AN879

Using the Microchip Ultra Low-Power Wake-Up Module

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INTRODUCTION

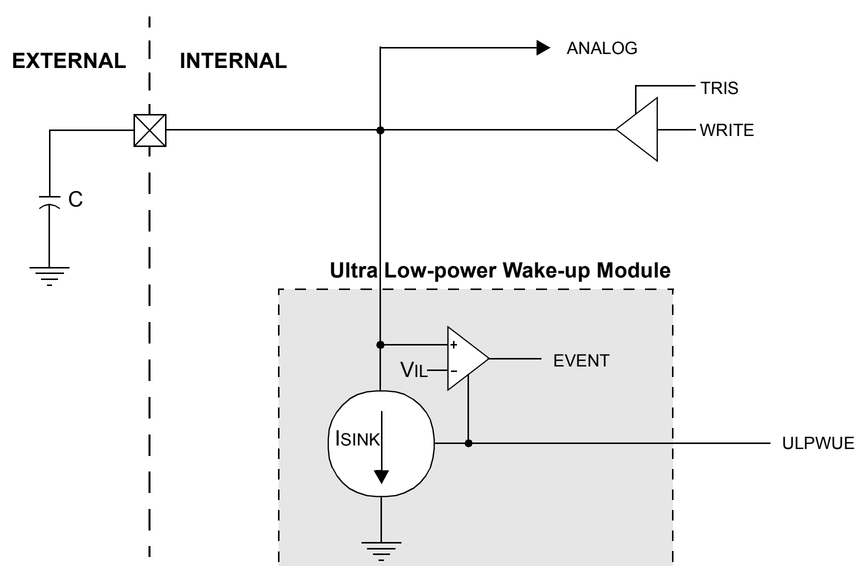
This application note describes ways to reduce system current consumption with the use of the Ultra Low-power Wake-up (ULPWU) module. The PIC16F684 and PIC16F88X are examples of devices with this feature.

The primary use of this module is as an ULPWU timer, but its functionality can be expanded to function as a temperature sensor and/or a low-voltage detector. The main and expanded functions of this module are explained in this document.

Many low-power applications require that the microprocessor wake-up from a Sleep state on a periodic basis to check the status of some signal. It can then react based on a measurement of that signal and go back to Sleep until the next timed wake-up. This is a widely used method for reducing overall system current consumption. These types of applications require a low-power periodic wake-up and can be accomplished by activating a low-power timer prior to placing the device in a Sleep mode. Upon rollover, the timer interrupt can then wake-up the part after some predefined period. A 32 kHz crystal timer used on one of the secondary clock sources is very popular if accuracy is required. Some parts also have dedicated internal low-power, low-frequency oscillators that can be used.

One solution for a lower current periodic wake-up timer is a simple RC timer that can be charged prior to Sleep and left to slowly discharge. A change in state event can be used to wake the part when the RC voltage reaches the digital input threshold voltage. This sounds ideal, but the problem is that a normal digital-input structure consumes high-crowbar currents when a slowly changing voltage is applied to it. The digital-input structure will consume a few hundred micro amps when driven by an analog voltage that is not close to the rail voltages (V_{SS} and V_{DD}). To combat these high-crowbar currents, Microchip has introduced an ULPWU module, which provides an analog input that can be used to implement a RC timer. The basic module block diagram is shown in Figure 1.

FIGURE 1: ULTRA LOW-POWER WAKE-UP PIN DIAGRAM(1)



Note 1: RA0 cannot be read as a digital pin when ULPWU is enabled.

The module operates as a low-power analog comparator that compares the voltage on the external capacitor C to a reference V_{IL}. The module generates an event output when the analog comparator changes state. The change in state event can generate an interrupt-on-change. The module provides a very weak current source to discharge the external capacitor in a controlled manner. The code in Example 1 for PIC16F684 initializes the module, charges the capacitor, enables the module, and then goes to Sleep, waiting for an interrupt-on-change.

EXAMPLE 1: ULPWU CODE FOR THE PIC16F684

```
BANKSEL PORTA           ;Bank 0
BSF     PORTA, 0        ;Set RA0 data latch
MOVLW   H'7'            ;Turn off
MOVWF   CMCON0          ;comparators
BANKSEL ANSEL           ;Bank 1
BCF     ANSEL, 0        ;RA0 to digital I/O
BCF     TRISA, 0        ;Output high to
CALL    CapDelay        ;charge capacitor
BSF     PCON, ULPWUE    ;Enable ULP Wake-Up
BSF     IOCA, 0         ;Select RA0 IOC
BSF     TRISA, 0        ;RA0 to input
MOVLW   B'10001000'     ;Enable interrupt
MOVWF   INTCON          ;and clear flag
SLEEP                   ;Wait for IOC
NOP                     ;
```

The code in Example 2 for PIC16F88X devices charges the external capacitor, sets up the module and goes to Sleep, waiting for the ULPWU interrupt. The interrupt is level triggered and, if global interrupts are enabled, the Interrupt Service Routine (ISR) must disable either the ULPWU interrupt enable or the ULPWU module to clear the ULPWU interrupt flag and charge the external cap.

EXAMPLE 2: ULPWU CODE FOR THE PIC16F88X

```
BANKSEL PORTA           ;
BSF     PORTA, 0        ;Set RA0 data latch
BANKSEL ANSEL           ;
BCF     ANSEL, 0        ;RA0 to digital I/O
BANKSEL TRISA           ;
BCF     TRISA, 0        ;Output high to
CALL    CapDelay        ;charge capacitor
BANKSEL PIR2            ;
BCF     PIR2, ULPWUIF   ;Clear flag
BANKSEL PCON            ;
BSF     PCON, ULPWUE    ;Enable ULP Wake-up
BSF     TRISA,  0       ;RAO to input
BSF     PIE2, ULPWUIE   ;Enable interrupt
MOVLW   B'11000000'     ;Enable peripheral
                        ;interrupt
MOVWF    INTCON         ;
SLEEP                   ;Wait for interrupt
NOP                     ;
```

The trip voltage V_{IL} and the sink current I_{SINK} are basically independent of V_{DD}, but are sensitive to temperature and process variations. Data for the module is given in Table 1.

From the data in Table 1, it becomes clear that the variation in module parameters would limit the overall accuracy of the timer, when used as in Figure 1. The wake-up period can vary by as much as 30% between modules. For a large number of applications, it is acceptable to have a large variation in the wake-up period and thus, the module's accuracy is acceptable.

TABLE 1: MODULE DATA*

		V_{IL} (V_{DC})	I_{SINK} (nA)
-40°C	Min	0.58	104
	Typ	0.69	113
	Max	0.81	131
25°C	Min	0.48	121
	Typ	0.58	135
	Max	0.69	158
85°C	Min	0.38	130
	Typ	0.48	145
	Max	0.58	169
125°C	Min	0.30	142
	Typ	0.40	157
	Max	0.49	183

* Example data not characterized or tested

The module, when enabled, will add between 75 nA and 160 nA to the microprocessor's Sleep current, depending on process variations, temperature and voltage. The total expected Sleep current with the ULPWU module enabled should be only a few hundred nA for the PIC16F684 and PIC16F88X devices, since the Sleep current is typically 1 nA with all peripherals disabled.

The average system current consumption will be higher due to the energy required to charge the capacitor and the energy consumed to execute code between Sleep periods. The time between Sleep periods and active duty cycle of use will largely dictate the overall current consumption. A typical smoke detector or Tire Pressure Monitoring (TPM) system with sub 1 μA current consumption can be achieved.

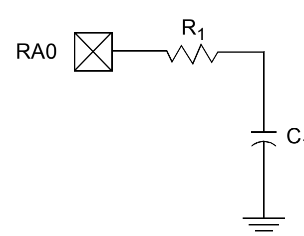
MODULE APPLICATIONS

The ULPWU module's accuracy and functionality can be improved by using it as a programmable timer or using some additional external components. This includes a programmable low-voltage detect and/or a temperature sensor. The following sections will briefly explain these functions.

Basic Timer

Although the operation of the basic wake-up timer has been discussed, there are more aspects to consider. Figure 2 shows the addition of a series resistor when compared to Figure 1. The resistor R_1 is added if C_1 is larger than 50 pF. This is done to reduce the peak current drawn from RA0 while charging C_1. For larger capacitors, Equation 1 gives the peak charge current drawn from RA0. The maximum allowable current drawn from pin 1 is 25 mA. A resistor of 200 ohm is sufficient for 5-volt supply voltages and large capacitors.

FIGURE 2: SERIAL RESISTOR



EQUATION 1:

$$I_{PEAK} = \frac{V_{DD}}{R_1} \quad \text{for } C_1 >> 50 \text{ pF}$$

I_{PEAK} = peak charge current

Equation 2 gives the discharge period. V_O is the initial capacitor voltage and will be the same as V_{DD}, if the capacitor is allowed to fully charge prior to starting the discharge process.

EQUATION 2:

$$T_{DISCHARGE} = \frac{(V_O - V_{IL}) \cdot C}{I_{SINK} + I_{LEAKAGE}}$$

$T_{DISCHARGE}$ = discharge period

V_O = initial capacitor voltage

V_{IL} = trip voltage

I_{SINK} = sink current

$I_{LEAKAGE}$ = capacitors internal leakage current

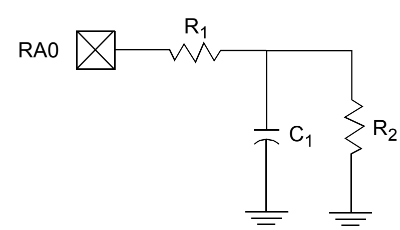
The discharge period is about 30 ms for a 1 nF capacitor, a V_O of 5 V_{DC} with a current sink of 140 nA, and V_{IL} of 0.6 V_{DC}. The internal current sink is fairly constant with voltage, assuming the voltage on the capacitor is V_{IL} or more. This results in a near linear voltage discharge of the capacitor over time. Keep in mind that the weak current sink is equivalent to very high-impedance of several tens of mega ohms. Such a high-impedance discharge system is very sensitive. Care must be given to layout, the influence of moisture, and the capacitor's self-discharge impedance.

To minimize noise and moisture effects, it is advisable to keep trace lengths short by placing the discharge capacitor close to the AN0 pin. Also, note that capacitors have some internal leakage that will shorten the discharge period. Different capacitors have different self-discharge characteristics that will become important, especially if long discharge periods are required. Some electrolytic capacitors have fairly high self-discharge rates that are temperature sensitive.

Use of External Components

For harsh noise and moisture conditions, the stability of the ULPWU module can be improved by adding an additional discharge resistor R_2, as in Figure 3. The voltage discharge on C_1, due to R_2, will follow Equation 3, if the current through R_2 is large compared to the discharge current I_{SINK}. Thus, the discharge period can be derived as in Equation 4.

FIGURE 3: DISCHARGE RESISTOR



EQUATION 3:

$$V(T) = V_O \cdot e^{\left(\frac{-T}{C_1 R_2}\right)}$$

V(T) = voltage across capacitor

V_O = initial capacitor voltage

T = time

EQUATION 4:

$$T_{DISCHARGE} = C_1 R_2 \ln\left(\frac{V_O}{V_{IL}}\right)$$

$T_{DISCHARGE}$ = charge period
V_O = initial capacitor voltage
V_{IL} = trip voltage

Calibrated Timer

The following section explains how the accuracy of the basic timer can be improved by controlling the charge period. The discharge period for both implementations shown in Figures 2 and 3 are dependent on V_O, C_1, V_{IL} and I_{SINK} or R_2. These parameters depend on process variations, temperature effects, usage and more. A software calibrated Sleep timer will compensate for some of these variations by controlling V_O. Timing the charge period of C_1 through R_1 allows control over the voltage on C_1 at the start of the Sleep period V_O. The discharge period $T_{DISCHARGE}$ is timed against the main clock source while the part is awake, then the charge period can be adjusted based on the $T_{DISCHARGE}$ error. This process is repeated until the desired accuracy is obtained. Repeat the calibration process after a fixed amount of normal Sleep periods, to maintain accuracy over time.

Pay close attention to the residual charge across C_1 at the start of the charge period. There may be charge left in C_1, depending on V_{IL} and whether or not the ULPWU module was disabled, and whether RA0 turned into an analog input, digital input or digital output. One approach is to fully discharge C_1 before starting the charge process. This approach increases accuracy, but will increase the overall current consumption.

The final capacitor voltage V_O, when charging C_1 through R_1, is given by Equation 5. The residual voltage across C_1 at the beginning of the charge period is represented by V_{RES} and the charge period is T_{CHARGE}.

EQUATION 5:

$$V_O = V_{RES} + (V_{DD} - V_{RES})\left[1 - e^{\frac{-T_{CHARGE}}{C_1 R_1}}\right]$$

T_{CHARGE} = charge period
V_O = final capacitor voltage
V_{RES} = residual voltage

Temperature Sensor

This section explains how to implement a temperature sensor that gives a reading relative to the standard temperature at which calibration was completed. The module parameters V_{IL} and I_{SINK} are dependent on temperature and process variations. The process dependent component must be identified in order to calculate the temperature from later measurements of V_{IL} and I_{SINK}. The process variation can be measured when the device is first turned on under controlled conditions such as at final product testing. These standard measured values can be stored in EEPROM and used for future reference.

To measure V_{IL}, sample the voltage across C_1 with the A/D converter after the output of the ULPWU module changes the status of bit ‘0’ on PORTA. The sampled voltage will be referenced to the A/D converter reference, which can be V_{DD} or an external voltage reference. V_{IL} has a negative temperature coefficient and is approximately -1.25 mV/°C. V_{IL} is calculated by using the method described in **Section “Use of External Components”**.

The sink current I_{SINK} is measured under standard conditions by using Equation 2 and has a positive temperature coefficient of approx. 140 pA/°C. The discharge time $T_{DISCHARGE}$ is a function of V_O, V_{IL} and temperature. Under standard conditions, V_O and temperature are controlled and V_{IL} is measured. From this, calculate the standard process dependent value for I_{SINK}.

Note:	The accuracy of the measurements is dependent on V_O, which can be V_{DD}, and the source for the A/D converter, which may or may not be V_{DD}. The method described in **Section “Use of External Components”** to calculate V_{IL} without an A/D is also dependent on a known value for V_O or V_{DD}.

Equations 7 and 8 are used to calculate temperature variation from the standard temperature using the measured or calculated values for ISINK and VIL.

Note 1:	The result is dependent on VDD or VO. The temperature dependency of VIL is linear with temperature, but ISINK has a significant second order term that is not shown. The second order term for ISINK can be ignored if the temperature deviation is relatively small.
2:	The data is preliminary and will be updated after full characterization is completed. The values ISTANDARD and VSTANDARD are the process dependent values for ISINK and VIL, as measured under standard conditions and stored in EEPROM.

EQUATION 6:

$$\Delta T \approx \frac{V_{IL} - V_{STANDARD}}{-1.25 \times 10^{-3}}$$

ΔT = temperature deviation
VSTANDARD = standard voltage
VIL = trip voltage

EQUATION 7:

$$\Delta T \approx \frac{I_{SINK} - I_{STANDARD}}{140 \times 10^{-12}}$$

ΔT = temperature deviation
ISINK = sink current
VSTANDARD = standard voltage

EQUATION 8:

$$V_{DD} \approx V_O = V_{IL} + \frac{T_{DISCHARGE} \cdot I_{SINK}}{C_1}$$

VO = total capacitor voltage
VIL = trip voltage
ISINK = sink current
TDISCHARGE = discharge period

Programmable Low-voltage Detect

VDD can be calculated using the ULPWU module in two basic ways; both methods are temperature dependent and based on the standard values for VIL and ISINK, as discussed in **Section "Temperature Sensor"**. The method is fairly accurate for applications where the system is subjected to small temperature variations. Refer to **Section "Temperature Sensing and Programmable Low-voltage Detect"** for applications where both VDD and temperature need to be measured across a large range.

INTERNAL CURRENT SINK DISCHARGE METHOD

This method uses the setup as in Figure 2 by measuring TDISCHARGE, while keeping the part active and measuring it against the main clock source. Before measuring TDISCHARGE, make sure that C_1 is fully charged to VDD by allowing a long enough charge period. Then, use Equation 9 to calculate VO or VDD.

EQUATION 9:

$$Vo = (Tdischarge \bullet \frac{Isink}{C1}) + Vil$$

VO = Total Capacitor Voltage
VIL = Trip Voltage
TDISCHARGE = Discharge Period
ISINK = Sink Current

The accuracy of the calculated VDD is dependent on VIL, TDISCHARGE, C_1 and ISINK. Interestingly, VIL has a negative temperature coefficient while ISINK has a positive temperature coefficient, which reduces the temperature dependency.

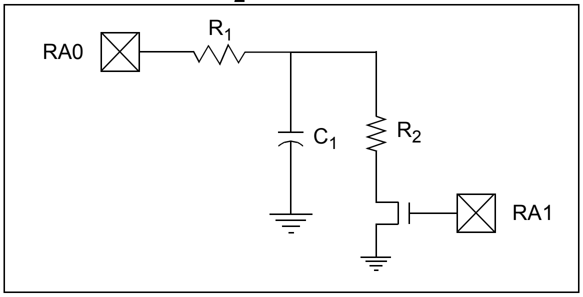
It is still possible to use this method if R_2 is required, as shown in Figure 3. VO or VDD is now calculated using Equation 10, as most of the dicharge is through R_2. Using this method, R_2 is more accurate and, for the most part, independent of temperature and process variations.

Connecting R_2 through an I/O controlled MOSFET provides a means for disconnecting R_2 from ground, as shown in Figure 4. The additional I/O enables the MOSFET when R2 is needed.

EQUATION 10:

$$V_O = V_{IL} \bullet e^{\frac{-T_{DISCHARGE}}{C_1 R_2}}$$

FIGURE 4: R_2 TO I/O



VIL CHARGE METHOD

This method uses the same setup as illustrated in Figure 3. This method is applicable if R_1 is much smaller than R_2. Again, the capacitor fully charges to VDD and the TDISCHARGE is measured while the part is still active. Equation 9 can be used to calculate VO or VDD, but note that the result is a multiple of VIL, which is temperature sensitive.

TEMPERATURE SENSING AND PROGRAMMABLE LOW-VOLTAGE DETECT

Section "Temperature Sensor" of this application note explains a simple method to measure temperature. Clearly, the accuracy of the result is dependent on knowing the VDD and the process dependent variation of the variable. Similarly, **Section "Programmable Low-voltage Detect"** explains how to calculate VDD, but the result depends on temperature and the process variation.

The accuracy of measuring the interdependent values VDD and temperature is greatly improved by knowing the standard values ISTANDARD and VSTANDARD, as explained in **Section "Temperature Sensor"**. The deviation of the measured unit from the standard value can then be used in an iterative process to calculate VDD and temperature. The following sequence can be followed (see Figure 5):

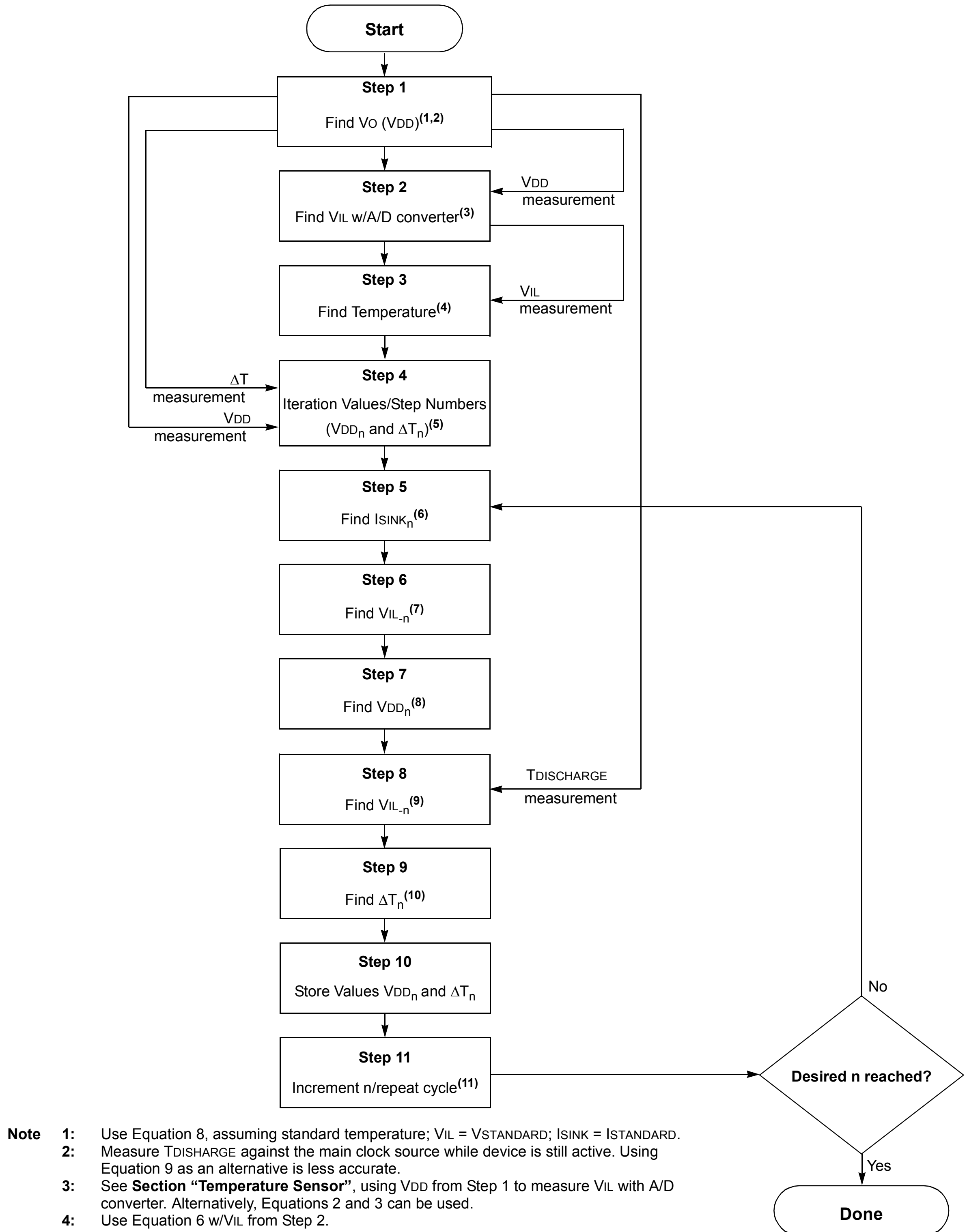
1. Calculate VO or VDD using Equation 8, assuming standard temperature, VIL = VSTANDARD and ISINK = ISTANDARD. The discharge period TDISCHARGE is measured against the main clock source, while the device is still active. Alternatively, using Equation 9 is less accurate.
2. Use the resulting VDD to measure VIL with the A/D converter, as explained in **Section "Temperature Sensor"**. Alternatively, VIL can be calculated using Equations 2 or 3.
3. Use the resulting VIL to calculate the temperature with Equation 6.
4. Save the Step 1 iteration values for VDD and temperature in VDD_n and ΔT_n, where n is the iteration step number.
5. Calculate $ISINK_n$ using Equation 7 with ΔT_n.
6. Calculate VIL_{-n} using Equation 6 with ΔT_n.
7. Calculate VDD_n with Equation 8, using the discharge period TDISCHARGE from the Step 1, or use Equation 9.
8. Use VO_{-n} to measure VIL_{-n}, with the A/D converter, or calculate VIL using Equations 2 or 3.
9. With VIL_{-n}, use Equation 6 to calculate the temperature ΔT_n.
10. Store the values for VDD_n and ΔT_n.
11. Increment n and go to Step 5, until desired n is reached.

The accuracy of the process can be evaluated by using the alternative methods for specific iterations. In addition, use the EEPROM write time as a temperature sensor for improving the accuracy of Step 1. The EEPROM write time is dependent on temperature and the variation from a standard-measured time can be used to calculate temperature.

CONCLUSION

The ULPWU module is a flexible module with unmatched current consumption that enables the designer to implement not only a wake-up timer, but also a low-cost PLVD (Programmable Low-voltage Detect) and temperature sensing functions. The module is especially attractive in lithium and other battery applications where very low Sleep currents are required.

FIGURE 5: CALCULATING VDD AND TEMPERATURE BLOCK DIAGRAM



Note 1: Use Equation 8, assuming standard temperature; $V_{IL} = V_{STANDARD}$; $I_{SINK} = I_{STANDARD}$.
2: Measure $T_{DISHARGE}$ against the main clock source while device is still active. Using Equation 9 as an alternative is less accurate.
3: See **Section "Temperature Sensor"**, using VDD from Step 1 to measure VIL with A/D converter. Alternatively, Equations 2 and 3 can be used.
4: Use Equation 6 w/VIL from Step 2.
5: Use iteration values for VDD and temperature from Step 1 as V_{DD_n} and ΔT_n, where n is the iteration step number.
6: Use Equation 7 with ΔT_n.
7: Calculate $V_{IL\text{-}n}$ using Equation 6 with ΔT_n.
8: Use Equation 8, using $T_{DISHARGE}$ from Step 1 or use Equation 9.
9: Use $V_{O\text{-}n}$ to measure $V_{IL\text{-}n}$, with the A/D converter or calculate VIL using Equations 2 or 3.
10: With $V_{IL\text{-}n}$, use Equation 6 to calculate the ΔT_n.
11: Increment n and go to Step 5, until desired n is reached.

NOTES:

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