hann
11. kaiser
12. nuttallwin
13. parzenwin
14. rectwin
15. taylorwin
16. triang
17. tukeywin

Each window has its own header file in the include folder, of the format:
fft_<window>_Q31.h. The MATLAB script, “C28xFixedPointLib_Window_Generator.m”, used to generate these files is included under examples_ccsv5\2833x_FixedPoint_Win\matlab; the script generates the windows using their default arguments, the user may choose to modify the script to generate specific windows with non-default arguments.

A fairly simple MATLAB script to generate a single window of a particular size can be accomplished with the following code snippet:

```matlab
fid = fopen('output.txt','W'); % Open the output file
%********************************************************************
% Hamming 32 pt.*
%********************************************************************
N=32; % Window length
string='Hamming32'; % Header string
%-------------------
x=hamming(N); % Create the window
x=x(1:N/2); % Only need 1st half of data
xQ31=round(x*(2^31)); % Round and put in Q31 format
fprintf(fid,'%s
',string); % Write header information
fprintf(fid,'%u,',xQ31); % Write the output to the file
fprintf(fid,'

'); % Insert a couple of linefeeds
%********************************************************************
fclose(fid); % Close the output file
```

**void mag(CFFT32_Handle); (OPTIONAL)** This routine obtains the Magnitude Square of the complex FFT output (in Q31 format) and stores back the result (in Q30 format) either in the computation buffer or in a dedicated array as commanded by the magptr element of the complex FFT module. Note that the magnitude output is stored in Q30 format. The size of the array to hold the magnitude outputs is N long words (Equal to the FFT length).

\[
X(k) = X_r(k) + jX_i(k) \]
\[
|X(k)|^2 = X_r(k)^2 + X_i(k)^2
\]

**Alignment Requirements:**
The computation buffer should be aligned to 4N words (16-bit words size) boundary or 2N long words (32-bit word size), in order to get the samples in bit reversed order by using the bit-reversal utility CFFT32_brev

**Linker Command File (Align computation buffer to 512 words for 128 point FFT)**
Example:
For 32 points CFFT user can use following templates to define the header structure.

```c
#define CFFT32_32P_DEFAULTS {
    (int32 *)NULL,
    (int32 *)NULL,
    32,
    5,
    (int32 *)NULL,
    (int32 *)NULL,
    0,
    0,
    128,
    (void (*)(void *))FFT32_init,
    (void (*)(void *))FFT32_izero,
    (void (*)(void *))FFT32_calc,
    (void (*)(void *))CFFT32_mag,
    (void (*)(void *))CFFT32_win
}
```

The following sample code obtains the complex FFT value.

```c
#include fft.h
#define N 32
/* Data buffer alignment */
#pragma DATA_SECTION(ipcb, "FFTipcb");
#pragma DATA_SECTION(ipcbsrc, "FFTipcbsrc");
long ipcbsrc[2*N];
long ipcb[2*N];
/* Header structure initialization */
CFFT32 fft=CFFT32_32P_DEFAULTS;
main()
{
    ..........
    // Generate sample waveforms:
    for(i=0; i < (N*2); i=i+2)
    {
        ipcbsrc[i] =(long)real[i] //Q31
        ipcbsrc[i+1] = (long)imag[i]; //Q31
    }
    ..........
    /* Real part bit reversing */
    CFFT32_brev(ipcbsrc, ipcb, N);
    /* Imaginary part bit reversing */
    CFFT32_brev(&ipcbsrc[1], &ipcb[1], N);
    fft.ipcbptr=ipcb;  /* FFT computation buffer */
    fft.init(&fft);  /* Twiddle factor pointer init */
```
fft.calc(&fft); /* Compute the FFT */
}

**Benchmark Information:**
All buffers and stack are placed in internal memory (zero-wait states in data space).

<table>
<thead>
<tr>
<th>Samples (N-pt FFT)</th>
<th>Execution Time Q31 (cycles)</th>
<th>Execution Time Q30 (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>1930</td>
<td>1994</td>
</tr>
<tr>
<td>64</td>
<td>4703</td>
<td>4895</td>
</tr>
<tr>
<td>128</td>
<td>11156</td>
<td>11668</td>
</tr>
<tr>
<td>256</td>
<td>25897</td>
<td>27177</td>
</tr>
<tr>
<td>512</td>
<td>59070</td>
<td>62142</td>
</tr>
<tr>
<td>1024</td>
<td>132819</td>
<td>139987</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>32-bit Complex FFT (FFT32_calc())</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
</tr>
<tr>
<td>64</td>
</tr>
<tr>
<td>128</td>
</tr>
<tr>
<td>256</td>
</tr>
<tr>
<td>512</td>
</tr>
<tr>
<td>1024</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>32-bit Complex FFT (CFFT32_mag())</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
</tr>
<tr>
<td>64</td>
</tr>
<tr>
<td>128</td>
</tr>
<tr>
<td>256</td>
</tr>
<tr>
<td>512</td>
</tr>
<tr>
<td>1024</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>32-bit Complex FFT (CFFT32_win())</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
</tr>
<tr>
<td>64</td>
</tr>
<tr>
<td>128</td>
</tr>
<tr>
<td>256</td>
</tr>
<tr>
<td>512</td>
</tr>
<tr>
<td>1024</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>32-bit Complex FFT (CFFT32_dual_win())</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
</tr>
<tr>
<td>64</td>
</tr>
<tr>
<td>128</td>
</tr>
<tr>
<td>256</td>
</tr>
<tr>
<td>512</td>
</tr>
<tr>
<td>1024</td>
</tr>
</tbody>
</table>

Table 5.3: Complex FFT routines

**Notes:**
CASE 1: Twiddle factor (Q31 format) placed in internal memory (Zero wait state access)
CASE 2: Twiddle factor (Q30 format) placed in internal memory (Zero wait state access)

The section “FFTtf” holds 3072 twiddle factors, each 32-bits or 2 words wide. A total of 6144 (0x1800) contiguous words need to be allotted this section in memory. When running in emulation mode it may be necessary to allocate an entire RAM block in the linker command
file. For e.g.

```
FFTtf   >   RAML7,   PAGE = 1
```

When running out of FLASH in either emulation or standalone mode the twiddle factors must be stored in flash. Define a flash section of sufficient size (at least 0x1800) in either page 0 or 1 of the memory map and allocate “FFTtf” to it as follows

```
FFTtf   >   FLASHC,   PAGE = 0
```

For better performance or time-critical code, you can optionally copy over the twiddle factors from FLASH to RAM at runtime by defining separate load and run addresses.

In the linker command file define the section FFTtf as follows

```
FFTtf : LOAD = FLASHC, PAGE = 0
       RUN = RAML7, PAGE = 1
       LOAD_START(_FFTtfLoadStart),
       LOAD_SIZE(_FFTtfLoadSize),
       RUN_START(_FFTtfRunStart)
```

In the main C file, declare the following variables

```
extern uint16_t FFTtfLoadStart, FFTtfLoadSize, FFTtfRunStart;
```

Finally use the memcpy function to copy over the section from FLASH to RAM

```
memcpy((uint32_t *)&FFTtfRunStart, (uint32_t *)&FFTtfLoadStart,
       (uint32_t *)&FFTtfLoadSize);
```
5.2.5 32 Bit Real Fast Fourier Transform Module

Description:
This real FFT module computes the FFT of N-point real sequence using $\frac{N}{2}$-point complex FFT routine.

Header File:
fft.h

Availability:
C-Callable Assembly (CcA)

Object Definition:
The structure of the RFFT32 object is as follows

```c
typedef struct {
    int32 *ipcbptr;
    int32 *tfptr;
    int16 size;
    int16 nrstage;
    int32 *magptr;
    int32 *winptr;
    int32 peakmag;
    int16 peakfrq;
    int16 ratio;
    void (*init)(void *);
    void (*calc)(void *);
    void (*split)(void *);
    void (*mag)(void *);
    void (*win)(void *);
}RFFT32;
```

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ipcbptr</td>
<td>Input data</td>
<td>Pointer to 32-bit integer array</td>
<td>Q31</td>
<td>Computation buffer pointer, this buffer must be aligned to 2N word (32-bit word size) boundary for N point real FFT</td>
</tr>
<tr>
<td>tfptr</td>
<td>Twiddle factor pointer</td>
<td>Pointer to 32-bit integer array</td>
<td>Q30 or Q31</td>
<td>Not initialized by user. It will assigned by FFT32_init function</td>
</tr>
<tr>
<td>size</td>
<td>FFT sample size</td>
<td>Int16</td>
<td>Q0</td>
<td>Must be a power of 2</td>
</tr>
<tr>
<td>nrstage</td>
<td>Number of stages</td>
<td>Int16</td>
<td>Q0</td>
<td>$nrstages = \log_2(size)$</td>
</tr>
<tr>
<td>magptr</td>
<td>Magnitude output</td>
<td>Pointer to 32-bit integer array</td>
<td>Q30</td>
<td>Magnitude buffer pointer</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>winptr</td>
<td>Window input</td>
<td>Pointer to 32-bit integer array</td>
<td>Q31</td>
<td>Window coefficient pointer for windowed FFT, only used for real FFT</td>
</tr>
<tr>
<td>peakmag</td>
<td>Peak magnitude</td>
<td>32-bit integer</td>
<td>Not used</td>
<td>Not used</td>
</tr>
<tr>
<td>ratio</td>
<td>Twiddle factor search step</td>
<td>Int16</td>
<td>Q0</td>
<td>ratio=4096/size</td>
</tr>
<tr>
<td>init</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>Twiddle factor initialization function</td>
</tr>
<tr>
<td>calc</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>FFT calculation function</td>
</tr>
<tr>
<td>split</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>Split function computation</td>
</tr>
<tr>
<td>mag</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>Magnitude calculation function</td>
</tr>
<tr>
<td>win</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>Not used</td>
</tr>
</tbody>
</table>

Special Constants and Data types:

**RFFT32** The module definition is created as a data type. This makes it convenient to instance an interface to the FFT module. To create multiple instances of the module simply declare variables of type RFFT32

**RFFT32_Handle** User defined Data type of pointer to RFFT32 Module

**RFFT32_xxxP_DEFAULTS**: xxx= 32, 64, 128, 256, 512, 1024, 2048, 4096 Structure symbolic constant to initialize RFFT32 module to compute “xxx” point real FFT. This provides the initial values to the terminal variables as well as method pointers.

Methods:

```
void init(RFFT32_Handle);
void calc(RFFT32_Handle);
void split(RFFT32_Handle);
void mag(RFFT32_Handle); (OPTIONAL)
void win(RFFT32_Handle); (OPTIONAL)
```

**void init(RFFT32_Handle);** The FFT initialization routine updates the twiddle factor pointer with the address of twiddle factor table. Twiddle factors are assembled into “FFTtf” section and contains 3072 entries (32-bit words) to facilitate complex FFT computation of up to 4096 points. The table has \( \frac{N^2}{4} \) entries, where N is the maximum supported FFT. The
entries are as follows:

\[ \sin(2 \pi \times 0/4096) \]
\[ \sin(2 \pi \times 1/4096) \]

... 

\[ \sin(2 \pi \times 1024/4096) \text{ or } \cos(2 \pi \times 0/4096) \]
\[ \sin(2 \pi \times 1025/4096) \text{ or } \cos(2 \pi \times 1/4096) \]

... 

\[ \sin(2 \pi \times 2047/4096) \text{ or } \cos(2 \pi \times 1023/4096) \]
\[ \sin(2 \pi \times 2048/4096) \text{ or } \cos(2 \pi \times 1024/4096) \]

... 

\[ \sin(2 \pi \times 3071/4096) \text{ or } \cos(2 \pi \times 2047/4096) \]

Therefore, the total space (in words) that needs to be allocated for the twiddle factor table is 6144 or 0x1800.

**void calc(RFFT32_Handle);** This routine performs radix 2, \( N/2 \) point in-place complex FFT computation on the bit-reversed data sequence (in Q31 format) pointed by the ipcbptr of the FFT module and produce in-order data (in Q31 format) representing frequency domain information. The \( 1/N \) scaling of FFT is distributed across the stages. Note that the input and output data are in Q31 format.

**void split(RFFT32_Handle);** Split function obtains the first \( N/2 + 1 \) complex spectral bins of the \( N \)-point real valued input sequence from the output of \( N/2 \)-point complex FFT. Hence, the size of the computation buffer is \( N + 2 \) long words, to store the \( N/2 + 1 \) spectral bins in complex form.

**void win(RFFT32_Handle);** (OPTIONAL) This function window the bit reversed complex data sequence (in Q31 format) in the computation buffer using the window coefficients (in Q31 format) pointed by the winptr element of FFT module to reduce the leakage effect. Size of the window coefficient array is \( N/2 \) long words (1/2 of the FFT length). Note that the windowing function should be invoked only if the computation buffer contains the data sequence in bit reversed order. The size of the window coefficient array is \( N/2 \) long words (1/2 of the FFT length). Note that the windowing function should be invoked once the input data has been reordered in bit-reversed format. The window coefficients, for 32 to 4096 point FFTs, are provided for the following windows:

1. barthannwin
2. bartlett
3. blackman
4. blackmanharris
5. bohmanwin
6. chebwin
7. flattopwin
8. gausswin
9. hamming
10. hann
11. kaiser
12. nuttallwin
13. parzenwin
14. rectwin
15. taylorwin
16. triang
17. tukeywin

Each window has its own header file in the include folder, of the format: `fft_<window>_Q31.h`. The MATLAB script, “C28xFixedPointLib_Window_Generator.m”, used to generate these files is included under examples_ccsv5/2833x_FixedPoint_Win\matlab; the script generates the windows using their default arguments, the user may choose to modify the script to generate specific windows with non-default arguments.

A fairly simple MATLAB script to generate a single window of a particular size can be accomplished with the following code snippet:

```matlab
fid = fopen('output.txt','W'); % Open the output file
%********************************************************************
% Hamming 32 pt. *
%********************************************************************
N=32; % Window length
string='Hamming32'; % Header string
%-------------------
x=hamming(N); % Create the window
x=x(1:N/2); % Only need 1st half of data
xQ31=round(x*(2^31)); % Round and put in Q31 format
fprintf(fid,'%s
',string); % Write header information
fprintf(fid,'%u,',xQ31); % Write the output to the file
fprintf(fid,'

'); % Insert a couple of linefeeds
%********************************************************************
fclose(fid); % Close the output file
```

**void mag(RFFT32_Handle); (OPTIONAL)** This routine obtains the Magnitude Square of $(\frac{N}{2} + 1)$ complex spectral bin obtained from split operation and stores back the result (in Q30 format) either in the computation buffer or in a dedicated array as commanded by the `magptr` element of FFT module. Note that the magnitude output is stored in Q30 format. The size of the array to hold $(\frac{N}{2} + 1)$ magnitude outputs is equal to $(\frac{N}{2} + 1)$ long words (1/2 of the real FFT length + 1).

$$G(k) = G_r(k) + jG_i(k)$$

$$|G(k)|^2 = G_r(k)^2 + G_i(k)^2$$

**Alignment Requirements:**
The computation buffer should be aligned to 2N words (16-bit words size) boundary or N long words (32-bit word size), in order to get the samples in bit reversed order by using the bit-reversal utility RFFT32_brev.

**Linker Command File (Align computation buffer to 256 words for 128 point FFT)**
Example:

For 32 points RFFT user can use following templates to define the header structure. Note the values for the object elements; a \( \frac{N}{2} \) complex FFT is used to do an \( N \) point real FFT and the object elements must be initialized appropriately.

```c
#define RFFT32_32P_DEFAULTS {
    (int32 *)NULL,
    (int32 *)NULL,
    16,
    4,
    (int32 *)NULL,
    (int32 *)NULL,
    0,
    0,
    256,
    (void (*)(void *))FFT32_init,
    (void (*)(void *))FFT32_calc,
    (void (*)(void *))RFFT32_split,
    (void (*)(void *))RFFT32_mag,
    (void (*)(void *))RFFT32_win
}
```

The following sample code obtains the real FFT value.

```c
#include fft.h
#define N 32 //FFT size
//Buffer alignment
#pragma DATA_SECTION(ipcb, "FFTipcb");
#pragma DATA_SECTION(ipcbsrc, "FFTipcbsrc");
long ipcbsrc[N];
long ipcb[N+2];

/* Create an Instance of FFT module */
RFFT32 fft=RFFT32_32P_DEFAULTS;
main()
{
    ........
    // Generate sample waveforms:
    for(i=0; i < (N); i++)
    {
        ipcbsrc[i] =(long)real[i] //Q31
    }
    ........
    RFFT32_brev(ipcbsrc, ipcb, N); /* Bit reverse */
    fft.ipcbptr=ipcb; /* FFT computation buffer */
    fft.init(&fft); /* Twiddle factor pointer init */
    fft.calc(&fft); /* Compute the FFT */
```
fft.split(&fft); /* perform the split operation to get the N/2 + 1 spectrum */
}

**Benchmark Information:**
All buffers and stack are placed in internal memory (zero-wait states in data space).

<table>
<thead>
<tr>
<th>Samples (N-pt FFT)</th>
<th>Execution Time Q31 (cycles)</th>
<th>Execution Time Q30 (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>765</td>
<td>781</td>
</tr>
<tr>
<td>64</td>
<td>1930</td>
<td>1994</td>
</tr>
<tr>
<td>128</td>
<td>4703</td>
<td>4895</td>
</tr>
<tr>
<td>256</td>
<td>11156</td>
<td>11668</td>
</tr>
<tr>
<td>512</td>
<td>25897</td>
<td>27177</td>
</tr>
<tr>
<td>1024</td>
<td>59070</td>
<td>62142</td>
</tr>
<tr>
<td>2048</td>
<td>132819</td>
<td>139987</td>
</tr>
</tbody>
</table>

**32-bit Real FFT (RFFT32_split())**

<table>
<thead>
<tr>
<th>Samples (N-pt FFT)</th>
<th>Execution Time Q31 (cycles)</th>
<th>Execution Time Q30 (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>407</td>
<td>799</td>
</tr>
<tr>
<td>64</td>
<td>799</td>
<td>1583</td>
</tr>
<tr>
<td>128</td>
<td>1583</td>
<td>3151</td>
</tr>
<tr>
<td>256</td>
<td>3151</td>
<td>6287</td>
</tr>
<tr>
<td>512</td>
<td>6287</td>
<td>12559</td>
</tr>
<tr>
<td>1024</td>
<td>12559</td>
<td>25103</td>
</tr>
<tr>
<td>2048</td>
<td>25103</td>
<td>407</td>
</tr>
</tbody>
</table>

**32-bit Real FFT (RFFT32_mag())**

<table>
<thead>
<tr>
<th>Samples (N-pt FFT)</th>
<th>Execution Time Q31 (cycles)</th>
<th>Execution Time Q30 (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>319</td>
<td>582</td>
</tr>
<tr>
<td>64</td>
<td>582</td>
<td>1108</td>
</tr>
<tr>
<td>128</td>
<td>1108</td>
<td>2160</td>
</tr>
<tr>
<td>256</td>
<td>2160</td>
<td>4264</td>
</tr>
<tr>
<td>512</td>
<td>4264</td>
<td>8472</td>
</tr>
<tr>
<td>1024</td>
<td>8472</td>
<td>16888</td>
</tr>
<tr>
<td>2048</td>
<td>16888</td>
<td>319</td>
</tr>
</tbody>
</table>

**32-bit Real FFT (RFFT32_win())**

<table>
<thead>
<tr>
<th>Samples (N-pt FFT)</th>
<th>Execution Time Q31 (cycles)</th>
<th>Execution Time Q30 (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>258</td>
<td>498</td>
</tr>
<tr>
<td>64</td>
<td>498</td>
<td>978</td>
</tr>
<tr>
<td>128</td>
<td>978</td>
<td>1938</td>
</tr>
<tr>
<td>256</td>
<td>1938</td>
<td>3858</td>
</tr>
<tr>
<td>512</td>
<td>3858</td>
<td>7698</td>
</tr>
<tr>
<td>1024</td>
<td>7698</td>
<td>15378</td>
</tr>
<tr>
<td>2048</td>
<td>15378</td>
<td>258</td>
</tr>
</tbody>
</table>

Table 5.5: Real FFT routines

**Notes:**
CASE 1: Twiddle factor is in Q31 format and placed in internal memory (Zero wait state access)
CASE 2: Twiddle factor is in Q30 format and placed in internal memory
The section “FFTtf” holds 3072 twiddle factors, each 32-bits or 2 words wide. A total of 6144 (0x1800) contiguous words need to be allotted this section in memory. When running in emulation mode it may be necessary to allocate an entire RAM block in the linker command file. For e.g.

FFTtf > RAML7, PAGE = 1

When running out of FLASH in either emulation or standalone mode the twiddle factors must be stored in flash. Define a flash section of sufficient size (at least 0x1800) in either page 0 or 1 of the memory map and allocate “FFTtf” to it as follows

FFTtf > FLASHC, PAGE = 0

For better performance or time-critical code, you can optionally copy over the twiddle factors from FLASH to RAM at runtime by defining separate load and run addresses.

In the linker command file define the section FFTtf as follows

```
FFTtf : LOAD = FLASHC, PAGE = 0
       RUN = RAML7, PAGE = 1
LOAD_START(_FFTtfLoadStart),
LOAD_END(_FFTtfLoadEnd),
RUN_START(_FFTtfRunStart)
```

In the main C file, declare the following variables

```
extern uint16_t FFTtfLoadStart, FFTtfLoadSize, FFTtfRunStart;
```

Finally use the memcpy function to copy over the section from FLASH to RAM

```
memcpy((uint32_t *)&FFTtfRunStart, (uint32_t *)&FFTtfLoadStart,
       (uint32_t *)&FFTtfLoadSize);
```
5.2.6 16 Bit FIR Filter Module

Description:
This module implements 1 block (point by point) FIR Filter using DMAC instructions that effectively executes 2 filter taps in a cycle. There are two functions in this module, `FIR16_calc` can support up to $2^{5}^{th}$ order FIR filter, while `FIR16_Alt_calc` can support up to a $65535^{th}$ order filter.

Header File:
filter.h

Availability:
C-Callable Assembly (CcA)

Object Definition:
The structure of the FIR16 object is as follows:

```c
typedef struct {
    int32 *coeff_ptr;
    int32 *dbuffer_ptr;
    int16 cbindex;
    int16 order;
    int16 input;
    int16 output;
    void (*init)(void *);
    void (*calc)(void *);
}FIR16;
```

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>coeff_ptr</td>
<td>Coefficient</td>
<td>Pointer to 32-bit</td>
<td>Q15</td>
<td>Pointer to the Filter coefficient array. Please notice the FIR filter</td>
</tr>
<tr>
<td></td>
<td>pointer</td>
<td>integer buffer</td>
<td></td>
<td>coefficients in this buffer are not arranged in natural order</td>
</tr>
<tr>
<td>dbuffer_ptr</td>
<td>Delay buffer</td>
<td>Pointer to 32-bit</td>
<td>Q15</td>
<td>Pointer to the Delay buffer. Please notice the elements in this buffer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>integer buffer</td>
<td></td>
<td>are not arranged in natural order</td>
</tr>
<tr>
<td>cbindex</td>
<td>Circular buffer index</td>
<td>int16</td>
<td>Q0</td>
<td>Calculated by <code>FIR16_init</code> function in terms of the order (range: 0x00~FE); it serves as the wraparound point for the delay buffer whereas <code>FIR16_Alt_init</code> will zero it out.</td>
</tr>
</tbody>
</table>

Continued on next page
### Table 5.6 – continued from previous page

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>order</td>
<td>Order of the filter</td>
<td>int16</td>
<td>Q0</td>
<td>Filter order, one less than the number of taps. Note that if the order is odd, FIR16_Alt_init will increase the order by 1 to make it even; this is done to facilitate the computation routine and is not an increase in the true order of the filter.</td>
</tr>
<tr>
<td>input</td>
<td>Input to the filter</td>
<td>int16</td>
<td>Q15</td>
<td>N/A</td>
</tr>
<tr>
<td>output</td>
<td>Output of the filter</td>
<td>int16</td>
<td>Q15</td>
<td>N/A</td>
</tr>
<tr>
<td>init</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>This initialization function initializes cbindex and zeros out the delay buffer</td>
</tr>
<tr>
<td>calc</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>This module calculates the FIR filtering using dual MAC instruction DMAC</td>
</tr>
</tbody>
</table>

**Special Constants and Data types:**

**FIR16** The module definition is created as a data type. This makes it convenient to instance an interface to the FIR16 Filter module. To create multiple instances of the module simply declare variables of type FIR16

**FIR16_Handle** User defined Data type of pointer to FIR16 Module

**FIR16_DEFAULTS** Structure symbolic constant is to initialize FIR16 Module. This provides the initial values to the terminal variables as well as method pointers.

**FIR16_ALT_DEFAULTS** Structure symbolic constant is to initialize FIR16 Module in order to run the alternate 16-bit FIR routine. This provides the initial values to the terminal variables as well as method pointers.

**Methods:**

```c
void FIR16_init(FIR16_Handle);
void FIR16_calc(FIR16_Handle);
void FIR16_Alt_init(FIR16_Handle);
void FIR16_Alt_calc(FIR16_Handle);
```

Each FIR implementation has two functions, an initialization and computation function. The input argument to these functions is the module handle.

**Note:**

1. The delay buffer is assigned to a section, “firldb”, which should be aligned to 256 word boundary in the data memory (RAM) for the FIR16 module. The FIR16_Alt module does not require any alignment

2. The coefficients are placed in a section, “firfilt”, that can be placed anywhere in the data memory (RAM)

**Background Information:**

In general, an Nth order FIR filter is described by the difference equation
Application Programming Interface (Fixed Point Library)

\[ y(n) = \sum_{k=0}^{N} h_k \times x(n - k) \]

or, equivalently, by the system function

\[ H(z) = \sum_{k=0}^{N} h_k \times z^{-k} \]

Furthermore, the unit sample response of the FIR system is identical to the coefficients \( h(k) \), that is

\[ h(n) = \begin{cases} h_n, & 0 < n < N \\ 0, & \text{otherwise} \end{cases} \]

The signal flow diagram of the FIR filter, representing the above mentioned difference equation is given below. The following Tapped delay implementation is canonical, which means that the number of storage element in the structure is equal to the order of the Filter.

Figure 5.4: FIR Filter

The FIR filter is essentially a sum of product operating on an array of values maintained in a delay line. Note that the number of filter co-efficients will always be greater than the order of the filter by 1.

The following diagram depicts the filter tap computation using DMAC instruction, computation proceeds from the oldest values to the newest and the DMAC instruction computes 2 filter taps per cycle. Delay buffer is addressed using circular addressing scheme that will wrap around the pointer to the beginning of the pointer when the pointer reaches the last location of delay buffer.
Note that the FIR16 module uses the C28x circular buffer addressing mode which requires the delay buffer to be aligned to a 256 words boundary and therefore, the delay buffer length is restricted to 256 words. Hence, this FIR filter module allows filter implementation of up to the $255^{th}$ order. The FIR16_Alt module, however, uses the C2xLP circular addressing mode which can support a buffer of up to 65536 words and allows a filter implementation of up to the $65535^{th}$ order.

\[
\begin{align*}
A &= A + (h_1 \times x_1) \\
P &= P + (h_0 \times x_0)
\end{align*}
\]

Figure 5.5: DMAC ACC:P, *XAR6%++, XAR7++
Figure 5.6: Filter Input/Output
Figure 5.7: Filtering Process
Coefficients generation:
The FIR coefficients can be generated by MATLAB Filter Design and Analysis Tool (FDATool) in fixed point format and written to a header file, which the user can then include in their CCS project. The coefficients generated by MATLAB may also be copied directly into “fir.h” replacing the contents of FIR16_LPF32_TEST allowing the user to easily test their filter with the provided CCS example.

MATLAB will generate FIR_ORDER+1 coefficients as signed 16-bit integers with fractional 15 bits i.e., Q15 format. If the order is even, the size of the delay line buffer, `dbuf`, must be (FIR_ORDER + 3)/2. If the order is odd, the size should be (FIR_ORDER + 1)/2

```c
#define FIR_ORDERREV (FIR_ORDER + 1) // even
```

The calculation routines use the DMAC instruction, it does two multiply-accumulates in a single cycle; it requires the coefficients be reordered so that the output of the filter is generated in the right order. The C code to do this is as follows:

```c
#if(FIR_ORDER & 0x01) // odd
#define FIR_ORDERREV (FIR_ORDER + 1) // even
#else
#define FIR_ORDERREV (FIR_ORDER + 2) // even
#endif
```

The size of the array is:
```c
#define FIR_ORDERREV (FIR_ORDER + 1) // even
```

The reason being that we use the DMAC operation which will multiply
// the coefficients in 32-bit chunks, we don’t want an odd size coefficient
// buffer and risk corrupting the delay line
#ifndef __cplusplus
#pragma DATA_SECTION(coeff, "coefffilt");
#else
#pragma DATA_SECTION("coefffilt");
#endif
int16_t coeff[FIR_ORDER+2];

#ifndef __cplusplus
#pragma DATA_SECTION(revCoeff, "coefffilt");
#else
#pragma DATA_SECTION("coefffilt");
#endif
int16_t revCoeff[FIR_ORDER+2];

// Reorder the coefficients
// FIR_ORDER even -> (FIR_ORDER+1)+1 e.g. FIR_ORDER = 32, size = 34 words
// odd -> (FIR_ORDER+1) e.g. FIR_ORDER = 31, size = 32 words
for(i = 0; i < FIR_ORDER + 2; i = i + 2){
    revCoeff[FIR_ORDER_REV-i-1] = coeff[i/2+FIR_ORDER_REV/2];
    revCoeff[FIR_ORDER_REV-i-2] = coeff[i/2];
}

1. Open Matlab command window, click “fdatooll”, the FDATool GUI will pop out. Select the
parameters, filter type and other options which you prefer, click Design Filter. The design
process is finished (5.8).

![Figure 5.8: 1)](image_url)
2. Go to Targets-> Generate C header (5.9).

![Filter Design & Analysis Tool](image)

Figure 5.9: 2)

3. After 2), the Generate C header dialogue box pops out and in ‘Data type to use in export’, check ‘Export as’ Signed 16-bit or 32-bit integer (depends on 16 bit FIR or 32 bit FIR). Click ‘Generate’ (5.10).
4. Save the header file. The coefficient can directly port to ‘fir.h’ (5.11).

Example:
In the example project associated with FIR16_calc, users don’t need to worry about the order of coefficient since one section of the code will arrange it for user.
#include <filter.h>

// Filter Symbolic Constants
#define FIR_ORDER 32
#define SIGNAL_LENGTH 128

#if(FIR_ORDER & 0x01) // odd
#define FIR_ORDER_REV (FIR_ORDER + 1) // even
#else
#define FIR_ORDER_REV (FIR_ORDER + 2) // even
#endif

// If using the alternate FIR filter, replace with
// FIR16 fir= FIR16_ALT_DEFAULTS;
FIR16 fir= FIR16_DEFAULTS;

t32_t dbuffer[(FIR_ORDER+3)/2];
t16_t sigIn[SIGNAL_LENGTH];
t16_t sigOut[SIGNAL_LENGTH];
t16_t coeff[FIR_ORDER+2];
t16_t revCoeff[FIR_ORDER+2];

// Start of main()
int main(void)
{
    ........
    if((FIR_ORDER & 0x01) == 0){
        revCoeff[FIR_ORDER_REV-1] = 0;
    }
    // Reorder the coefficients
    for(i = 0; i < FIR_ORDER + 2; i = i + 2){
        revCoeff[FIR_ORDER_REV-i-1] = coeff[i/2+FIR_ORDER_REV/2];
        revCoeff[FIR_ORDER_REV-i-2] = coeff[i/2];
    }
    ........
    // Initialize FIR16 object
    fir.order = FIR_ORDER;
    fir.dbuffer_ptr = &dbuffer[0];
    fir.coef_ptr = (int32_t *)&revCoeff[0];
    fir.init(&fir);

    // FIR calculation
    for(i = 0; i < SIGNAL_LENGTH; i++){
        fir.input = xn; // Q15 format
        fir.calc(&fir);
        yn = fir.output;
    }
}
**Benchmark Information:**

All buffers and stack are placed in internal memory (zero-wait states in data space).

<table>
<thead>
<tr>
<th>FIR Taps (1 block)</th>
<th>C-Callable ASM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FIR16_calc</strong></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>47 cycles</td>
</tr>
<tr>
<td>16</td>
<td>51 cycles</td>
</tr>
<tr>
<td>32</td>
<td>59 cycles</td>
</tr>
<tr>
<td>64</td>
<td>75 cycles</td>
</tr>
<tr>
<td>128</td>
<td>107 cycles</td>
</tr>
<tr>
<td>256</td>
<td>171 cycles</td>
</tr>
<tr>
<td><strong>FIR16_Alt_calc</strong></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>49 cycles</td>
</tr>
<tr>
<td>16</td>
<td>53 cycles</td>
</tr>
<tr>
<td>32</td>
<td>61 cycles</td>
</tr>
<tr>
<td>64</td>
<td>77 cycles</td>
</tr>
<tr>
<td>128</td>
<td>108 cycles</td>
</tr>
<tr>
<td>256</td>
<td>172 cycles</td>
</tr>
<tr>
<td>512</td>
<td>300 cycles</td>
</tr>
<tr>
<td>1024</td>
<td>556 cycles</td>
</tr>
</tbody>
</table>

Table 5.7: 16-bit FIR Routines
5.2.7 32 Bit FIR Filter Module

Description:
This module implements FIR Filter using QMACL instructions that effectively executes 1 filter tap in a cycle. There are two functions in this module, `FIR32_calc` can support up to 127th order FIR filter, while `FIR32_Alt_calc` can support up to a 32767th order filter.

Header File:
`filter.h`

Availability:
C-Callable Assembly (CcA)

Object Definition:
The structure of the FIR32 object is as follows

```c
typedef struct {
    int32 *coeff_ptr;
    int32 *dbuffer_ptr;
    int16 cbindex;
    int16 order;
    int16 input;
    int16 output;
    void (*init)(void *);
    void (*calc)(void *);
}FIR32;
```

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>coeff_ptr</td>
<td>Coefficient pointer</td>
<td>Pointer to 32-bit integer buffer</td>
<td>Q31</td>
<td>Pointer to the Filter coefficients are arranged in natural order.</td>
</tr>
<tr>
<td>dbuffer_ptr</td>
<td>Delay buffer</td>
<td>Pointer to 32-bit integer buffer</td>
<td>Q31</td>
<td>Pointer to the Delay buffer. 32-bit elements in delay buffer are arranged in natural order.</td>
</tr>
<tr>
<td>cbindex</td>
<td>Circular buffer index</td>
<td>int16</td>
<td>Q0</td>
<td>Calculated by <code>FIR32_init</code> function in terms of the order (range: 0x00~FE); it serves as the wraparound point for the delay buffer whereas <code>FIR32_Alt_init</code> will zero it out.</td>
</tr>
<tr>
<td>order</td>
<td>Order of the filter</td>
<td>int16</td>
<td>Q0</td>
<td>Filter order, one less than the number of taps.</td>
</tr>
<tr>
<td>input</td>
<td>Input to the filter</td>
<td>int16</td>
<td>Q31</td>
<td>N/A</td>
</tr>
<tr>
<td>output</td>
<td>Output of the filter</td>
<td>int16</td>
<td>Q30</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Continued on next page
### Table 5.8 – continued from previous page

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>init</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>This initialization function initializes cbindex and clean up delay buffer</td>
</tr>
<tr>
<td>calc</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>This module calculates the FIR filtering using QMACL instruction</td>
</tr>
</tbody>
</table>

### Special Constants and Data types:

**FIR32**  
The module definition is created as a data type. This makes it convenient to instance an interface to the FIR32 Filter module. To create multiple instances of the module simply declare variables of type FIR32

**FIR32_Handle**  
User defined Data type of pointer to FIR32 Module

**FIR32_DEFAULTS**  
Structure symbolic constant is to initialize FIR32 Module. This provides the initial values to the terminal variables as well as method pointers.

**FIR32_DEFAULTS**  
Structure symbolic constant is to initialize FIR32 Module in order to run the alternate 32-bit FIR routines. This provides the initial values to the terminal variables as well as method pointers.

### Methods:

- `void FIR32_init(FIR32_Handle);`
- `void FIR32_calc(FIR32_Handle);`
- `void FIR32_Alt_init(FIR32_Handle);`
- `void FIR32_Alt_calc(FIR32_Handle);`

Each FIR implementation has two functions, an initialization and computation function. The input argument to these functions is the module handle.

### Coefficients generation:

The method to generate the 32 bit FIR filter coefficients is the same as that described under the 16 bit FIR Module description, with the only difference that in step 3, the user chooses to generate the coefficients as signed 32-bit integers with fractional length of 31.

For the `FIR32_calc` function, the coefficients need no be reordered but for the `FIR32_Alt_calc` routine they need to be in reverse order.

### Note:

1. The delay buffer is assigned to a section, “firldb”, which should be aligned to 256 word boundary in the data memory (RAM) for the FIR16 module. The FIR16_Alt module does not require any alignment
2. The coefficients are placed in a section, “firfilt”, that can be placed anywhere in the data memory (RAM)

### Example:

The following sample code runs a 32-bit FIR filter:

```c
#include <filter.h>

#define FIR_ORDER 43
#define SIGNAL_LENGTH 128

FIR32 fir = FIR32_DEFAULTS;
int32_t dbuffer[FIR_ORDER+1];
```
```c
int32_t sigIn[SIGNAL_LENGTH];
int32_t sigOut[SIGNAL_LENGTH];
const int32_t coeff[FIR_ORDER+1] = FIR32_LPF32_TEST;
// Alternate FIR32 requires reordering of the coefficients
// int32_t revCoeff[FIR_ORDER+1];
int main(void)
{
    ........
    // Alternate FIR32 requires reordering of the coefficients
    // for(i = 0; i < FIR_ORDER_REV + 1; i++){
    //     revCoeff[FIR_ORDER_REV-i] = coeff[i];
    // }
    ........
    // Initialize FIR32 object
    fir.order = FIR_ORDER;
    fir.dbuffer_ptr = dbuffer;
    fir.coeff_ptr = (int32_t*)coeff;
    fir.init(&fir);

    for(i=0; i < SIGNAL_LENGTH; i++){
        fir.input = xn;  //Input data
        fir.calc(&fir);  //FIR convolution operation
        yn = fir.output;  //Output data
    }
}

Benchmark Information:
All buffers and stack are placed in internal memory (zero-wait states in data space).

<table>
<thead>
<tr>
<th>FIR Taps (1 block)</th>
<th>C-Callable ASM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FIR32_calc</strong></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>45 cycles</td>
</tr>
<tr>
<td>16</td>
<td>53 cycles</td>
</tr>
<tr>
<td>32</td>
<td>69 cycles</td>
</tr>
<tr>
<td>64</td>
<td>101 cycles</td>
</tr>
<tr>
<td>128</td>
<td>165 cycles</td>
</tr>
<tr>
<td><strong>FIR32_Alt_calc</strong></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>46 cycles</td>
</tr>
<tr>
<td>16</td>
<td>54 cycles</td>
</tr>
<tr>
<td>32</td>
<td>70 cycles</td>
</tr>
<tr>
<td>64</td>
<td>102 cycles</td>
</tr>
<tr>
<td>128</td>
<td>166 cycles</td>
</tr>
<tr>
<td>256</td>
<td>294 cycles</td>
</tr>
<tr>
<td>512</td>
<td>550 cycles</td>
</tr>
<tr>
<td>1024</td>
<td>1062 cycles</td>
</tr>
</tbody>
</table>

Table 5.9: 32-bit FIR Routines
```
5.2.8 16 Bit IIR Filter Module

**Description:**
This module implements Direct II Form cascade Second Order Sections (SOS) IIR filter structure using “biquad” with 16-bit delay line.

**Header File:**
filter.h

**Availability:**
C-Callable Assembly (CcA)

**Object Definition:**
The structure of the IIR5BIQ16 object is as follows

```c
typedef struct {
    void (*init)(void *);
    void (*calc)(void *);
    int32 *coeff_ptr;
    int32 *dbuffer_ptr;
    int16 nbiq;
    int16 input;
    int16 isf;
    int16 qfmat;
    int16 output;
} IIR5BIQ16;
```

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>init</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>Delay buffer clean up and initialization function</td>
</tr>
<tr>
<td>calc</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>IIR filter calculation function</td>
</tr>
<tr>
<td>coeff_ptr</td>
<td>Coefficients</td>
<td>Pointer to 16-bit</td>
<td>Q15</td>
<td>Pointer to the Filter coefficient array. Arrangement can be referred to “Background Information” section.</td>
</tr>
<tr>
<td></td>
<td>pointer</td>
<td>integer array</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dbuffer_ptr</td>
<td>Delay buffer</td>
<td>Pointer to 16-bit</td>
<td>Q15</td>
<td>Delay buffer arrangement can be referred to “Background Information” section.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>integer array</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nbiq</td>
<td>Number of biquad</td>
<td>int16</td>
<td>Q0</td>
<td>Number of bi-quad (SOS) elements. Calculated by ezii16.m</td>
</tr>
<tr>
<td></td>
<td>elements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input</td>
<td>Input data</td>
<td>int16</td>
<td>Q15</td>
<td>Should be normalized to Q15 format</td>
</tr>
</tbody>
</table>

Continued on next page
## Table 5.10 – continued from previous page

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>isf</td>
<td>Input scaling coefficients</td>
<td>int16</td>
<td>Q15</td>
<td>Dynamic adjustment coefficients in order to prevent from out of dynamic range. Calculated by eziir16.m</td>
</tr>
<tr>
<td>qfmt</td>
<td>Q format value</td>
<td>int16</td>
<td>Q0</td>
<td>Q format chosen to be run in order to prevent from out of dynamic range. Calculated by eziir16.m</td>
</tr>
<tr>
<td>output</td>
<td>Output data</td>
<td>int16</td>
<td>Q14</td>
<td>Output data converted into Q14.</td>
</tr>
</tbody>
</table>

### Special Constants and Data types:

**IIR5BIQ16** The module definition is created as a data type. This makes it convenient to instance an interface to the IIR5BIQ16 Filter module. To create multiple instances of the module simply declare variables of type IIR5BIQ16

**IIR5BIQ16_handle** User defined data type of pointer to IIR5BIQ16 Module

**IIR5BIQ16_DEFAULTS** Structure symbolic constant is to initialize IIR5BIQ16 Module. This provides the initial values to the terminal variables as well as method pointers.

### Methods:

```c
void init(IIR5BIQ16_handle);
void calc(IIR5BIQ16_handle);
```

These definitions implement two methods viz., the initialization and IIR filter computation function. The input argument to these functions is the module handle

### Coefficients generation:

The IIR coefficients are generated by ‘eziir16.m’. Details can be found in Appendix A.

### Note:

For generating IIR coefficients, IIR5BIQ16 module cannot work independently from Mat-lab scripts “eziir16.m” (<base>\examples_ccsv5\2833x_FixedPoint_IIR16\matlab). User can run this script to get specified filter coefficients and copied it to the header file “iir.h”.

### Background Information:

In general, an IIR filter is described by the difference equation

$$y(n) = - \sum_{k=1}^{N} a_k y(n-k) + \sum_{k=0}^{M} b_k x(n-k)$$

or, equivalently, by the system function

$$H(z) = \frac{\sum_{k=0}^{M} b_k \times z^{-k}}{1 - \sum_{k=1}^{N} a_k \times z^{-k}}$$

Problems of implementing the above system with finite precision arithmetic have motivated the development of various filter structures. Direct Form I II implementation of IIR filter is extremely sensitive to parameter quantization, in general, and are not recommended in practical applications. It has been shown that breaking up the transfer function into lower-order sections
and connecting these in cascade or parallel can reduce this sensitivity to coefficient quantization. Hence, we choose to use cascade configuration of direct form II structured Second order section (SOS) in our implementation. The SOS's are commonly referred to as Biquads. The following block diagram shows the Cascade implementation of 4th order IIR filter using two biquads.

![Figure 5.12: Second Order Stage (SOS) or Biquad](image)

The SOS coefficients generated by the MATLAB for given set of filter specification provides unity gain in the pass-band and attenuates the remaining frequency component. Though the input to output gain does not peak above unity, the intermediate node gain in the biquad sections would vary significantly depending on the filter characteristics. The user should devise a technique to limit the peak gain at all the intermediate nodes to unity in order to avoid the overflow.

The first step is to identify the node gains in each SOS with respect to the input and then scale the input of each subsection appropriately to avoid the overflow. Scaling the input to each section is equivalent to scaling the ‘b’ coefficients of the preceding section. We have developed the “MATLAB” script to design the IIR filter without overflow issues. The script carries out the node gain analysis and scales the signal level at various points by scaling the “b” coefficients to limit the gain at all the node in the filter to unity. The scaled SOS coefficients, Input Scaling factor, the Q format used to represent coefficients and number of biquad used to obtain the requested filter characteristics are stored in a file, to initialize the IIR5BIQ16 filter module. Input Scaling factor limits the gain at the first node of the first biquad to unity. The user must use the eziiir16 filter design script to generate filter coefficient for this module.
Figure 5.13: Coefficient and Delay buffer Storage
Example:
The following sample code obtains the filtered result with 16 bit IIR filter.

```c
#include <filter.h>

/* Filter Symbolic Constants */
#define SIGNAL_LENGTH 1000

#pragma DATA_SECTION(iir, "iirfilt");
IIR5BIQ32 iir=IIR5BIQ16_DEFAULTS;

#pragma DATA_SECTION(dbuffer,"iirfilt");
long dbuffer[2*IIR16_LPF_NBIQ];
........
const long coeff[5*IIR16_LPF_NBIQ]=IIR16_LPF_COEFF;

void main()
{
    ........
    /* IIR Filter Initialisation */
    iir.dbuffer_ptr=dbuffer;
    iir.coef_ptr=(long *)coeff;
    iir.qfmat=IIR16_LPF_QFMAT;
    iir.nbiq=IIR16_LPF_NBIQ;
    iir.isf=IIR16_LPF_ISF;
    iir.init(&iir);

    /* IIR Filter calculation */
    for(i=0; i < SIGNAL_LENGTH; i++)
    {
        iir.input=xn;
        iir.calc(&iir);
        yn=iir.output32;
    }
}
```

Benchmark Information:
All buffers and stack are placed in internal memory (zero-wait states in data space).

<table>
<thead>
<tr>
<th>NBIQ</th>
<th>C-Callable</th>
<th>ASM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23 cycles</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>49 cycles</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>103 cycles</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>190 cycles</td>
<td></td>
</tr>
</tbody>
</table>
5.2.9 32 Bit IIR Filter Module

**Description:**
This module implements Direct II Form cascade Second Order Sections (SOS) IIR filter structure using “biquad” with 32-bit delay line.

**Header File:**
filter.h

**Availability:**
C-Callable Assembly (CcA)

**Object Definition:**
The structure of the IIR5BIQ32 object is as follows

```c
typedef struct {
    void (*init)(void *);
    void (*calc)(void *);
    int32 *coeff_ptr;
    int32 *dbuffer_ptr;
    int16 nbiq;
    int32 input;
    int16 isf;
    int32 output32;
    int16 output16;
    int16 qfmat;
} IIR5BIQ32;
```

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>init</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>Delay buffer clean up and initialization function</td>
</tr>
<tr>
<td>calc</td>
<td>Member function</td>
<td>Function pointer</td>
<td>N/A</td>
<td>IIR filter calculation function</td>
</tr>
<tr>
<td>coeff_ptr</td>
<td>Coefficients</td>
<td>Pointer to 32-bit</td>
<td>Q31</td>
<td>Pointer to the Filter coefficient array. Arrangement can be referred</td>
</tr>
<tr>
<td></td>
<td>pointer</td>
<td>integer array</td>
<td></td>
<td>to “Background Information” section.</td>
</tr>
<tr>
<td>dbuffer_ptr</td>
<td>Delay buffer</td>
<td>Pointer to 32-bit</td>
<td>Q31</td>
<td>Delay buffer arrangement can be referred to “Background Information”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>integer array</td>
<td></td>
<td>section.</td>
</tr>
<tr>
<td>nbiq</td>
<td>Number of biquad</td>
<td>int32</td>
<td>Q0</td>
<td>Number of biquad (SOS) elements. Calculated by ezir32.m</td>
</tr>
<tr>
<td>input</td>
<td>Input data</td>
<td>int32</td>
<td>Q31</td>
<td>Should be normalized to Q31 format.</td>
</tr>
</tbody>
</table>

Continued on next page
Table 5.11 – continued from previous page

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Format</th>
<th>Q-values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>isf</td>
<td>Input scaling coefficients</td>
<td>int32</td>
<td>Q31</td>
<td>Dynamic adjustment coefficients in order to prevent from out of dynamic range. Calculated by eziir32.m</td>
</tr>
<tr>
<td>qfmat</td>
<td>Q format value</td>
<td>int32</td>
<td>Q0</td>
<td>Q format chosen to be run in order to prevent from out of dynamic range. Calculated by eziir32.m</td>
</tr>
<tr>
<td>output32</td>
<td>Output data</td>
<td>int32</td>
<td>Q30</td>
<td>Output data in Q30 format.</td>
</tr>
<tr>
<td>output16</td>
<td>Output data</td>
<td>int16</td>
<td>Q14</td>
<td>Output data in Q14 format.</td>
</tr>
</tbody>
</table>

Special Constants and Data types:

**IIR5BIQ32** The module definition is created as a data type. This makes it convenient to instantiate an interface to the IIR5BIQ32 Filter module. To create multiple instances of the module simply declare variables of type IIR5BIQ32

**IIR5BIQ32_handle** User defined Data type of pointer to IIR5BIQ32 Module

**IIR5BIQ32_DEFAULTS** Structure symbolic constant is to initialize IIR5BIQ32 Module. This provides the initial values to the terminal variables as well as method pointers.

**Methods:**

```c
void init(IIR5BIQ32_handle);
void calc(IIR5BIQ32_handle);
```

These definitions implements two methods viz., the initialization and IIR filter computation function. The input argument to these functions is the module handle

**Coefficients generation:**

The IIR coefficients are generated by ‘eziir32.m’. Details can be found in Appendix A.

**Note:**

For generating IIR coefficients, IIR5BIQ32 module cannot work independently from Matlab scripts “eziir32.m” (<base>/examples_ccsv5/2833x_FixedPoint_IIR32/matlab). User can run this script to get specified filter coefficients and copied it to the header file “iir.h”.

**Background Information:**

In general, an IIR filter is described by the difference equation

\[ y(n) = - \sum_{k=1}^{N} a_k y(n - k) + \sum_{k=0}^{M} b_k x(n - k) \]

or, equivalently, by the system function

\[ H(z) = \frac{\sum_{k=0}^{M} b_k \times z^{-k}}{1 - \sum_{k=1}^{N} a_k \times z^{-k}} \]

Problems of implementing the above system with finite precision arithmetic have motivated the development of various filter structures. Direct Form I II implementation of IIR filter is ex-
Application Programming Interface (Fixed Point Library)

tremely sensitive to parameter quantization, in general, and are not recommended in practical applications. It has been shown that breaking up the transfer function into lower-order sections and connecting these in cascade or parallel can reduce this sensitivity to coefficient quantization. Hence, we choose to use cascade configuration of direct form II structured Second order section (SOS) in our implementation. The SOS's are commonly referred to as Biquads. The following block diagram shows the Cascade implementation of 4th order IIR filter using two biquads.

![Figure 5.14: Second Order Stage (SOS) or Biquad](image)

The SOS coefficients generated by the MATLAB for given set of filter specification provides unity gain in the pass-band and attenuates the remaining frequency component. Though the input to output gain does not peak above unity, the intermediate node gain in the biquad sections would vary significantly depending on the filter characteristics. The user should devise a technique to limit the peak gain at all the intermediate nodes to unity in order to avoid the overflow.

The first step is to identify the node gains in each SOS with respect to the input and then scale the input of each subsection appropriately to avoid the overflow. Scaling the input to each section is equivalent to scaling the “b” coefficients of the preceding section. We have developed the “MATLAB” script to design the IIR filter without overflow issues. The script carries out the node gain analysis and scales the signal level at various points by scaling the “b” coefficients to limit the gain at all the node in the filter to unity. The scaled SOS coefficients, Input Scaling factor, the Q format used to represent coefficients and number of biquad used to obtain the requested filter characteristics are stored in a file, to initialize the IIR5BIQ32 filter module. Input Scaling factor limits the gain at the first node of the first biquad to unity. The user must use the eziir16 filter design script to generate filter co-efficient for this module.
**Application Programming Interface (Fixed Point Library)**

**Figure 5.15: Coefficient and Delay buffer Storage**

**Example:**
The following sample code obtains the filtered result with 16 bit IIR filter.

```c
#include <filter.h>
```

---

<table>
<thead>
<tr>
<th>Coefficient Buffer</th>
<th>Delay Buffer</th>
</tr>
</thead>
<tbody>
<tr>
<td>32-bit width</td>
<td>32-bit width</td>
</tr>
<tr>
<td>coeff_ptr</td>
<td></td>
</tr>
<tr>
<td>[ a_{21} ]</td>
<td>[ d_k(n-1) \text{ LSW} ]</td>
</tr>
<tr>
<td>[ a_{11} ]</td>
<td>[ d_k(n-1) \text{ MSW} ]</td>
</tr>
<tr>
<td>[ b_{21} ]</td>
<td>[ d_k(n-2) \text{ LSW} ]</td>
</tr>
<tr>
<td>[ b_{11} ]</td>
<td>[ d_k(n-2) \text{ MSW} ]</td>
</tr>
<tr>
<td>[ b_{01} ]</td>
<td></td>
</tr>
<tr>
<td>[ a_{22} ]</td>
<td>[ d_2(n-1) \text{ LSW} ]</td>
</tr>
<tr>
<td>[ a_{12} ]</td>
<td>[ d_2(n-1) \text{ MSW} ]</td>
</tr>
<tr>
<td>[ b_{22} ]</td>
<td>[ d_2(n-2) \text{ LSW} ]</td>
</tr>
<tr>
<td>[ b_{12} ]</td>
<td>[ d_2(n-2) \text{ MSW} ]</td>
</tr>
<tr>
<td>[ b_{02} ]</td>
<td></td>
</tr>
<tr>
<td>[ \vdots ]</td>
<td>[ \vdots ]</td>
</tr>
<tr>
<td>[ \ddots ]</td>
<td>[ \ddots ]</td>
</tr>
<tr>
<td>[ a_{2k} ]</td>
<td>[ d_1(n-1) \text{ LSW} ]</td>
</tr>
<tr>
<td>[ a_{1k} ]</td>
<td>[ d_1(n-1) \text{ MSW} ]</td>
</tr>
<tr>
<td>[ b_{2k} ]</td>
<td>[ d_1(n-2) \text{ LSW} ]</td>
</tr>
<tr>
<td>[ b_{1k} ]</td>
<td>[ d_1(n-2) \text{ MSW} ]</td>
</tr>
<tr>
<td>[ b_{0k} ]</td>
<td>[ d_1(n-2) \text{ MSW} ]</td>
</tr>
<tr>
<td>[ \text{Low Address} ]</td>
<td>[ \text{High Address} ]</td>
</tr>
</tbody>
</table>
/* Filter Symbolic Constants */
#define SIGNAL_LENGTH 1000

/* Create an Instance of IIR5BIQD32 module and place the object in "iirfilt" section */
#pragma DATA_SECTION(iir, "iirfilt");
IIR5BIQ32 iir=IIR5BIQ32_DEFAULTS;

/* Define the Delay buffer for the cascaded 6 biquad IIR filter and place it in "iirfilt" section */
#pragma DATA_SECTION(dbuffer,"iirfilt");
long dbuffer[2*IIR32_LPF_NBIQ];

const long coeff[5*IIR32_LPF_NBIQ]=IIR32_LPF_COEFF;

void main()
{
    /* IIR Filter Initialisation */
    iir.dbuffer_ptr=dbuffer;
    iir.coeff_ptr=(long *)coeff;
    iir.qfmat=IIR32_LPF_QFMAT;
    iir.nbiq=IIR32_LPF_NBIQ;
    iir.isf=IIR32_LPF_ISF;
    iir.init(&iir);

    /* Calculation section */
    for(i=0; i < SIGNAL_LENGTH; i++)
    {
        iir.input=xn;
        iir.calc(&iir);
        yn=iir.output32;
    }
}

**Benchmark Information:**
All buffers and stack are placed in internal memory (zero-wait states in data space).

<table>
<thead>
<tr>
<th>NBIQ</th>
<th>C-Callable ASM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22 cycles</td>
</tr>
<tr>
<td>2</td>
<td>48 cycles</td>
</tr>
<tr>
<td>4</td>
<td>110 cycles</td>
</tr>
<tr>
<td>8</td>
<td>202 cycles</td>
</tr>
</tbody>
</table>
6 Revision History

V1.20.00.00: Moderate Update, October 23, 2014
- Revised documentation.
- Re-factored all library and example projects to use CGT v6.2.5.
- Updated all examples to work with CCS v5.
- FIR16/32: Added alternate routines that uses C2xLP circular addressing allowing the filters to exceed the 256(128) tap limit of the current FIR routines. Added examples and matlab scripts to demonstrate how these routines work.
- fft.h: Corrected the errors in the RFFT32_<n>P_DEFAULT macros.
- Added 17 different windowing tables for FFTs up to 4096 points, each in their own header file. Also added the MATLAB script to generate them.
- Added RFFT windowing function - applies the window to both the even and odd entries of the bit reversed input buffer.
- Fixed data overrun issue with RFFT32_brev caused by not zeroing out AH prior to using a shifted ACC (AL) as a loop counter.
- Fixed issue with FIR16_calc where the loop count and wrap around address were incorrectly set to 1 less than the proper value - this was causing the filter to not use the last coefficient as well as the last element of the delay line buffer.
- Fixed issue with FIR32_init which would either not zero out the entire delay line (odd order filter) or zero out an extra word (even order filter). Also calculated the wrapparound offset “cbindex” one time instead of FIR_calc calculating it on each invocation.
- Corrected size of input (32-bits) in the IIR5BIQ32 structure.
- Fixed issue with incorrect loop count in the FIR32_calc routine.
- RFFT32_brev will now bit-reverse order both even and odd locations.
- Added split function that derives the complex spectrum of a 2N point real sequence, after it is run through a complex N point FFT, to get the real FFT.
- Added new magnitude function for the real FFT, that computes the magnitude of the spectrum from 0 Hz to the Nyquist frequency, about which point the magnitude plot is symmetric.

V1.01: Minor Update, January 10, 2011
- Added section on running FFTs out of RAM in standalone mode. Library re-compiled with fpu support.

V1.00: First Release, November 1, 2010
- Official release. Includes the Real FFT and real FFT and 16 bit and 32 bit FIR/IIR fixed point filter library.

Beta 1: Test Release, May 7, 2002
- Includes the Real, real FFT, 16 bit FIR, 16 and 32 bit IIR fixed point filter library.
A.1 IIR Filter Specifications

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Stopband and Passband Conditions</th>
<th>Stopband</th>
<th>Passband</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPF</td>
<td>$F_P &lt; F_S$, Both Scalar</td>
<td>$[F_S, F_N]$</td>
<td>$[0, F_P]$</td>
</tr>
<tr>
<td>HPF</td>
<td>$F_P &lt; F_S$, Both Scalar</td>
<td>$[0, F_S]$</td>
<td>$[F_P, F_N]$</td>
</tr>
<tr>
<td>BPF</td>
<td>$F_{S1} &lt; F_P1 &lt; F_P2 &lt; F_{S2}$, ( F_P = [F_{P1}, F_{P2}] ) &amp; $F_S = [F_{S1}, F_{S2}]$ are Vector</td>
<td>$[0, F_{S1}]$ &amp; $[F_{S2}, F_N]$</td>
<td>$[F_{P1}, F_{P2}]$</td>
</tr>
<tr>
<td>BSF</td>
<td>$F_{P1} &lt; F_{S1} &lt; F_{S2} &lt; F_{P2}$, ( F_P = [F_{P1}, F_{P2}] ) &amp; $F_S = [F_{S1}, F_{S2}]$ are Vector</td>
<td>$[F_{S1}, F_{S2}]$</td>
<td>$[0, F_{P1}]$ &amp; $[F_{P2}, F_N]$</td>
</tr>
</tbody>
</table>

Table A.1: Description of Stop band and Pass band Filter Parameters

The information presented in the table is illustrated in the following diagrams:
Figure A.2: HPF Filter Specification

Figure A.3: BPF Filter Specification

Figure A.4: BSF Filter Specification
A.2 ezIIR Filter Design Script Usage

ezIIR filter design script facilitates the user to design cascade IIR filter using Second Order Section (SOS) without any overflow issues in the internal nodes of the filter.

Step 1:
Invoke the MATLAB software and modify the current working directory to C:\TI\controlSUITE\libs\dsp\FixedPointLib\v1_20_00_00\examples_ccsv5\2833x_FixedPoint_IIR$\matlab (here $ = 16 or 32)

>> cd C:\TI\controlSUITE\libs\dsp\FixedPointLib\v100\examples_ccsv4\2833x_FixedPoint_IIR$\matlab (here $=16 or 32)

Step 2:
Execute the ezIIR16 or ezIIR32 script and input the required filter response parameters

Note: ezIIR16 script generates filter co-efficients for IIR5BIQ16 module
ezIIR32 script generates filter co-efficients for IIR5BIQ32 module

The script requests the user to provide following information for filter design viz.,

1. Type of Filter
2. Type of Response
3. Sampling frequency in Hz
4. Pass Band Ripples in Decibels
5. Stop Band Attenuation in Decibels
6. Pass Band Frequency in Hz
7. Stop Band Frequency in Hz
8. Name of the file to store the outputs

```
  » C:\TI\controlSUITE\libs\dsp\FixedPointLib\v1_20_00_00\examples_ccsv5\2833x_FixedPoint_IIR16\matlab
  » ezIIR16

ezIIR FILTER DESIGN SCRIPT
Butterworth : 1
Chebyshev(Type 1) : 2
Chebyshev(Type 2) : 3
Elliptic : 4
Select Any one of the above IIR Filter Type : 1
Low pass : 1
High Pass : 2
Band Pass : 3
Band Stop : 4
Select Any one of the above Response : 1
Enter the Sampling frequency : 20000
Enter the Pass band Ripples in dB(RP) : 1
Enter the stop band Ripples in dB(RS) : 20
Enter the pass band corner frequency(FP) : 2000
Enter the stop band corner frequency(FS) : 3000
Enter the name of the file for coeff storage : filter.dat
```
Step 3:
ezIIR Filter design script outputs the following information viz.,

1. Set of SOS coefficients
2. Input Scaling Factor required to avoid the overflow in the first biquad
3. Number of Biquad required to obtain the specified filter characteristics
4. Q Format used to represent the scaled SOS filter coefficients
5. Displays the filter response in figure window 1 and window 2 (Fig A.2 A.2)
   Figure window 1, displays the magnitude response in normal scale
   Figure window 2, displays the magnitude response in logarithmic scale

FILTER.DAT

```
#define IIR16_COEFF {\n    0,3794,0,307,307,\n    -2159,7894,668,1335,668,\n    -3483,8904,541,1082,541,\n    -6131,10923,13364,26729,13364}\n
#define IIR16_ISF  4398
#define IIR16_NBIQ 4
#define IIR16_QFMAT 13
```
Figure A.5: Filter response using normal scale

Figure A.6: Filter response using logarithmic scale
Step 4: Rename the symbolic constants uniquely as required and copy it to the IIRCOEF file in order to initialize the filter object in the main system file.
A.3 ezIIR IIR Filter Design Examples

A.3.1 LPF Design

LPF Specification:

Filter Type : Butterworth
Pass Band cutoff frequency (FP) : 3000 Hz
Stop Band cutoff frequency (FS) : 4000 Hz
Sampling Frequency : 20 KHz
Pass Band Attenuation (RP) : 1 dB
Stop Band Attenuation (RS) : 30 dB

LPF Design using ezIIR script:

```
>> ezir16
ezIIR FILTER DESIGN SCRIPT
Butterworth : 1
Chebyshev(Type 1) : 2
Chebyshev(Type 2) : 3
Elliptic : 4
Select Any one of the above IIR Filter Type : 1
Low pass : 1
High Pass : 2
Band Pass : 3
Band Stop : 4
Select Any one of the above Response : 1
Enter the Sampling frequency : 20000
Enter the Pass band Ripples in dB (RP) : 1
Enter the stop band Rippled in dB (RS) : 30
Enter the pass band corner frequency (FP) : 3000
Enter the stop band corner frequency (FS) : 4000
Enter the name of the file for coeff storage : lpf.dat

Q format of the IIR filter coefficients:

12

Input Scaling value:

0.4995

Number of Biquads:

6

LPF.DAT

#define IIR16_COEFF {
-373,2423,132,264,132,\n-516,2500,561,1121,561,\n-819,2665,603,1207,603,\n```


\begin{verbatim}
#define IIR16_ISF 2046
#define IIR16_NBIQ 6
#define IIR16_QFMAT 12
\end{verbatim}

Figure A.7: Low Pass Filter response using normal scale
A.3.2 HPF Design

HPF Specification:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Type</td>
<td>Chebyshev Type I</td>
</tr>
<tr>
<td>Pass Band cutoff frequency (FP)</td>
<td>4000Hz</td>
</tr>
<tr>
<td>Stop Band cutoff frequency (FS)</td>
<td>3000Hz</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>20KHz</td>
</tr>
<tr>
<td>Pass Band Attenuation (RP)</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>Stop Band Attenuation (RS)</td>
<td>30 dB</td>
</tr>
</tbody>
</table>

HPF Design using ezIIR script:

```
>> eziir16
ezIIR FILTER DESIGN SCRIPT
Butterworth    : 1
Chebyshev(Type 1) : 2
Chebyshev(Type 2) : 3
Elliptic       : 4
Select Any one of the above IIR Filter Type : 2
Low pass       : 1
High Pass      : 2
```
| Band Pass | 3 |
| Band Stop | 4 |
| Select Any one of the above | Response : 2 |
| Enter the Sampling frequency | 20000 |
| Enter the Pass band Ripples in dB (RP) | 0.1 |
| Enter the stop band Ripple in dB (RS) | 30 |
| Enter the pass band corner frequency (FP) | 4000 |
| Enter the stop band corner frequency (FS) | 3000 |
| Enter the name of the file for coeff storage | hpf.dat |

Q format of the IIR filter coefficients:
12

Input Scaling value:
0.6830

Number of Biquads:
4

**HPF.DAT**

```c
#define IIR16_COEFF {
    0,-1298,0,-456,456,
    -1106,-1198,1486,-2971,1486,
    -2372,1138,1356,-2711,1356,
    -3523,2655,10912,-21824,10912
}
#define IIR16_ISF 2798
#define IIR16_NBIQ 4
#define IIR16_QFMAT 12
```
Figure A.9: High Pass Filter response using normal scale

Figure A.10: High Pass Filter response using logarithmic scale
A.3.3 BPF Design

BPF Specification:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Type</td>
<td>Chebyshev Type II</td>
</tr>
<tr>
<td>Pass Band cutoff frequency (FP)</td>
<td>[3000, 4000] Hz</td>
</tr>
<tr>
<td>Stop Band cutoff frequency (FS)</td>
<td>[2500, 4500] Hz</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>20KHz</td>
</tr>
<tr>
<td>Pass Band Attenuation (RP)</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>Stop Band Attenuation (RS)</td>
<td>30 dB</td>
</tr>
</tbody>
</table>

BPF Design using ezIIR script:

```
>> ezir16
ezIIR FILTER DESIGN SCRIPT
Butterworth : 1
Chebyshev(Type 1) : 2
Chebyshev(Type 2) : 3
Elliptic : 4
Select Any one of the above IIR Filter Type : 3
Low pass : 1
High Pass : 2
Band Pass : 3
Band Stop : 4
Select Any one of the above Response : 3
Enter the Sampling frequency : 20000
Enter the Pass band Ripples in dB(RP) : 0.1
Enter the stop band Rippled in dB(RS) : 30
Enter the pass band corner frequency(FP) : [3000, 4000]
Enter the stop band corner frequency(FS) : [2500, 4500]
Enter the name of the file for coeff storage : bpf.dat

Q format of the IIR filter coefficients:
11
Input Scaling value:
0.3849
Number of Biquads:
5
```

**BPF.DAT**

```
#define IIR16_COEFF {
-986,1448,-408,0,408,\n-1323,889,648,96,648,\n-1452,2263,672,-1082,672,\n-1830,952,950,-264,950,\n-1877,2581,17695,-25335,17695}
```
Figure A.11: Band Pass Filter response using normal scale
A.3.4 BSF Design

BSF Specification:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Type</td>
<td>Elliptic</td>
</tr>
<tr>
<td>Pass Band cutoff frequency (FP)</td>
<td>[3000, 4000]Hz</td>
</tr>
<tr>
<td>Stop Band cutoff frequency (FS)</td>
<td>[3400, 3600]Hz</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>20KHz</td>
</tr>
<tr>
<td>Pass Band Attenuation (RP)</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>Stop Band Attenuation (RS)</td>
<td>30 dB</td>
</tr>
</tbody>
</table>

BSF Design using ezIIR script:

```
>> ezii16
ezIIR FILTER DESIGN SCRIPT
Butterworth       : 1
Chebyshev(Type 1) : 2
Chebyshev(Type 2) : 3
Elliptic          : 4
Select Any one of the above IIR Filter Type : 4
Low pass          : 1
High Pass         : 2
```
Band Pass : 3  
Band Stop : 4  
Select Any one of the above Response : 4  
Enter the Sampling frequency : 20000  
Enter the Pass band Ripples in dB(RP) : 0.1  
Enter the stop band Rippled in dB(RS) : 30  
Enter the pass band corner frequency(FP) : [3000,4000]  
Enter the stop band corner frequency(FS) : [3400,3600]  
Enter the name of the file for coeff storage : bsf.dat  

Q format of the IIR filter coefficients:  
11  

Input Scaling value:  
0.1848  

Number of Biquads:  
3  

**BSF.DAT**

```
#define IIR16_COEFF {
  -1515,1638,859,-790,859,
  -1883,1378,1998,-1631,1998,
  -1901,2198,21576,-21934,21576}
#define IIR16_ISF 379
#define IIR16_NBIQ 3
#define IIR16_QFMAT 11
```
Figure A.13: Band Stop Filter response using normal scale

Figure A.14: Band Stop Filter response using logarithmic scale
## A.4 Test coefficients for IIR filter

To demonstrate the IIR5BIQ16 & IIR5BIQ16 filter modules, we have generated filter co-efficient for LPF, HPF, BPF and BSF responses using eziir16 & eziir32 script and placed it in IIR.H header file.

These test co-efficients are generated using the same filter specification given in filter design examples in previous section.

### IIR.H : Test Co-efficients for IIR5BIQ16 Module

```
IIR.H : Test Co-efficients for IIR5BIQ16 Module

<table>
<thead>
<tr>
<th>/* LPF co-efficients for IIR16 module */</th>
</tr>
</thead>
<tbody>
<tr>
<td>#define IIR16_LPF_COEFF (\</td>
</tr>
<tr>
<td>-746,4846,1056,2111,1056,\</td>
</tr>
<tr>
<td>-1032,5001,1120,2239,1120,\</td>
</tr>
<tr>
<td>-1639,5330,1192,2385,1192,\</td>
</tr>
<tr>
<td>-2647,5877,1211,2422,1211,\</td>
</tr>
<tr>
<td>-4206,6722,872,1745,872,\</td>
</tr>
<tr>
<td>-6573,8005,4861,9722,4861)</td>
</tr>
<tr>
<td>#define IIR16_LPF_ISF 4092</td>
</tr>
<tr>
<td>#define IIR16_LPF_NBIQ 6</td>
</tr>
<tr>
<td>#define IIR16_LPF_QFMAT 13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>/* HPF co-efficients for IIR16 module */</th>
</tr>
</thead>
<tbody>
<tr>
<td>#define IIR16_HPF_COEFF (\</td>
</tr>
<tr>
<td>0,-2597,0,-3340,3340,\</td>
</tr>
<tr>
<td>-2211,-2396,1746,-3492,1746,\</td>
</tr>
<tr>
<td>-4745,2276,2007,-4014,2007,\</td>
</tr>
<tr>
<td>-7046,5310,13685,-27370,13685)</td>
</tr>
<tr>
<td>#define IIR16_HPF_ISF 5595</td>
</tr>
<tr>
<td>#define IIR16_HPF_NBIQ 4</td>
</tr>
<tr>
<td>#define IIR16_HPF_QFMAT 13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>/* BPF co-efficients for IIR16 module */</th>
</tr>
</thead>
<tbody>
<tr>
<td>#define IIR16_BPF_COEFF (\</td>
</tr>
<tr>
<td>-1078,1437,-367,0,367,\</td>
</tr>
<tr>
<td>-1395,935,713,43,713,\</td>
</tr>
<tr>
<td>-1496,2176,594,-917,594,\</td>
</tr>
<tr>
<td>-1855,994,1022,-329,1022,\</td>
</tr>
<tr>
<td>-1890,2462,18610,-25359,18610)</td>
</tr>
<tr>
<td>#define IIR16_BPF_ISF 721</td>
</tr>
<tr>
<td>#define IIR16_BPF_NBIQ 5</td>
</tr>
<tr>
<td>#define IIR16_BPF_QFMAT 11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>/* BSF co-efficients for IIR16 module */</th>
</tr>
</thead>
<tbody>
<tr>
<td>#define IIR16_BSF_COEFF (\</td>
</tr>
<tr>
<td>-1532,1626,859,-781,859,\</td>
</tr>
<tr>
<td>-1889,1374,2032,-1644,2032,\</td>
</tr>
<tr>
<td>-1906,2168,22098,-22158,22098)</td>
</tr>
<tr>
<td>#define IIR16_BSF_ISF 366</td>
</tr>
<tr>
<td>#define IIR16_BSF_NBIQ 3</td>
</tr>
<tr>
<td>#define IIR16_BSF_QFMAT 11</td>
</tr>
</tbody>
</table>
```
IIR Filter Design Package User’s Guide

IIR.H : Test Co-efficients for IIR5BIQ32 Module

{\bf /* LPF co-efficients for IIR32 module */}
#define IIR32_LPF_COEFF (
   -24444800,158794151,8647611,17295223,8647611,\n   -33805581,163869390,36741777,73483554,36741777,\n   -53695266,174653202,39535955,79071910,39535955,\n   -86750921,192575355,40880726,81761451,40880726,\n   -137806611,220256787,30931379,61862757,30931379,\n   -215373186,262311922,564004144,1128008289,564004144)
#define IIR32_LPF_ISF 134086103
#define IIR32_LPF_NBIQ 6
#define IIR32_LPF_QFMAT 28

{\bf /* HPF co-efficients for IIR32 module */}
#define IIR32_HPF_COEFF (\
   0,-85096979,0,-29857202,29857202,\
   -72466417,-78522171,97363917,-194727833,97363917,\
   -155480100,74571693,88837952,-177675903,88837952,\
   -230891969,173985995,715131301,-1430262602,715131301)
#define IIR32_HPF_ISF 183338477
#define IIR32_HPF_NBIQ 4
#define IIR32_HPF_QFMAT 28

{\bf /* BPF co-efficients for IIR32 module */}
#define IIR32_BPF_COEFF (\
   -70620977,94154018,-24080177,0,24080177,\
   -91416523,61304763,46717868,2819319,46717868,\
   -98072227,142585344,38933432,-60070942,38933432,\
   -121545500,65135203,66986143,-21532217,66986143,\
   -123895267,161346553,1219596683,-1661914443,1219596683)
#define IIR32_BPF_ISF 47247113
#define IIR32_BPF_NBIQ 5
#define IIR32_BPF_QFMAT 27

{\bf /* BSF co-efficients for IIR32 module */}
#define IIR32_BSF_COEFF (\
   -100408845,106578277,56314524,-51161340,56314524,\
   -123814194,90035192,133182068,-107730821,133182068,\
   -124894576,142053666,1448196385,-1452129490,1448196385)
#define IIR32_BSF_ISF 23999390
#define IIR32_BSF_NBIQ 3
#define IIR32_BSF_QFMAT 27
Bibliography


IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI’s standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

TI products are not authorized for use in safety-critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, unless officers of the parties have executed an agreement specifically governing such use. Buyers represent that they have all necessary expertise in the safety and regulatory ramifications of their applications, and acknowledge and agree that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use. TI further, Buyers must fully indemnify TI and its representatives against any damages arising out of the use of TI products in such safety-critical applications.

TI products are neither designed nor intended for use in military/aerospace applications or environments unless the TI products are specifically designated by TI as military-grade or “enhanced plastic.” Only products designated by TI as military-grade meet military specifications. Buyers acknowledge and agree that any such use of TI products which TI has not designated as military-grade is solely at the Buyer’s risk, and that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI products are neither designed nor intended for use in automotive applications or environments unless the specific TI products are designated by TI as compliant with ISO/TS 16949 requirements. Buyers acknowledge and agree that, if they use any non-designated products in automotive applications, TI will not be responsible for any failure to meet such requirements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products
- Amplifiers: amplifier.ti.com
- Data Converters: dataconverter.ti.com
- DLP® Products: www.dlp.com
- DSP: dsp.ti.com
- Clocks and Timers: www.ti.com/clocks
- Interface: interface.ti.com
- Logic: logic.ti.com
- Power Mgmt: power.ti.com
- Microcontrollers: microcontroller.ti.com
- RFID: www.ti-rfid.com
- RF/IF and ZigBee® Solutions: www.ti.com/lp rf

Applications
- Audio: www.ti.com/audio
- Automotive: www.ti.com/automotive
- Broadband: www.ti.com/broadband
- Digital Control: www.ti.com/digitalcontrol
- Medical: www.ti.com/medical
- Military: www.ti.com/military
- Optical Networking: www.ti.com/opticalnetwork
- Security: www.ti.com/security
- Telephony: www.ti.com/telephony
- Video & Imaging: www.ti.com/video
- Wireless: www.ti.com/wireless

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2014, Texas Instruments Incorporated

Oct 20, 2014