Section 37. Charge Time Measurement Unit (CTMU)

HIGHLIGHTS

This section of the manual contains the following major topics:

Note: This family reference manual section is meant to serve as a complement to device data sheets. Depending on the device variant, this manual section may not apply to all PIC32 devices.

Please consult the note at the beginning of the **"Charge Time Measurement Unit (CTMU)"** chapter in the current device data sheet to check whether this document supports the device you are using.

Device data sheets and family reference manual sections are available for download from the Microchip Worldwide Web site at: http://www.microchip.com

37.1 INTRODUCTION

The Charge Time Measurement Unit (CTMU) is a flexible analog module that has a configurable current source with a digital configuration circuit built around it. The CTMU can be used for differential time measurement between pulse sources and can be used for generating an asynchronous pulse. By working with other on-chip analog modules, the CTMU can be used for high resolution time measurement, measure capacitance, measure relative changes in capacitance or generate output pulses with a specific time delay. The CTMU is ideal for interfacing with capacitive-based sensors.

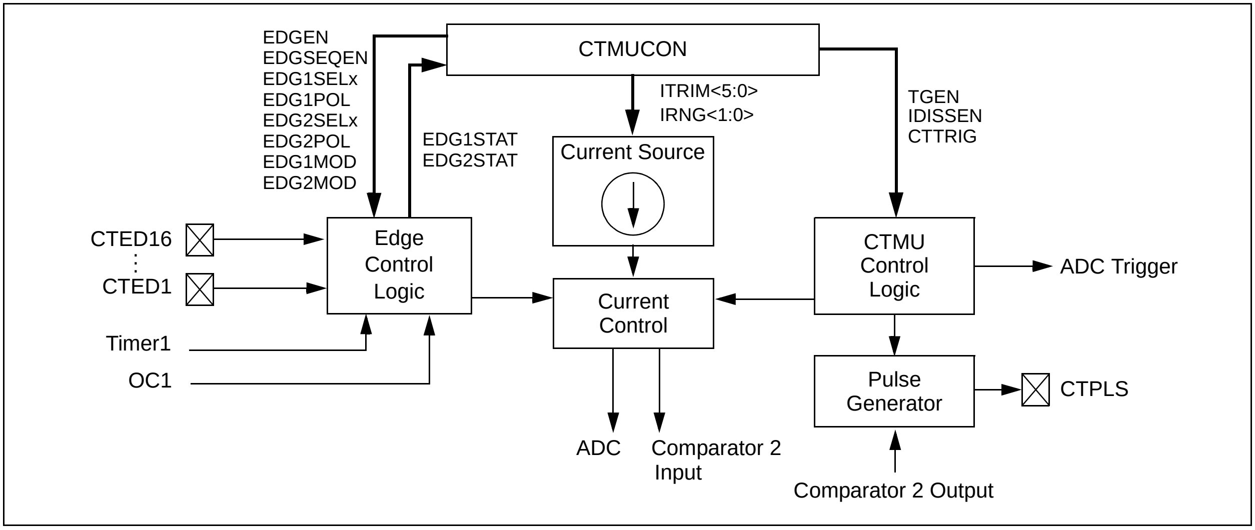
The module includes the following key features:

- Up to 32 channels available for capacitive or time measurement input
- On-chip precision current source
- 16-edge input trigger sources
- Selection of edge or level-sensitive inputs
- Polarity control for each edge source
- Control of edge sequence
- Control of response to edges
- High precision time measurement
- Time delay of external or internal signal asynchronous to system clock
- Integrated temperature sensing diode
- Control of current source during auto-sampling
- Four current source ranges
- Time measurement resolution of one nanosecond

The CTMU works in conjunction with the Analog-to-Digital Converter (ADC) to provide up to 32 channels for time or charge measurement, depending on the specific device and the number of ADC channels available. When configured for time delay, the CTMU is connected to one of the analog comparators. The level-sensitive input edge sources can be selected from four sources: two external inputs, Timer1 or Output Compare Module 1. For information on available input sources, refer to the specific device data sheet.

A block diagram of the CTMU is shown in Figure 37-1.

Figure 37-1: CTMU Block Diagram



37.2 REGISTERS

The CTMUCON register contains control bits for configuring the CTMU module edge source selection, edge source polarity selection, edge sequencing, ADC trigger, analog circuit capacitor discharge and enables. In addition, this register has bits for selecting the current source range and current source trim.

Table 37-1 summarizes the CTMU-related register. A detailed description of the register follows the summary.

Table 37-1: CTMU SFR Summary[1]

Name	Bit Range	Bit 31/23/15/7	Bit 30/22/14/6	Bit 29/21/13/5	Bit 28/20/12/4	Bit 27/19/11/3	Bit 26/18/10/2	Bit 25/17/9/1	Bit 24/16/8/0
CTMUCON	31:24	EDG1MOD	EDG1POL	EDG1SEL<3:0>				EDG2STAT	EDG1STAT
	23:16	EDG2MOD	EDG2POL	EDG2SEL<3:0>				—	—
	15:8	ON	—	CTMUSIDL	TGEN	EDGEN	EDGSEQEN	IDISSEN	CTTRIG
	7:0	ITRIM<5:0>						IRNG<1:0>	

Legend: — = unimplemented, read as ‘0’. Address offset values are shown in hexadecimal.
Note 1: Not all registers have associated SET, CLR, and INV registers. Refer to the specific device data sheet for details.

Register 37-1: CTMUCON: CTMU Control Register

Bit Range	Bit 31/23/15/7	Bit 30/22/14/6	Bit 29/21/13/5	Bit 28/20/12/4	Bit 27/19/11/3	Bit 26/18/10/2	Bit 25/17/9/1	Bit 24/16/8/0
31:24	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
	EDG1MOD	EDG1POL	EDG1SEL<3:0>(1)				EDG2STAT	EDG1STAT
23:16	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	U-0	U-0
	EDG2MOD	EDG2POL	EDG2SEL<3:0>(1)				—	—
15:8	R/W-0	U-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
	ON	—	CTMUSIDL	TGEN	EDGEN	EDGSEQEN	IDISSEN	CTTRIG
7:0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
	ITRIM<5:0>						IRNG<1:0>	

Legend:			
R = Readable bit	W = Writable bit	U = Unimplemented bit, read as ‘0’	
-n = Value at POR	‘1’ = Bit is set	‘0’ = Bit is cleared	x = Bit is unknown

bit 31 **EDG1MOD:** Edge1 Edge Sampling Select bit

1 = Input is edge-sensitive
0 = Input is level-sensitive

bit 30 **EDG1POL:** Edge 1 Polarity Select bit

1 = Edge1 programmed for a positive edge response
0 = Edge1 programmed for a negative edge response

bit 29-26 **EDG1SEL<3:0>:** Edge 1 Source Select bits(1)

1111 = CTED16 selected
•
•
•
0000 = CTED1 selected

bit 25 **EDG2STAT:** Edge2 Status bit

Indicates the status of Edge2 and can be written to control edge source

1 = Edge2 has occurred
0 = Edge2 has not occurred

bit 24 **EDG1STAT:** Edge1 Status bit

Indicates the status of Edge1 and can be written to control edge source

1 = Edge1 has occurred
0 = Edge1 has not occurred

bit 23 **EDG2MOD:** Edge2 Edge Sampling Select bit

1 = Input is edge-sensitive
0 = Input is level-sensitive

bit 22 **EDG2POL:** Edge 2 Polarity Select bit

1 = Edge2 programmed for a positive edge response
0 = Edge2 programmed for a negative edge response

bit 21-18 **EDG2SEL<3:0>:** Edge 2 Source Select bits(1)

1111 = CTED16 selected
•
•
•
0000 = CTED1 selected

bit 17-16 **Unimplemented:** Read as ‘0’

bit 15 **ON:** ON Enable bit

1 = Module is enabled
0 = Module is disabled

Note 1: Refer to the **“CTMU”** chapter in the specific device data sheet for the list of available trigger sources.

Register 37-1: CTMUCON: CTMU Control Register (Continued)

bit 14 **Unimplemented:** Read as ‘0’

bit 13 **CTMUSIDL:** Stop in Idle Mode bit
1 = Discontinue module operation when device enters Idle mode
0 = Continue module operation in Idle mode

bit 12 **TGEN:** Time Generation Enable bit
1 = Enables edge delay generation
0 = Disables edge delay generation

bit 11 **EDGEN:** Edge Enable bit
1 = Edges are not blocked
0 = Edges are blocked

bit 10 **EDGSEQEN:** Edge Sequence Enable bit
1 = Edge1 must occur before Edge2 can occur
0 = No edge sequence is needed

bit 9 **IDISSEN:** Current Discharge Enable bit
1 = Analog current source output is grounded
0 = Analog current source output is not grounded

bit 8 **CTTRIG:** Trigger Control bit
1 = Trigger output is enabled
0 = Trigger output is disabled

bit 7-2 **ITRIM<5:0>:** Current Source Trim bits
111111 = Minimum negative change from nominal current
•
•
•
100010
100001 = Maximum negative change from nominal current
011111 = Maximum positive change from nominal current
011110
•
•
•
000001 = Minimum positive change from nominal current
000000 = Nominal current output specified by IRNG<1:0>

bit 1-0 **IRNG<1:0>:** Current Range Select bits
11 = 100 times base current
10 = 10 times base current
01 = Base current level (0.55 μA nominal)
00 = 1000 times base current

Note 1: Refer to the **“CTMU”** chapter in the specific device data sheet for the list of available trigger sources.

37.3 CTMU OPERATION

The CTMU works by using a constant current source to charge a circuit. The type of circuit depends on the type of measurement being made. In the case of capacitance measurement, the current is fixed and the amount of time the current is applied to the circuit is fixed. The amount of voltage read by the ADC is then a measurement of the capacitance of the circuit. In the case of time measurement, the current, as well as the capacitance of the circuit, is fixed and charge time varies. In this case, the voltage read by the ADC is then representative of the amount of time elapsed from the time the current source starts and stops charging the circuit.

If the CTMU is being used as a time delay, both capacitance and current source are fixed, as well as the voltage supplied to the comparator circuit. The delay of a signal is determined by the amount of time taken for the voltage to charge to the comparator threshold voltage.

37.3.1 Theory of Operation

The operation of the CTMU is based on the equation for charge, as shown in Equation 37-1.

Equation 37-1:

$$I = C \cdot \frac{dV}{dt}$$

More simply, the amount of charge measured in coulombs in a circuit is defined as current in amperes (I) multiplied by the amount of time in seconds that the current flows (t). Charge is also defined as the capacitance in farads (C) multiplied by the voltage of the circuit (V), as shown in Equation 37-2.

Equation 37-2:

$$I \cdot t = C \cdot V$$

The CTMU module provides a constant, known current source. The ADC is used to measure (V) in the equation, leaving two unknowns: capacitance (C) and time (t). Equation 37-2 can be used to calculate capacitance or time, by either the relationship shown in Equation 37-3 and using the known fixed capacitance of the circuit, or by Equation 37-4 using a fixed time that the current source is applied to the circuit.

Equation 37-3:

$$t = \frac{(C \cdot V)}{I}$$

Equation 37-4:

$$C = \frac{(I \cdot t)}{V}$$

37.3.2 Current Source

At the heart of the CTMU is a precision current source, designed to provide a constant reference for measurements. The level of current is user-selectable across four ranges, or a total of two orders of magnitude, with the ability to trim the output in ±2% increments (nominal). The current range is selected by the IRNG<1:0> bits (CTMUCON<1:0>) with a value of ‘01’ representing the lowest range.

Current trim is provided by the ITRIM<5:0> bits (CTMUCON<7:2>). These six bits allow trimming of the current source in steps of approximately 2% per step. Note that half of the range adjusts the current source positively and the other half reduces the current source. A value of ‘000000’ is the neutral position (no change). A value of ‘100001’ (see **Note 1**) is the maximum negative adjustment (approximately -62%) and ‘011111’ (see **Note 2**) is the maximum positive adjustment (approximately +62%).

Note 1: The value '100001' = -31 & 0x3F → iTRIM = -31 * Delta I, approximately -62% of nominal.

2: The value '011111' = +31 & 0x3F → iTRIM = +31 * Delta I, approximately +62% of nominal.

37.3.3 Edge Selection and Control

CTMU measurements are controlled by edge events occurring on the module’s two input channels. Each channel, referred as Edge 1 and Edge 2, can be configured to receive input pulses from one of the sixteen edge input pins. The inputs are selected using the EDG1SEL<3:0> and EDG2SEL<3:0> bit pairs (CTMUCON<29:26> and CTMUCON<21:18>).

In addition to source, each channel can be configured for event polarity using the EDG1POL and EDG2POL bits (CTMUCON<30>and CTMUCON<22>). The input channels can also be filtered for an edge event sequence (Edge 1 occurring before Edge 2) by setting the EDGSEQEN bit (CTMUCON<10>).

37.3.4 Edge Status

The CTMUCON register also contains two status bits: EDG1STAT (CTMUCON<24>) and EDG2STAT (CTMUCON<25>). Their primary function is to show if an edge response has occurred on the corresponding channel. The CTMU automatically sets a particular bit when an edge response is detected on its channel. The level-sensitive or edge-sensitive nature of the input channels means that the status bits are set immediately if the channel’s configuration changes and remains in the new state.

The CTMU module uses the edge status bits to control the current source output to external analog modules (such as the ADC). Current is supplied to external modules only when one (but not both) of the status bits is set and shuts current off when both bits are either set or cleared. This allows the CTMU to measure current only during the interval between edges. After both the status bits are set, it is necessary to clear them before another measurement is taken. Both the bits should be cleared simultaneously, if possible, to avoid re-enabling the CTMU current source.

In addition to being set by the CTMU hardware, the edge status bits can also be set by software. This allows the user’s application to manually enable or disable the current source. Setting either one (but not both) of the bits enables the current source. Setting or clearing both bits at once disables the source.

37.3.5 Interrupts

The CTMU sets its interrupt flag (CTMUIF) whenever the current source is enabled and then disabled. If edge sequencing is not enabled (i.e., Edge 1 must occur before Edge 2), it is necessary to monitor the edge status bits and determine which edge occurred last and caused the interrupt.

37.4 CTMU MODULE INITIALIZATION

The following sequence is a general guideline used to initialize the CTMU module:

1. Select the current source range using the IRNG<1:0> bits (CTMUCON<1:0>).
2. Adjust the current source trim using the ITRIM<5:0> bits (CTMUCON<7:2>).
3. Configure the edge input sources for Edge 1 and Edge 2 by setting the EDG1SEL and EDG2SEL bits (CTMUCON<29:26> and CTMUCON<21:18>).
4. Configure the input polarities for the edge inputs using the EDG1POL bit (CTMUCON<30>) and EDG2POL bit (CTMUCON<22>). The default configuration is for negative edge polarity (high-to-low transitions).
5. Enable edge sequencing using the EDGSEQEN bit (CTMUCON<10>). By default, edge sequencing is disabled.
6. Select the operating mode (Measurement or Time Delay) with the TGEN bit (CTMUCON<12>). By default, the time delay mode is disabled.
7. Configure the module to automatically trigger an analog-to-digital conversion when the second edge event has occurred using the CTTRIG bit (CTMUCON<8>). The conversion trigger is disabled by default.
8. Discharge the connected circuit by setting the IDISSEN bit (CTMUCON<9>). After waiting a sufficient time for the circuit to discharge, clear the IDISSEN bit.
9. Disable the module by clearing the ON bit (CTMUCON<15>).
10. Clear the Edge Status bits, EDG2STAT<3:0> and EDG1STAT<3:0> (CTMUCON<29:26> and CTMUCON<21:18>).
11. Enable both edge inputs by setting the EDGEN bit (CTMUCON<11>).
12. Enable the module by setting the ON bit (CTMUCON<15>).

Depending on the type of measurement or pulse generation being performed, one or more additional modules may also need to be initialized and configured with the CTMU module:

- Edge Source Generation: In addition to the external edge input pins, other modules, such as ICx, OCx, and Timer1 can be used as edge sources for the CTMU. Refer to the specific device data sheet for available sources.
- Capacitance or Time Measurement: The CTMU module uses the ADC to measure the voltage across a capacitor that is connected to one of the analog input channels.
- Pulse Generation: When generating system clock independent output pulses, the CTMU module uses Comparator 2 and the associated comparator voltage reference.

For specific information on initializing these modules, refer to the applicable section in the *“PIC32 Family Reference Manual”* for the appropriate module.

37.5 CALIBRATING THE CTMU MODULE

The CTMU requires calibration for precise measurements of capacitance and time, as well as for accurate time delay. If the application requires only measurement of a relative change in capacitance or time, calibration is usually not necessary. An example of this type of application would include a capacitive touch switch, in which the touch circuit has a baseline capacitance and the added capacitance of the human body changes the overall capacitance of a circuit.

If actual capacitance or time measurement is required, two hardware calibrations must take place: the current source needs calibration to set it to a precise current, and the circuit being measured needs calibration to measure and/or nullify all other capacitance other than that to be measured.

37.5.1 Current Source Calibration

The current source on-board the CTMU module has a range of ±62% nominal for each of four current ranges. Therefore, for precise measurements, it is possible to measure and adjust this current source by placing a high precision resistor, R_{CAL}, onto a special analog channel. An example circuit is shown in Figure 37-2. The current source measurement is performed using the following steps:

1. Initialize the ADC.
2. Initialize the CTMU by configuring the module for Pulse Generation (TGEN = 1) mode.
3. Enable the current source by setting the EDG1STAT bit (CTMUCON<24>).
4. Issue settling time delay.
5. Perform analog-to-digital conversion.
6. Calculate the current source current using $I = V/R_{CAL}$, where R_{CAL} is a high precision resistance and V is measured by performing an analog-to-digital conversion.

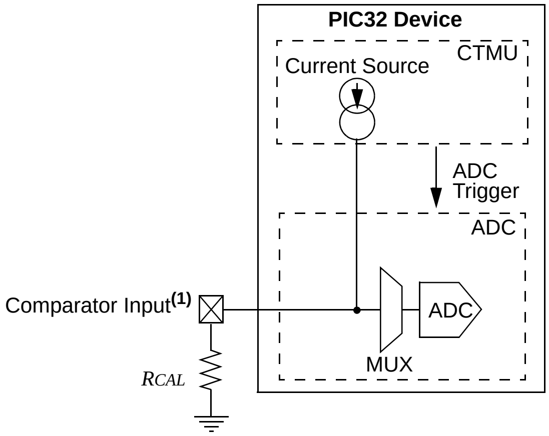
The CTMU current source may be trimmed with the trim bits in the CTMUCON register using an iterative process to get an exact desired current. Alternatively, the nominal value without adjustment may be used. It may be stored by the software for use in all subsequent capacitive or time measurements.

Figure 37-2 shows the external connections for current source calibration, as well as the relationship of the different analog modules required.

CTMU charge pump calibration should be done only on the special pin that connects to the Comparator module associated with the CTMU. Use of any other ANx pin will add around 2.5 kΩ of series resistance to the measurement from the analog multiplexer in front of the ADC. This effect can be ignored only for the smallest current settings. For larger current settings, the uncertainty in the extra series resistance overwhelms the overall resistance accuracy from the calibration resistor.

To calculate the value for R_{CAL}, the nominal current must be chosen and then the resistance can be calculated. For example, if the ADC reference voltage is 3.3V, use 70% of full scale, or 2.31V as the desired approximate voltage to be read by the ADC. If the range of the CTMU current source is selected to be 0.55 µA, the required resistor value is calculated as R_{CAL} = 2.31V/0.55 µA, for a value of 4.2 MΩ. Similarly, if the current source is chosen to be 5.5 µA, R_{CAL} would be 420,000Ω and 42,000Ω if the current source is set to 55 µA.

Figure 37-2: CTMU Current Source Calibration Circuit



Note 1: Refer to the **"Comparator"** and **"CTMU"** chapters in the specific device data sheet to determine which comparator and comparator input pin is used by the CTMU module.

Choose a value of 70% full-scale voltage to ensure that the ADC is in a range that is above the noise floor. If exact current is chosen to incorporate the trimming bits from the CTMUCON register, the resistor value of *RCAL* must be adjusted accordingly. *RCAL* may be adjusted to allow for available resistor values. *RCAL* should be of the highest precision available, the amount of precision required for the circuit that the CTMU will be used to measure. A recommended minimum precision would be 0.1% tolerance.

Example 37-1 shows a typical method for performing a CTMU current calibration. This method manually triggers the ADC and it is performed to demonstrate the process. It is also possible to automatically trigger the conversion by setting the CTTRIG bit (CTMUCON<8>).

> **Note:** A complete MPLAB project based on this calibration routine is available on the Microchip website at: http://www.microchip.com/CodeExamplesByFunc.aspx. From the landing page, scroll down and select **Touch Sense (mTouch)** as the application.

Example 37-1: Current Calibration Routine

```
// Device setup - TO DO: Set up device with #pragma's

int main(void)
{
    unsigned long int  ADC_Sum;              // For averaging multiple ADC measurements
    unsigned short int iAvg,                 // Averaging index
                       Naverages = 1024,     // Number of averages < 2^22 (22=32-10 bits of ADC)
                       Log2Naverages = 10;   // Right shift equal to 1/Naverages
    short int          iTrim;                // Current trim index
    unsigned short int VmeasADC, VavgADC;    // Measured Voltages, 65536 = Full Scale

    // TO DO: Disable JTAG and enable multivector interrupt table
    // Set up UART2 for transmission of button data
    // TO DO: Set up pins

    // CTMU Setup
    CTMUCONbits.TGEN = 1;                    // Enable direct output to C2INB/AN2 pin
    CTMUCONbits.IRNG = 0x3;                  // Current Range

    // Turn on CTMU after setting current trim below

// ADC Setup
    AD1CON2 = 0x0; // VR+ = AVDD, V- = AVSS, Don't scan, MUX A only

    // ADC clock derived from peripheral buss clock
    // Tadc = 4 * Tpbus = 4 * 25 ns = 100 ns > 65 ns required
    // Tadc = 2*(1+1)*Tpbus
    // Tadc = 2*(AD1CON3<7:0>+1)*Tpbus
    AD1CON3 =        1;
    AD1CSSL = 0x0;                           // No channels scanned
    AD1CHSbits.CH0SA = 2;                    // Select channel AN2 (PG1D/AN2/C2INB)
    ANSELA = 0x0000;                         // No ADC pins
    ANSELB = 1<<0;                           // RB0: for AN2/C2INB, which is connected to Rcal
    ANSELC = 0x0000;                         // No ADC pins
    IEC0bits.AD1IE = 0;                      // Disable ADC interrupts
    AD1CON1bits.ON = 1;                      // Turn on ADC

// Sweep over all possible current trim values
    for ( iTrim = -31; iTrim < 32; iTrim++ )
    {
        CTMUCONbits.ITRIM = iTrim & 0x3F; // Set current trim value
        CTMUCONbits.ON = 1;               // Turn on CTMU
        // TO DO: Add delay of 1 ms

        ADC_Sum = 0;
        for ( iAvg = 0; iAvg < Naverages; iAvg++ )
        {
            CTMUCONCLR = 0x03000000;     // Clear Status bits at same time
            AD1CON1bits.SAMP = 1;        // Manual sampling start
            CTMUCONbits.IDISSEN = 1;     // Ground charge pump

            // TO DO: Add delay of 500 us;
           CTMUCONbits.IDISSEN = 0;                 // End drain of circuit
            LATASET = 1<<8;              // Turn on RA8

            CTMUCONbits.EDG1STAT = 1;    // Begin charging the circuit
            LATASET = 1<<7;              // Turn on RA7

           // TO DO: Wait 25 us
           AD1CON1bits.SAMP = 0;         // Begin analog-to-digital conversion
           CTMUCONbits.EDG2STAT = 1;     // Stop charging circuit
           while (!AD1CON1bits.DONE)     // Wait for ADC conversion
           {
               // Do Nothing
            }
            AD1CON1bits.DONE = 0;     // ADC conversion done, clear flag
            VmeasADC = ADC1BUF0;      // Get the value from the ADC
            ADC_Sum += VmeasADC;      // Update averaging sum

        }//end for ( iAvg = 0; iAvg < Naverages; iAvg++ )
        CTMUCONbits.ON = 0;           // Turn off CTMU

        VavgADC = ADC_Sum >> (Log2Naverages-6); // Full scale = 2^10<<6 = 65536

        // TO DO: Transmit iTrim and VavgADC using UART

    }// end for ( iTrim = -31; iTrim < 32; iTrim++ )

}// end main()
```

37.5.2 Capacitance Calibration

A small amount of capacitance from the internal ADC sample capacitor as well as stray capacitance from the circuit board traces and pads that affect the precision of capacitance measurements. The measurement of the stray capacitance can be taken by making sure the desired capacitance to be measured has been removed. The measurement is then performed using the following steps:

1. Initialize the ADC and the CTMU.
2. Set the EDG1STAT bit (= 1).
3. Wait for a fixed delay of time, t.
4. Clear the EDG1STAT bit.
5. Perform an analog-to-digital conversion.
6. Calculate the stray and analog-to-digital sample capacitances using Equation 37-5.

Equation 37-5:

$$C_{OFFSET} = C_{STRAY} + C_{AD} = \frac{(I \cdot t)}{V}$$

Where:

I is known from the current source measurement step
t is a fixed delay
V is measured by performing an analog-to-digital conversion.

This measured value is then stored and used for calculations of time measurement or subtracted for capacitance measurement. For calibration, it is expected that the capacitance of $C_{STRAY} + C_{AD}$ is approximately known. C_{AD} is approximately 4 pF.

An iterative process may need to be used to adjust the time, t, that the circuit is charged to obtain a reasonable voltage reading from the ADC. The value of t may be determined by setting C_{OFFSET} to a theoretical value, and then solving for t. For example, if C_{STRAY} is theoretically calculated to be 11 pF, and V is expected to be 70% of VDD or 2.31V, t would be equal to Equation 37-6 or 63 µs.

Equation 37-6:

$$t = (4pF + 11pF) \bullet \frac{2.31V}{0.55\mu A} = 63\mu s$$

A charge delay of 63 µs represents 2520 instructions when the system is operating at 40 MHz (2520 = 40 MHz * 63 µs). If the CTMU charge pump is set to 100 x base current (55 µA), the charge time is cut by a factor of 100, or 25.2 instructions. This can easily be implemented by 25 `NOP` instructions in the code.

Example 37-2 shows a typical method for measuring capacitance after the CTMU's charge pump has been calibrated.

> **Note:** A complete MPLAB project based on this calibration routine is available on the Microchip website at: http://www.microchip.com/CodeExamplesByFunc.aspx. From the landing page, scroll down and select **Touch Sense (mTouch)** as the application.

Example 37-2: Capacitance Calibration Routine

```
// Device setup - TO DO: Set up device with #pragma's

int main(void)
{
    unsigned long int  ADC_Sum;              // For averaging multiple ADC measurements
    unsigned short int iAvg,                 // Averaging index
                       Naverages = 1024,     // Number of averages < 2^22 (22=32-10 bits of ADC)
                       Log2Naverages = 10;   // Right shift equal to 1/Naverages
    short int          iTrim;                // Current trim index
    unsigned short int VmeasADC, VavgADC;    // Measured Voltages, 65536 = Full Scale

    // TO DO: Disable JTAG and enable multivector interrupt table
    // Set up UART2 for transmission of button data.
    // TO DO: Set up pins

    // CTMU Setup
    CTMUCONbits.TGEN = 1;                    // Enable direct output to C2INB/AN2 pin
    CTMUCONbits.IRNG = PLIB_CTMU_CurrentRange_100xBase;     //Current Range: 100 x 0.55 = 55 uA

    // ADC Setup
    AD1CON2 = 0x0;                           // VR+ = AVDD, V- = AVSS, Don't scan, MUX A only

    // ADC clock derived from peripheral buss clock
    // Tadc = 4 * Tpbus = 4 * 25 ns = 100 ns > 65 ns required
    // Tadc = 2*(1 +1)*Tpbus
    // Tadc = 2*(AD1CON3<7:0>+1)*Tpbus
    AD1CON3 =        1;

    AD1CSSL = 0x0;                           // No channels scanned
    AD1CHSbits.CH0SA = 2;                    // Select channel AN2
    ANSELA = 0x0000;                         // No ADC pins
    ANSELB = 1<<0;                           // RB0: for AN2/C2INB, which is connected to Rcal
    ANSELC = 0x0000;                         // No ADC pins
    IEC0bits.AD1IE = 0;                      // Disable ADC interrupts
    AD1CON1bits.ON = 1;                      // Turn on ADC

// Sweep over all possible current trim values
    for ( iTrim = -31; iTrim < 32; iTrim++ )
    {
        CTMUCONbits.ITRIM = iTrim & 0x3F;            // Set current trim value
        CTMUCONbits.ON = 1;                          // Turn on CTMU
        // TO DO: Wait 1 ms for CTMU start-up

        ADC_Sum = 0;
        for ( iAvg = 0; iAvg < Naverages; iAvg++ )
        {
           AD1CON1bits.SAMP = 1;                     // Manual sampling start
           CTMUCONbits.IDISSEN = 1;                  // Ground charge pump
           // TO DO: Wait 1 ms for grounding
           CTMUCONbits.IDISSEN = 0;                  // End drain of circuit
           CTMUCONbits.EDG1STAT = 1;                 // Begin charging the circuit
           // Use Equation 37-6 to solve for charge time with current = 55 uA
           // Charge time =  0.63 us, or 25.2 NOPs at 40 MHz system clock
           // TO DO: Wait 25 NOPs
            AD1CON1bits.SAMP = 0;                    // Begin analog-to-digital conversion
            CTMUCONbits.EDG1STAT = 0;                // Stop charging circuit
            while (!AD1CON1bits.DONE)                // Wait for ADC conversion
           {
                // Do Nothing
            }
            AD1CON1bits.DONE = 0;                    // ADC conversion done, clear flag
            VmeasADC = ADC1BUF0;                     // Get the value from the ADC
            ADC_Sum += VmeasADC;                     // Update averaging sum

        }// end for ( iAvg = 0; iAvg < Naverages; iAvg++ )
```

Example 37-2: Capacitance Calibration Routine (Continued)

```
        CTMUCONbits.ON = 0;                         // Turn off CTMU

        VavgADC = ADC_Sum >> (Log2Naverages-6);     //Full scale = 2^10<<6 = 65536

        // TO DO: Transmit iTrim and VavgADC using UART

        if ( VavgADC > 50000 )                      // Stop, ADC voltage too high
        {
            break;
        }

    }// end for ( iTrim = -31; iTrim < 32; iTrim++ )

    return 0;

}// end main()
```

37.6 MEASURING CAPACITANCE WITH THE CTMU

There are two separate methods of measuring capacitance with the CTMU. The first is the absolute method, in which the actual capacitance value is required. The second is the relative method, in which the actual capacitance is not required, rather an indication of a change in capacitance is required.

37.6.1 Absolute Capacitance Measurement

> **Note:** The ADC must be configured correctly for proper CTMU functionality. If necessary, ensure that the ADC is pointing to an unused pin.

For absolute capacitance measurements, both the current and capacitance calibration steps found in **37.5 “Calibrating the CTMU Module”** should be followed. Capacitance measurements are performed using the following steps:

1. Initialize the ADC.
2. Initialize the CTMU.
3. Set the EDG1STAT bit.
4. Wait for a fixed delay, *T*.
5. Clear the EDG1STAT bit.
6. Perform an analog-to-digital conversion.
7. Calculate the total capacitance, $C_{TOTAL} = (I * T)/V$, where *I* is known from the current source measurement step (**37.5.1 “Current Source Calibration”**), *T* is a fixed delay and *V* is measured by performing an analog-to-digital conversion.
8. Subtract the stray and analog-to-digital capacitance (C_{OFFSET} from **37.5.2 “Capacitance Calibration”**) from C_{TOTAL} to determine the measured capacitance.

37.6.2 Relative Charge Measurement

> **Note:** The ADC must be configured correctly for proper CTMU functionality. If necessary, ensure that the ADC is pointing to an unused pin.

An application may not require precise capacitance measurements. For example, when detecting a valid press of a capacitance-based switch, detecting a relative change of capacitance is of interest. In this type of application, when the switch is open (or not touched), the total capacitance is the capacitance of the combination of the board traces, the ADC, etc. A larger voltage will be measured by the ADC. When the switch is closed (or is touched), the total capacitance is larger due to the addition of the capacitance of the human body to the above listed capacitances and a smaller voltage will be measured by the ADC.

Detecting capacitance changes can be accomplished with the CTMU using these steps:

1. Initialize the ADC and the CTMU.
2. Set the EDG1STAT bit.
3. Wait for a fixed delay.
4. Clear the EDG1STAT bit.
5. Perform an analog-to-digital conversion.

The voltage measured by performing the analog-to-digital conversion is an indication of the relative capacitance. In this case, no calibration of the current source or circuit capacitance measurement is needed.

A sample software routine for a capacitive touch switch is shown in Example 37-3. In this example, the prior calibration of the 8-Key Direct Sensor Daughter Board can be used to equalize the measured voltages by adjusting charge time for variations in each button circuit's capacitance. Alternatively, a fixed charge time can be used if the software supports separate trigger levels for each button. For simplicity, the routine only checks the second button (9) on the 8-Key Direct Sensor Daughter Board.

> **Note:** A more advanced version that measures all eight buttons is available on the Microchip website at: http://www.microchip.com/CodeExamplesByFunc.aspx. From the landing page, scroll down and select **Touch Sense (mTouch)** as the application.

Example 37-3: Routine for Capacitive Touch Switch

```
// Taken from HardwareProfile.h
#define NUM_DIRECT_KEYS  8

static unsigned short int ButtonADCChannels[NUM_DIRECT_KEYS] = {0,1,4,5,6,7,8,9};

// Device setup
//TO DO: Setup up device with #pragma's

int main(void)
{
    unsigned long int  ADC_Sum;              // For averaging multiple ADC measurements
    unsigned short int iAvg,                 // Averaging index
                       Naverages = 32,       // Number of averages < 2^22
                       Log2Naverages = 5;    // Right shift equal to 1/Naverages
    short int          iButton,              // Button Index
                       iChan,                // ADC channel index
                       CurrentButtonStatus;  // Bit field of buttons that are pressed
    unsigned short int VmeasADC, VavgADC;    // Measured Voltages, 65536 = Full Scale
    unsigned short int ButtonVmeasADC[NUM_DIRECT_KEYS]; // Report out all voltages at once

    // TO DO: Disable JTAG and enable multivector interrupt table

    // Set up UART2 for transmission of button data.
    // TO DO: Set up pins

    // CTMU Setup
    CTMUCONbits.IRNG = 0x3;                  // Current Range
    CTMUCONbits.ON = 1;                      // Turn on CTMU

    // TO DO: Wait 1 ms for CTMU to warm-up

    // ADC Setup
    AD1CON2 = 0x0;                           // VR+ = AVDD, V- = AVSS, Don't scan, MUX A only

    // ADC clock derived from peripheral buss clock
    // Tadc = 4 * Tpbus = 4 * 25 ns = 100 ns > 65 ns required
    // Tadc = 2*(1+1)*Tpbus
    // Tadc = 2*(AD1CON3<7:0>+1)*Tpbus
    AD1CON3 =        1;

    AD1CSSL = 0x0;                           // No channels scanned

    // Taken from mTouchCapADC.c
    ANSELA = (1<<0) | (1<<1); //RA0,1
    ANSELB = (1<<2) | (1<<3) | (1<<13) | (1<<14) | (1<<15); //RB2,3,13,14,15
    ANSELC = (1<<0) | (1<<1) | (1<<2) | (1<<3); //RC0,1,2,3

    IEC0bits.AD1IE = 0;                      // Disable ADC interrupts

    AD1CON1bits.ON = 1;                      // Turn on ADC

while ( 1 )
    {
        CurrentButtonStatus = 0;
        for ( iButton = 0; iButton < NUM_DIRECT_KEYS; iButton++ )
        {
            iChan = ButtonADCChannels[iButton];
            AD1CHSbits.CH0SA = iChan;

            ADC_Sum = 0;
            iButton = 2;
            AD1CON1bits.SAMP = 1;                    // Manual sampling start
            CTMUCONbits.IDISSEN = 1;                 // Ground charge pump
            DelayMs(1);                              // Wait 1 ms for grounding
            CTMUCONbits.IDISSEN = 0;                 // End drain of circuit
```

Example 37-3: Routine for Capacitive Touch Switch (Continued)

```
            switch (iButton)
            CTMUCONbits.EDG1STAT = 1;                // Begin charging the circuit
            // TO DO: Wait 33 NOPs for Button 2 charge
            AD1CON1bits.SAMP = 0;                    // Begin analog-to-digital conversion
            CTMUCONbits.EDG1STAT = 0;                // Stop charging circuit

            while (!AD1CON1bits.DONE)                // Wait for ADC conversion
            {
                // Do Nothing
            }
            AD1CON1bits.DONE = 0;                    // ADC conversion done, clear flag
            VmeasADC = ADC1BUF0;                     // Get the value from the ADC
            ADC_Sum += VmeasADC;                     // Update averaging sum

    }// end for ( iAvg = 0; iAvg < Naverages; iAvg++ )

        if ( Log2Naverages-6 > 0 )
        {
            VavgADC = ADC_Sum >> (Log2Naverages-6);  // Full scale = 2^10<<6 = 65536
        }
        else
        {
            VavgADC = ADC_Sum << (6-Log2Naverages);  // Full scale = 2^10<<6 = 65536
        }

        if ( VavgADC < 32768 )                       // Button is being pressed
        {
            CurrentButtonStatus += 1<<iButton;
        }
        ButtonVmeasADC[iButton] = VavgADC;

    }//end while ( 1 )

}//end main()
```

37.7 MEASURING TIME WITH THE CTMU MODULE

Time can be precisely measured after the ratio (C/I) is measured from the current and capacitance calibration step by following these steps:

1. Initialize the ADC and the CTMU.
2. Set the EDG1STAT bit.
3. Set the EDG2STAT bit.
4. Perform an analog-to-digital conversion.
5. Calculate the time between edges as $T = (C/I) * V$, where I is calculated in the current calibration step (**37.5.1 "Current Source Calibration"**), C is calculated in the capacitance calibration step (**37.5.2 "Capacitance Calibration"**) and V is measured by performing the analog-to-digital conversion.

It is assumed that the time measured is small enough that the capacitance, C_{OFFSET}, provides a valid voltage to the ADC. For the smallest time measurement, always set the ADC Channel Select register (AD1CHS) to the ADC input channel named Open. This minimizes any stray capacitance, keeping the total circuit capacitance close to that of the ADC itself (4-5 pF). To measure longer time intervals, an external capacitor may be connected to an ADC channel and this channel is selected when making a time measurement.

37.8 CREATING A DELAY WITH THE CTMU MODULE

A unique feature on board the CTMU module is its ability to generate system clock independent output pulses based on an external capacitor value. This is accomplished using the internal comparator voltage reference module, Comparator 2 input pin and an external capacitor. The pulse is output onto the CTPLS pin. To enable this mode, set the TGEN bit.

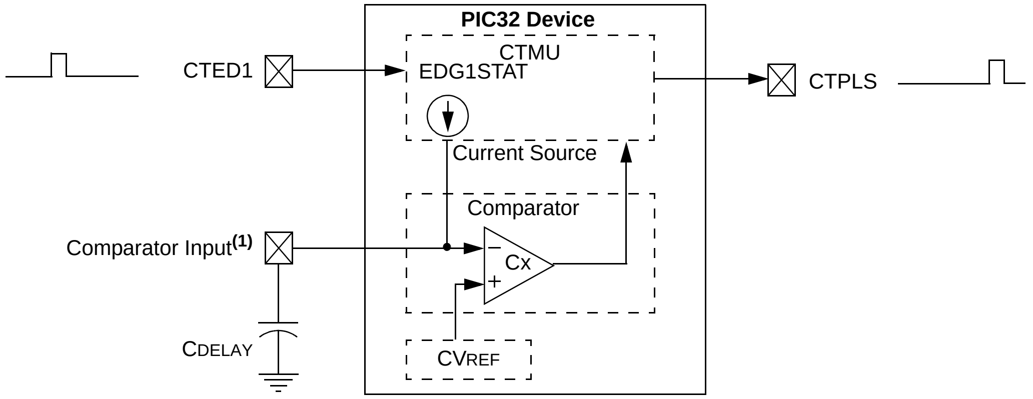
An example circuit is shown in Figure 37-3. C_{DELAY} is chosen by the user to determine the output pulse width on CTPLS. The pulse width is calculated by $T = (C_{DELAY}/I) * V$, where I is known from the current source measurement step (**37.5.1 "Current Source Calibration"**) and V is the internal reference voltage (CVREF).

An example use of this feature is for interfacing with variable capacitive-based sensors, such as a humidity sensor. As the humidity varies, the pulse-width output on CTPLS will vary. The CTPLS output pin can be connected to an input capture pin and the varying pulse width is measured to determine the humidity in the application.

Follow these steps to use this feature:

1. Initialize Comparator 2.
2. Initialize the comparator voltage reference.
3. Initialize the CTMU and enable time delay generation by setting the TGEN bit.
4. Set the EDG1STAT bit.
5. When C_{DELAY} charges to the value of the voltage reference trip point, an output pulse is generated on CTPLS.

Figure 37-3: Typical Connections and Internal Configuration for Pulse Delay Generation



Note 1: Please refer to the specific device data sheet for information related to the comparator input used in this mode.

37.9 MEASURING ON-CHIP TEMPERATURE WITH THE CTMU

The CTMU module can be used to measure the internal temperature of the device through an internal diode that is available. When EDG1STAT is not equal to EDG2STAT and TGEN = 0, the current is steered into the temperature sensing diode. The voltage across the diode is available as an input to the ADC module.

Figure 37-4 shows how this module can be used for temperature measurement. As the temperature rises, the voltage across the diode will drop by about 300 mV over a 150ºC range. Selecting a higher current drive strength will raise the voltage value by a few 100 mV.

37.9.1 Basic Principle

The forward voltage (*Vf*) of a P-N junction, such as a diode, is an extension of the equation for the junction’s thermal voltage, as shown in Equation 37-7:

Equation 37-7:

$$Vf = (kT/q) \ln (1 - If / Is)$$

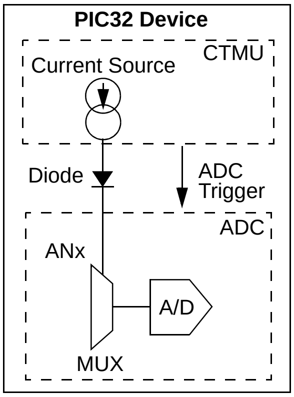
Where:

k is the Boltzmann constant (1.38 x 10-23 J K-1)
T is the absolute junction temperature in kelvin
q is the electron charge (1.6 x 10-19 C)
If is the forward current applied to the diode
Is is the diode’s characteristic saturation current

Since *k* and *q* are physical constants, and *Is* is a constant for the device, this only leaves *T* and *If* as independent variables. If *If* is held constant, it follows from the equation that *Vf* will vary as a function of *T*. As the natural log term of the equation will always be negative, the temperature will be negatively proportional to *Vf*.

In other words, as temperature increases, *Vf* decreases.

Figure 37-4: CTMU Temperature Measurement Circuit



37.10 OPERATION DURING SLEEP/IDLE MODES

37.10.1 Sleep Mode

When the device enters any Sleep mode, the CTMU module's current source is always disabled. If the CTMU is performing an operation that depends on the current source when Sleep mode is invoked, the operation may not terminate correctly. Capacitance and time measurements may return erroneous values.

37.10.2 Idle Mode

The behavior of the CTMU in Idle mode is determined by the CTMUSIDL bit (CTMUCON<13>). If the CTMUSIDL bit is cleared, the module will continue to operate in Idle mode. If the CTMUSIDL bit is set, the module's current source is disabled when the device enters Idle mode. If the module is performing an operation when Idle mode is invoked, in this case, the results will be similar to those with Sleep mode.

37.11 EFFECTS OF A RESET ON CTMU

Upon Reset, all registers of the CTMU are cleared. This leaves the CTMU module disabled, its current source is turned off and all configuration options return to their default settings. The module needs to be re-initialized following any Reset.

If the CTMU is in the process of taking a measurement at the time of Reset, the measurement will be lost. A partial charge may exist on the circuit that was being measured and should be properly discharged before the CTMU makes subsequent attempts to make a measurement. The circuit is discharged by setting, and then clearing, the IDISSEN bit (CTMUCON<9>) while the ADC is connected to the appropriate channel.

37.12 RELATED APPLICATION NOTES

This section lists application notes that are related to this section of the manual. These application notes may not be written specifically for the PIC32 device family, but the concepts are pertinent and could be used with modification and possible limitations. The current application notes related to the Charge Time Measurement Unit (CTMU) module are:

Title	**Application Note #**
No related application notes at this time.	N/A

Note:	Please visit the Microchip web site (www.microchip.com) for additional application notes and code examples for the PIC32 family of devices.

37.13 REVISION HISTORY

Revision A (March 2011)

This is the initial released revision of this document.

Revision B (February 2012)

This revision includes the following updates:

- Added Note 1 and Note 2 to **37.3.2 “Current Source”**
- Updated the last sentence of the first paragraph in **37.3.4 “Edge Status”**
- Added Note 1 to the CTMU Current Source Calibration Circuit (see Figure 37-2)
- Removed Setup for CTMU Calibration Routines (formerly Example 37-1)
- Updated the code in the Current Calibration Routine (see Example 37-1)
- Updated the code in the Capacitance Calibration Routine (see Example 37-2)
- Updated the code in the Routine for Capacitive Touch Switch Routine (see Example 37-3)
- Minor updates to text and formatting were incorporated throughout the document

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