TI Designs: TIDA-01518

Low-Power Flood and Freeze Detector Reference Design With Sub-1 GHz and 10-Year Coin Cell Battery Life

Description

This reference design uses Texas Instruments' low-power consumption digital dual temperature and humidity sensors and the SimpleLink™ ultra-low-power Sub-1 GHz wireless microcontroller (MCU) platform to demonstrate a flood and freeze detector with extremely long battery life and no wiring required.

Resources

TIDA-01518	Design Folder
HDC2010	Product Folder
TPD1E10B06	Product Folder

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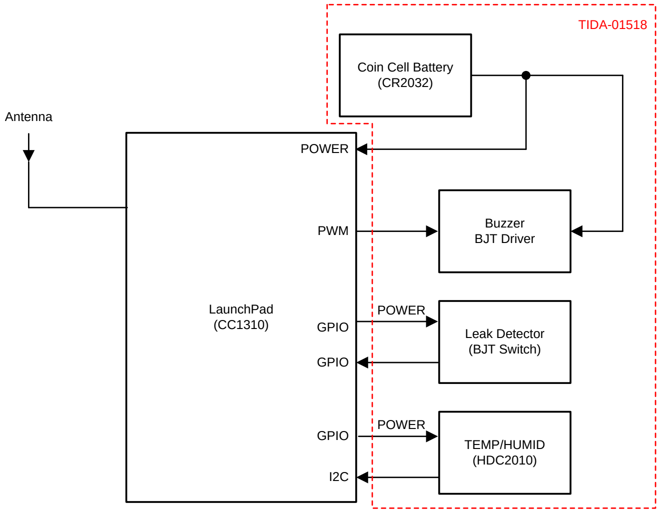
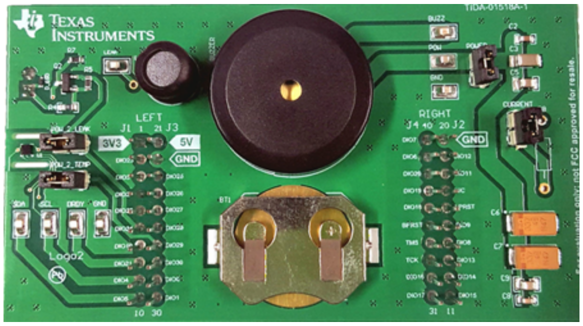
Features

- Ultra-Low-Power Design Resulting in 10-Year Battery Life From Single CR2032 Coin Cell
- Conductive Water Sensing Always Powered On To Enable Continuous Monitoring
- Designed For SimpleLink Sub-1 GHz Wireless Connectivity LaunchPad (LAUNCHXL-CC1310)
- Ability to Take High-Resolution Temperature and Humidity Data
- Simplistic Design That Leads to Lower Cost

Applications

- Leak and Flood Detection
- Freeze Detection
- Temperature and Humidity Sensing





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1 System Description

Water damage is one of the leading causes of property damage in homes today. There are many things that can cause water damage such as bursting or leaking pipes, faulty plumbing, water build-up from condensation or melting snow, or an overflowing toilet or sink. Regardless of the cause, the damage is the same and there is a need for a device that can detect the leak and allow the user to take preventative measures. This device must be wireless to fit in tight spaces where leaks might occur, be able to detect pooling water and overly humid conditions, and have the ability to alert the user either by an audible tone or text message alert. However, some of the major limitations of such a device is its battery life and cost. Because these sensors are battery powered, reliability becomes an issue because these sensors are often left for years at a time but still need to work. Also, replacing batteries can be expensive and cumbersome. There are many places in the house where a leak can occur, which would lead to the need of many sensors. Because of this, the price of individual sensors is important.

The average battery life of water leak detectors on the market today ranges between one and five years depending on power and battery configurations. By using the SimpleLink ultra-low-power wireless MCU platform and the Texas Instrument's ultra-low-power temperature and humidity sensor, this reference design can achieve a 10-year battery life off of a low-cost coin cell battery and demonstrate a wireless leak, freeze, and humidity detector.

At a high-level view, this reference design consists of a CR2032 coin cell battery, one ultra-low-power temperature and humidity sensor, a SimpleLink ultra-low-power MCU, two BJT switches, and a buzzer. One BJT switch acts as the water sensor, driving its output high when the water connects its base to ground; the other acts as the driver for the buzzer being driven by the PWM on the MCU. The temperature and humidity sensor are set in interrupt mode, checking every 10 minutes for a certain temperature and humidity threshold. The digital outputs from both the water sensor and the temperature and humidity sensor act as interrupts to wake the MCU, which then activates the buzzer and sends a message over the Sub-1 GHz radio that exists on the MCU. The use of low-cost, discrete components in combination with an MCU with a built-in radio transceiver achieves a design that minimizes the number of components and cost while maximizing the functionality.

This design guide addresses the component selection, design theory, and testing results of this reference design. The scope of this design guide gives system designers a head start in integrating TI’s ultra-low-power consumption digital temperature and humidity sensor and the SimpleLink ultra-low-power wireless MCU platform.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Input power source	CR2032 Lithium-ion coin cell battery (3-V nominal voltage)	Section 2.3.1
Sensor types	Humidity, temperature, and water	Section 2
Sensor data packet TX current consumption	2.369 mA (averaged)	Section 3.2.2.4
Leak alert packet TX current consumption	5.85 mA (averaged)	Section 3.2.2.4
Sleep-state current consumption	1.37 µA (averaged)	Section 3.2.2.4
Estimated battery life	> 10 years	Section 3.2.3
Radio transmission range	> 200 meters	Section 3.2.2.1
Operating humidity	≤ 70%	—
Operating temperature	–30°C to +60°C (limited by CR2032 coin cell operating range)	—
RF immunity	30 V/m from 10 kHz to 1 GHz	—
Working environment	Indoor and outdoor	—

2 System Overview

In this reference design, all hardware is powered directly off of the coin cell battery to save cost and increase efficiency. This is achieved through the use of low power and low-voltage circuitry. The central control for this design comes from the CC1310 LaunchPad. The CC1310 monitors flooding, humidity, or freezing conditions using the HDC2010 and the leak detector sensors. If any undesirable conditions are found, the CC1310 transmits an alarm message over the Sub-1 GHz radio and uses the PWM to drive the buzzer on the PCB.

2.1 Block Diagram

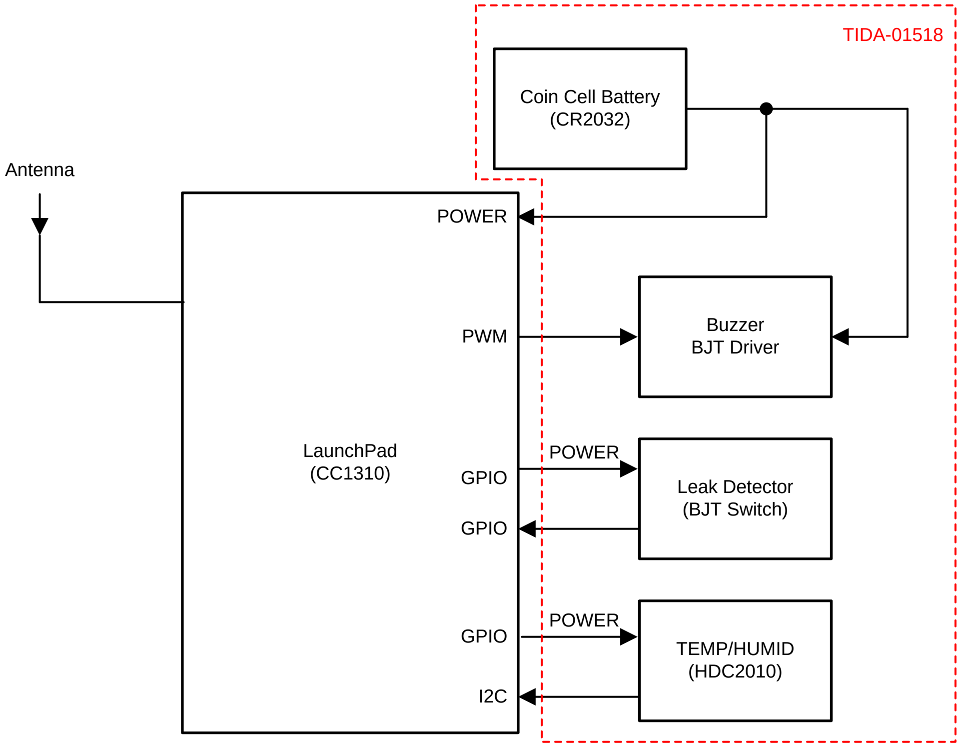

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Figure 1. TIDA-01518 Block Diagram

2.2 Highlighted Products

The following subsections highlight the products used in this reference design.

2.2.1 CC1310

The CC1310 is a member of the CC26xx and CC13xx family of cost-effective, ultra-low-power, 2.4-GHz and Sub-1 GHz RF devices. Very low active RF and microcontroller (MCU) current consumption, in addition to flexible low-power modes, provide excellent battery lifetime and allow long-range operation on small coin-cell batteries and in energy-harvesting applications.

The CC1310 device is the first device in a Sub-1 GHz family of cost-effective, ultra-low-power wireless MCUs. The CC1310 device combines a flexible, very low-power RF transceiver with a powerful 48-MHz Cortex®-M3 MCU in a platform supporting multiple physical layers and RF standards. A dedicated radio controller (Cortex-M0) handles low-level RF protocol commands that are stored in ROM or RAM, thus ensuring ultra-low power and flexibility. The low-power consumption of the CC1310 device does not come at the expense of RF performance; the CC1310 device has excellent sensitivity and robustness (selectivity and blocking) performance.

The CC1310 device is a highly integrated, true single-chip solution incorporating a complete RF system and an on-chip DC-DC converter.

Sensors can be handled in a very low-power manner by a dedicated autonomous ultra-low-power MCU that can be configured to handle analog and digital sensors; thus the main MCU (Cortex-M3) can maximize sleep time.

The CC1310 power and clock management and radio systems require specific configuration and handling by software to operate correctly, which has been implemented in the TI-RTOS. TI recommends using this software framework for all application development on the device. The complete TI-RTOS and device drivers are offered in source code free of charge.

- MCU:
  - Powerful ARM® Cortex-M3 processor
  - EEMBC CoreMark® Score: 142
  - EEMBC ULPBench™ Score: 158
  - Clock speed up to 48 MHz
  - 32KB, 64KB, and 128KB of in-system programmable flash
  - 8KB of SRAM for cache (or as general-purpose RAM)
  - 20KB of ultra-low-leakage SRAM
  - 2-pin cJTAG and JTAG debugging
  - Supports over-the-air (OTA) update
- Ultra-low-power sensor controller:
  - Can run autonomously from the rest of the system
  - 16-bit architecture
  - 2KB of ultra-low-leakage SRAM for code and data
- Efficient code-size architecture, placing parts of TI-RTOS, Drivers, and Bootloader in ROM
- Peripherals:
  - All digital peripheral pins can be routed to any GPIO
  - Four general-purpose timer modules (eight 16-bit or four 32-bit timers, PWM each)
  - 12-bit ADC, 200 ksamples/s, 8-channel analog MUX
  - Continuous time comparator
  - Ultra-low-power clocked comparator
  - Programmable current source
  - UART
  - 2× SSI (SPI, MICROWIRE, TI)
  - I^2C, I2S
  - Real-time clock (RTC)
  - AES-128 security module
  - True random number generator (TRNG)
  - Support for eight capacitive sensing buttons
  - Integrated temperature sensor
- External system:
  - On-chip internal DC-DC converter
  - Seamless integration with the SimpleLink CC1190 range extenders
- Low power:
  - Wide supply voltage range: 1.8 to 3.8 V
  - RX: 5.4 mA
  - TX at 10 dBm: 13.4 mA
  - Active-Mode MCU 48 MHz Running Coremark: 2.5 mA (51 µA/MHz)

  - Active-Mode MCU: 48.5 CoreMark/mA
  - Active-Mode sensor controller at 24 MHz: 0.4 mA + 8.2 µA/MHz
  - Sensor controller, one wakeup every second performing one 12-bit ADC sampling: 0.95 µA
  - Standby: 0.7 µA (RTC running and RAM and CPU retention)
  - Shutdown: 185 nA (wakeup on external events)
- RF core:
  - Excellent receiver sensitivity –124 dBm using long-range mode, –110 dBm at 50 kbps (Sub-1 GHz)
  - Excellent selectivity (±100 kHz): 56 dB
  - Excellent blocking performance (±10 MHz): 90 dB
  - Programmable output power up to 15 dBm
  - Single-ended or differential RF interface
  - Suitable for systems targeting compliance with worldwide radio frequency regulations:
    - ETSI EN 300 220, EN 303 204 (Europe)
    - FCC CFR47 Part 15 (US)
    - ARIB STD-T108 (Japan)
  - Wireless M-Bus and selected IEEE® 802.15.4g PHY
- RoHS-compliant package:
  - 7-mm × 7-mm RGZ VQFN48 (30 GPIOs)
  - 5-mm × 5-mm RHB VQFN32 (15 GPIOs)
  - 4-mm × 4-mm RSM VQFN32 (10 GPIOs)
- Tools and development environment:
  - Full-feature and low-cost development kits
  - Multiple reference designs for different RF configurations
  - Sensor Controller Studio
  - SmartRF™ Studio
  - SmartRF Flash Programmer 2
  - IAR Embedded Workbench® for ARM
  - Code Composer Studio™ (CCS) IDE

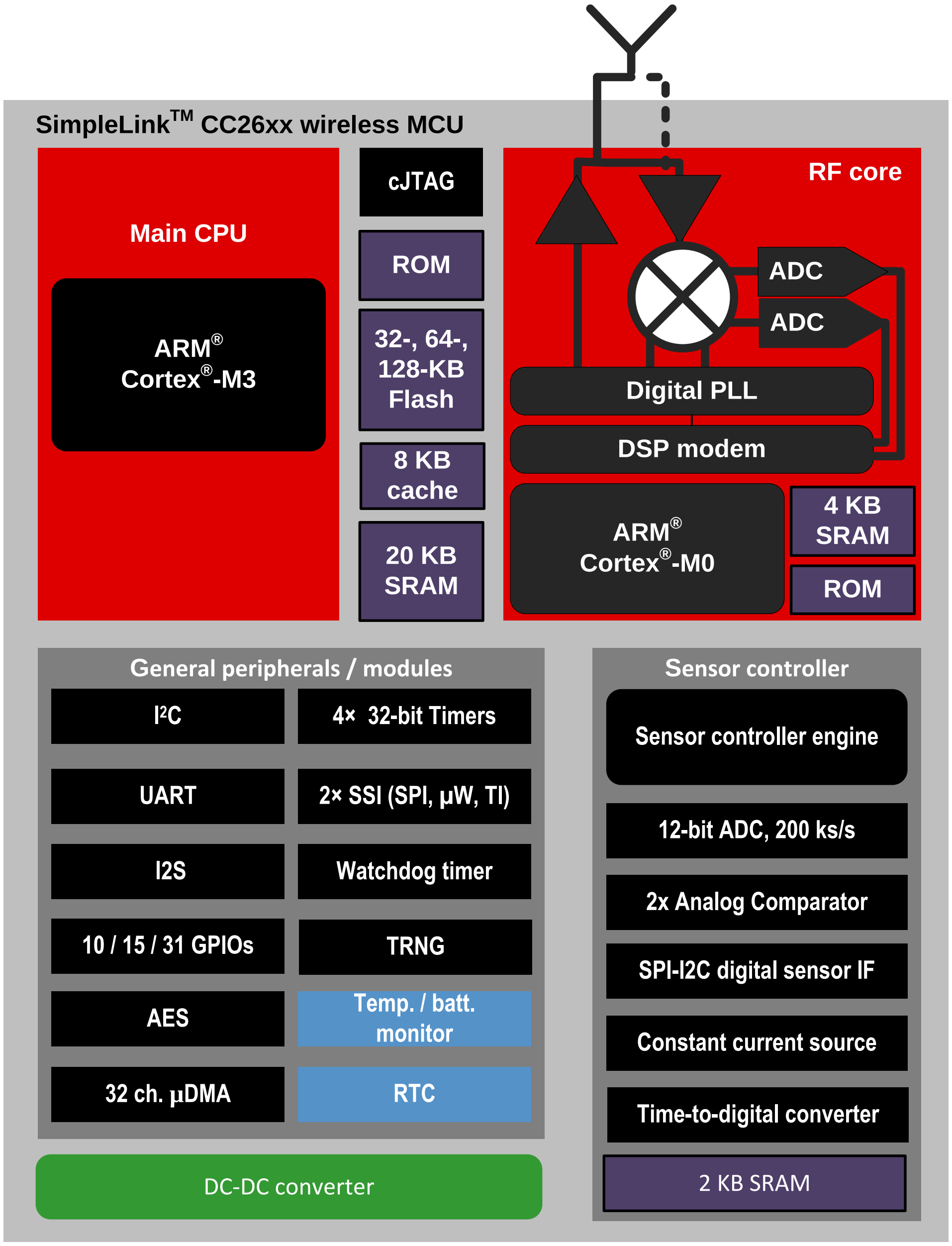


Figure 2. CC1310 Block Diagram

2.2.2 HDC2010

The HDC2010 is an integrated humidity and temperature sensor that provides high-accuracy measurements with very low power consumption, in an ultra-compact Wafer Level Chip Scale Package (WLCSP). The sensing element of the HDC2010 is placed on the bottom part of the device, which makes the HDC2010 more robust against dirt, dust, and other environmental contaminants. The capacitive-based sensor includes new integrated digital features and a heating element to dissipate condensation and moisture. The HDC2010 digital features include programmable interrupt thresholds to provide alerts/system wakeups without requiring an MCU to be continuously monitoring the system. Combined with programmable sampling intervals, low inherent power consumption, and support for 1.8-V supply voltage, these features make the HDC2010 well suited for battery-operated systems.

The HDC2010 provides high-accuracy measurement capability for a wide range of environmental monitoring applications and Internet of Things (IoT) such as smart thermostats, smart home assistants, and wearables. The HDC2010 can also be used to provide critical temperature and humidity data for cold chain transportation and storage of perishable goods to help ensure products like food and pharmaceuticals arrive fresh.

The HDC2010 is factory-calibrated to 0.2°C temperature accuracy and 2% relative humidity accuracy and includes a heating element to burn away condensation and moisture for increased reliability. The HDC2010 supports operation from –40°C to +125°C and from 0% to 100% relative humidity.

- Relative humidity range: 0% to 100%
- Humidity accuracy: ±2%
- Sleep current: 50 nA
- Average supply current (1 measurement per second):
  - RH only (11 bit): 300 nA
  - RH (11 bit) + temperature (11 bit): 550 nA
- Temperature range:
  - Operating: –40°C to +85°C
  - Functional: –40°C to +125°C
- Temperature accuracy: ±0.2°C typ
- Supply voltage: 1.62 to 3.6 V
- Automatic sampling rate (5 Hz, 2 Hz, 1 Hz, 0.2 Hz, 0.1 Hz, 1/60 Hz, 1/120 Hz) or on demand
- I^{2}C interface

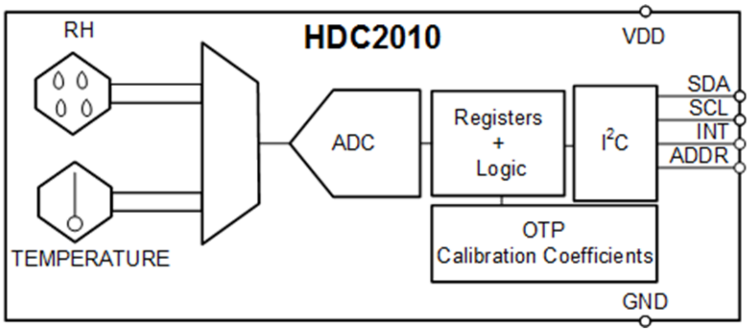


Figure 3. Functional Block Diagram of HDC2010YPAR

2.2.3 TPD1E10B06

The TPD1E10B06 device is a single-channel electrostatic discharge (ESD) transient voltage suppression (TVS) diode in a small 0402 package. This TVS protection product offers ±30-kV contact ESD, ±30-kV IEC air-gap protection, and has an ESD clamp circuit with a back-to-back TVS diode for bipolar or bidirectional signal support. The 12-pF line capacitance of this ESD protection diode is suitable for a wide range of applications supporting data rates up to 400 Mbps. The 0402 package is an industry standard and is convenient for component placement in space-saving applications.

Typical applications of this ESD protection product are circuit protection for audio lines (microphone, earphone, and speaker phone), SD interfacing, keypad or other buttons, V_{BUS} pin and ID pin of USB ports, and general-purpose I/O ports. This ESD clamp is good for the protection of the end equipment like e-books, tablets, remote controllers, wearables, set-top boxes, and electronic point of sale equipment.

- Provides system-level ESD protection for low-voltage I/O interface
- IEC 61000-4-2 level 4 ESD protection:
  - ±30-kV contact discharge
  - ±30-kV air-gap discharge
- IEC 61000-4-5 surge: 6 A (8/20 µs)
- I/O capacitance: 12 pF (typical)
- R_{DYN}: 0.4 Ω (typical)
- DC breakdown voltage: ±6 V (minimum)
- Ultra-low leakage current: 100 nA (maximum)
- 10-V clamping voltage (max at I_{PP} = 1 A)
- Industrial temperature range: –40°C to +125°C
- Space-saving 0402 footprint (1 mm × 0.6 mm × 0.5 mm)

2.3 System Design Theory

The following sections describe the theory and methods used to develop this reference design.

2.3.1 Design Theory of Battery Power

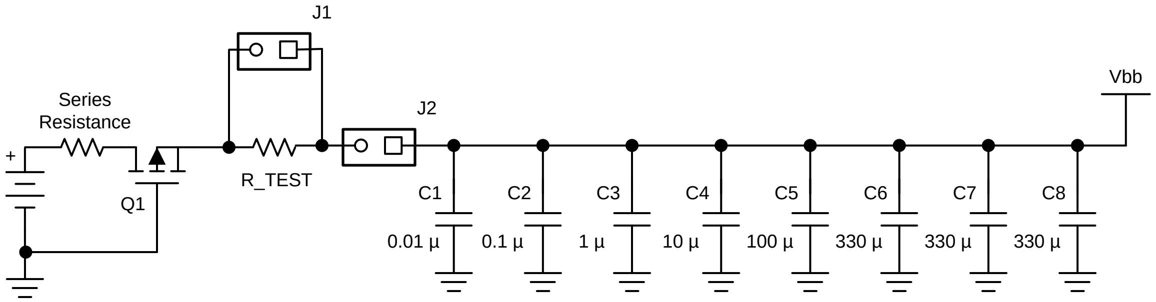


Figure 4. Battery Input Power Stage

The power source for this reference design is an Energizer® CR2032 lithium-ion coin cell. This battery is chosen for its low cost and high capacity-to-size ratio. The voltage characteristics of a lithium-ion CR2032 coin cell battery are also ideal. The output voltage remains relatively flat throughout the discharge life until the cell is nearly depleted. When the cell is depleted, the output voltage drops off relatively quickly.

Immediately following the battery is a low R_{DS_ON} P-channel MOSFET. The P-channel MOSFET prevents damage to the hardware if the coin cell battery is inserted backwards while minimizing the forward voltage drop in normal operation. A test resistor is placed in series with the power rail of this circuit to allow easy current measurements simply by measuring the voltage across J1 in this diagram. This resistor is not populated and can be any value that is convenient for power testing.

2.3.1.1 Calculating DC Bus Capacitor Value

As a battery reaches the end of its life, it starts experiencing significant increase in internal resistance and a decrease in terminal voltage. Capacitors C1 to C8 in Figure 4 are placed to keep the supply voltage from drooping too low during periods of high load, such as the activation of the buzzer or TX is active on the MCU.

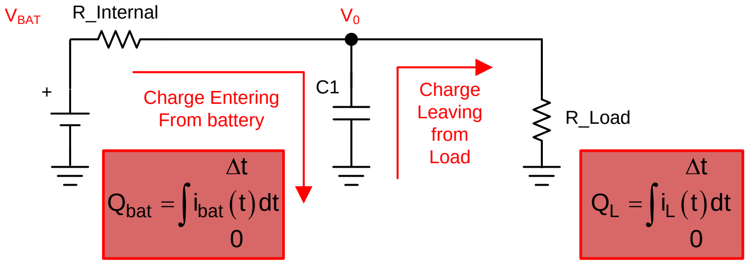


Figure 5. Battery Power Schematic

Using Figure 5 as reference, the current from the battery, i_{bat}, can be calculated using Equation 1:

$$i_{BAT} = \frac{V_{BAT} - V_O}{R_{INTERNAL}} \tag{1}$$

Capacitance is defined as ΔQ/ΔV change in charge per volt. ΔV Is the maximum allowable voltage drop on V_0, and ΔQ is the sum of the charge that enters the capacitor from the battery and the charge that leaves due to the load. To find the value for the ripple capacitor (C1), use Equation 2. These equations are for a linear model with a constant current.

$$C1 = \frac{\Delta Q}{V_{INIT} - V_{MIN}} \tag{2}$$

where:

- $V_{INIT} = V_{BAT} - I_Q \times R_{INTERNAL}$
- $\Delta Q = \Delta t\left(i_L - i_{BAT}\right) = \Delta t\left(i_L - \dfrac{V_{BAT} - V_O}{R_{INTERNAL}}\right)$
- V_{MIN}= Minimum allowable voltage for device to work
- V_0= Output voltage to rest of the circuit
- V_{BAT}= Nominal voltage on battery or end of life voltage
- $R_{Internal}$ = Internal resistance of battery
- I_Q = Current draw of previous state

Table 2. Power Supply Design Assumptions

SOURCE	TX	BUZZER
V_{BAT}	2.7 V	2.7 V
$V_0 = V_{MIN}$	1.8 V	1.8 V
i_L	14 mA	6 mA
I_Q	2.5 mA	2.5 mA
Δt	23 ms	100 ms

To calculate TX:

$$V_{INIT} = 2.7\ \text{V} - 2.5\ \text{mA} \times 250\ \Omega = 2.075 \tag{3}$$

$$C = \frac{23\ \text{ms} \times \left(14\ \text{mA} - \dfrac{2.7\ \text{V} - 1.8\ \text{V}}{250\ \Omega}\right)}{2.075 - 1.8} \approx 870\ \mu \tag{4}$$

For the buzzer:

$$V_{INIT} = 2.7\ V - 2.5\ mA \times 250\ \Omega = 2.075\ V \tag{5}$$

$$C = \frac{100\ ms \times \left(6\ mA - \dfrac{2.7\ V - 1.8\ V}{250\ \Omega}\right)}{2.075 - 1.8} \approx 873\ \mu \tag{6}$$

The choice of capacitor is chosen to be 1111 µF because it could be made by 3 × 330 µF tantalum capacitors and decade capacitors. This value (1111 µF) allows for more tolerance at end of life conditions. If it is found that this is not needed, one of the capacitors can be de-populated or changed to save cost.

2.3.2 Design Theory of Buzzer Circuit

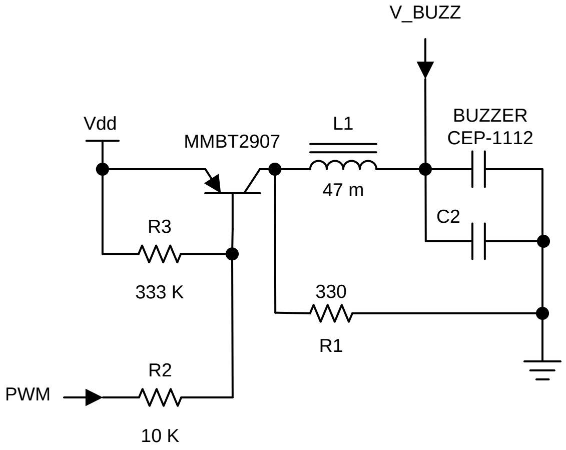


Figure 6. TIDA-01518 Buzzer Circuit

The capacitive nature of a piezo buzzer is what allows his circuit to work. The piezo buzzer acts as the capacitor in the LRC resonator shown in Figure 6. When the PWM turns on and off the S1, the circuit begins to resonate. Each piezo buzzer also has a particular resonant frequency at which the sound output power versus input power will be at a maximum. Values of L and C need to be chosen so the resonant frequency of the piezo buzzer matches that of the LC resonator. Typical capacitance values of piezo buzzers range from 16 to 30 nF; this is why the 47-mH inductor is chosen for this design because this gives the designer a resonant frequency range between 3850 and 5720 Hz, which is a typical frequency range for many piezo buzzers. The capacitor C2 is placed to tune the resonant frequency of the LC circuit match that of the piezo buzzer.

Table 3 shows the parameter values of interest for the piezo buzzer used in this reference design. These parameters are used to derive suitable values for the discrete components, C2 and R1.

Table 3. Piezo Buzzer Calculation Parameters

PARAMETER	VALUE
Buzzer type	CEP-1112 piezo buzzer
Capacitance	26 nF
Resonant frequency	4000 Hz
Sound pressure level	92 dB at 10 cm
Voltage source	$10\ V_{p\text{-}p}$
Voltage max	$30\ V_{p\text{-}p}$

To find the value of C2 that matches the resonant frequency:

$$F_r = \frac{1}{2\pi\sqrt{LC}} \text{ LC resonant frequency} \tag{7}$$

Plugging in the known values from Table 3, the equation becomes:

$$4000 = \frac{1}{2\pi\sqrt{47\ \text{mH} \times (C_{TOT})}} \tag{8}$$

Equation 8 is then rearranged to solve for the value of interest, C_{TOT}:

$$C_{TOT} = \frac{1}{(8000\pi)^2 \times 47\ \text{mH}} \approx 33\ \text{n} \tag{9}$$

Solving for the value of C2 yields:

$$C_{TOT} = 26\ \text{nF} + C_2 = 33\ \text{nF} \rightarrow C_2 = 7\ \text{n} \tag{10}$$

This value does not need to be precise; a value of 6.7 nF is adequate for this design. The value of R1 is important to this circuit because it control the amplitude of the output waveform. The lower the value of R1, the higher the output amplitude. If the value of R1 is set too low, the buzzer draws too much current. To find the approximate output peak voltage amplitude, Equation 11 is used:

$$V_{ABUZZ} = V_{DD} \times \frac{2}{\pi R}\sqrt{\frac{L}{C}} \tag{11}$$

Note that Equation 11 assumes one is at the resonant frequency of the circuit.

Just as an example, for a desired amplitude of 10 $V_{p\text{-}p}$ using the capacitance value found in the previous problem, the value of R1 is calculated as:

$$10\ \text{V} = 3\ \text{V} \times \frac{2}{\pi \times R_1}\sqrt{\frac{47\ \text{mH}}{32.7\ \text{nF}}} \tag{12}$$

$$R_1 = 228\ \Omega \approx 220\ \Omega \tag{13}$$

2.3.3 Design Theory of Wireless Communication

In this reference design, transmitting the sensor information to some central location for processing is necessary. However, because power consumption is always a concern in battery-based applications, the radio and processor must be low power. Also, the wireless protocol required for the end-equipment system is an important consideration for the selection of the radio device.

A TI's SimpleLink ultra-low-power wireless MCU platform, with a combined radio and MCU enables an extremely long battery life for sensor end-nodes. Furthermore, the CC1310 is a multi-standard device with software stack support for wM-Bus and IEEE 802.15.4g. This reference design uses TI's SimpleLink TI-15.4 Stack to interface to a star network, but the hardware as built can work with other protocols as well.

2.3.4 Design Theory of Leak Detection Circuit

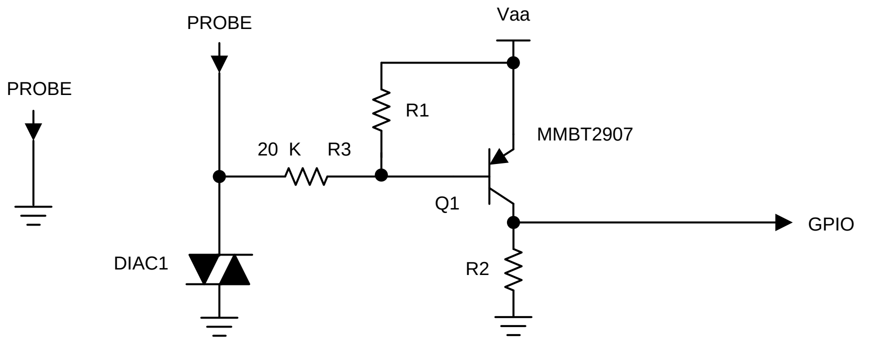


Figure 7. TIDA-01519 Leak Detection Schematic

The PNP water switch works by using water to make an electrical connection between ground and the base of the PNP transistor. Once the connection is made, the B_{JT} activates by pulling the collector to V_{aa}. This design uses the MMBT2907 PNP transistor due to its low cost.

A protective diode is put in place because the water probe is placed in a outside environment and is subjected to possible electrostatic discharges. This reference design uses the TPD1E10B06DPYR ESD protection diode.

2.3.4.1 Derivation of Resistance Between the Probes

This circuit relies on the resistive properties of water to work. For this design to work, the resistance between the probes must be known. Determining this by using known resistivity of water can be difficult because of the infinite parallel connections that exist between the two probes in water. Also simply using an ohm meter is also problematic because of the electrolytic properties of water cause false readings.

To accurately determine the resistance between the probes, apply a constant voltage across the probes submerge them in water and measure the current that passes through the water as shown in Figure 8.

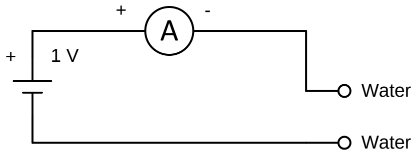


Figure 8. Test Setup of Water Resistance Measurement

After applying 1 V across the probes and measuring the current, the current flowing through the water is taken to be 3 µA, regardless of separation or depth in the water. The probes measure 1 cm in length and 1-mm×1-mm square in cross section.

Figure 9. Test Setup of Ammeter Water

From Ohm's Law, the resistance is calculated to be:

$$R = \frac{V}{I} = \frac{1\ \text{V}}{3\ \mu\text{A}} \approx 333\ \text{k}\Omega \tag{14}$$

2.3.4.2 Determining Resistance Value of R1

The primary factor in choosing the value of R1 is the minimum base-to-emitter voltage (V_{be}) that the B_{JT} becomes active. For this particular transistor, it is –0.4 V from the base to the emitter.

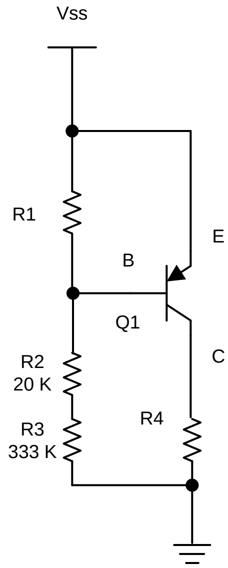


Figure 10. TIDA-01518 B_{JT} Circuit

The base-to-emitter voltage in this circuit is equal to the voltage drop across R1. The value of R1 can be calculated by solving Equation 15. The V_{be} voltage of this transistor is increased to –0.6 V to allow for error margin. V_{ss} is assumed to be 2 V because this would be the minimum voltage present in the circuit at end of life conditions.

$$0.8 = \frac{2 \times R_1}{R_1 + 333\ \text{k}\Omega + 20\ \text{k}\Omega} = 235.3\ \text{k}\Omega \tag{15}$$

This value represents the minimum value of R1; a higher value can be chosen for more sensitivity and lower current. With higher values of R1, the circuit is more prone to noise and false readings. For this design, a value of 560 kΩ is chosen.

2.3.5 Leak Detector Firmware Development

There are five main parts to the software: the initial boot-up thread, leak detected, temperature or humidity threshold, and push-button 1 and push-button 2. These are shown in the following software flow diagrams. These diagrams are divided based on the specific functions they perform.

2.3.5.1 *Initial Boot-up*

Once the device is turned on, the CPU enters the initial boot-up thread. From here, the CPU sets up the drivers for GPIO, I^{2}C, and Sub-1 GHz radio. After setting up the drivers, the boot thread sets the callback functions and interrupt for the GPIO connected to HDC2010, leak detector, and push-buttons. Finally, this thread configures the HDC2010 in to interrupt mode, set the threshold values for temperature and humidity, and set up the Sub-1 GHz protocols if desired before putting the device to sleep.

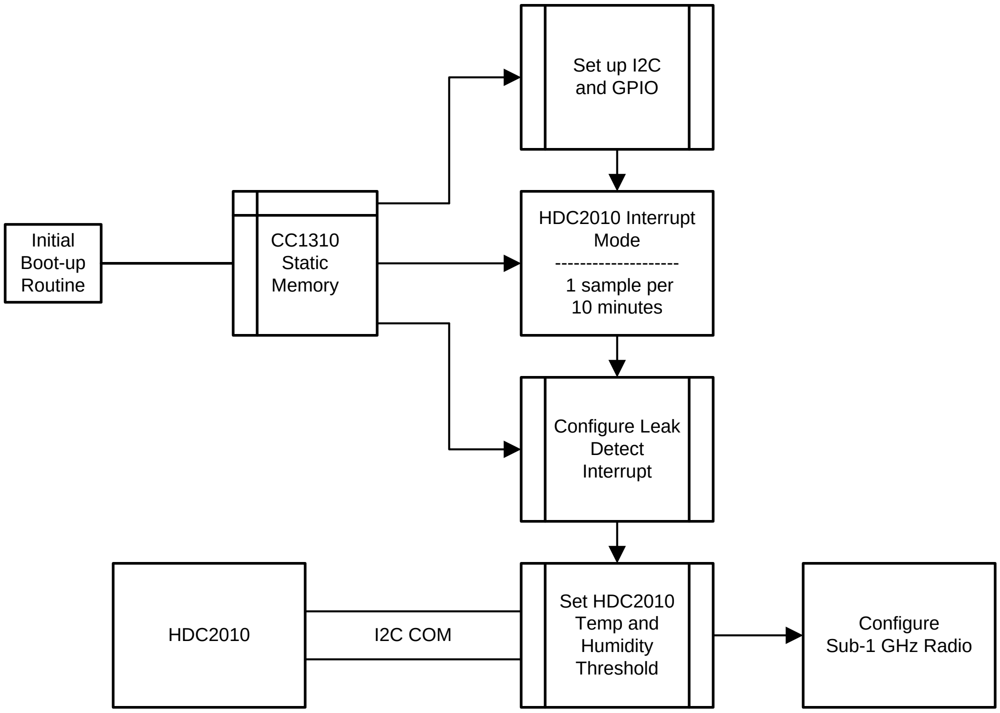


Figure 11. Software Flow Diagram of Initial Boot-up

2.3.5.2 Leak Detection

This interrupt is active on the rising edge of the GPIO connected to the leak detector. This interrupt first sends a message over the Sub-1 GHz radio to alert the user of the leak then will sound the buzzer until the GPIO connected to the leak sensor is asserted low.

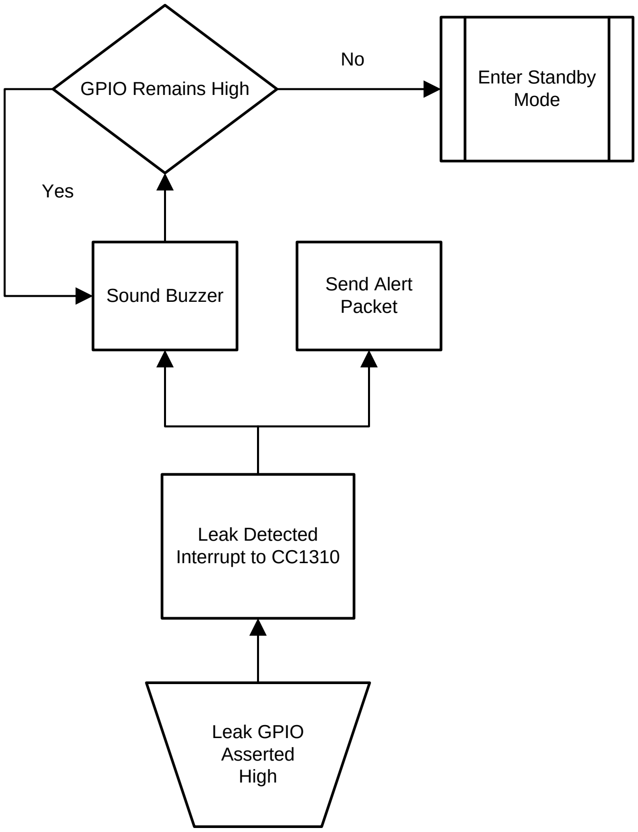


Figure 12. Software Flow Diagram of Water Leak Detected

2.3.5.3 Temperature and Humidity Monitoring Thread

This interrupt is active on the rising edge of the GPIO connected to the HDC2010. This interrupt first takes a temperature and humidity sample and determine which threshold is reached and make a decision on what message to send based on the threshold reached. If no threshold is reached, the device sends out a single sensor packet containing the HDC2010 data.

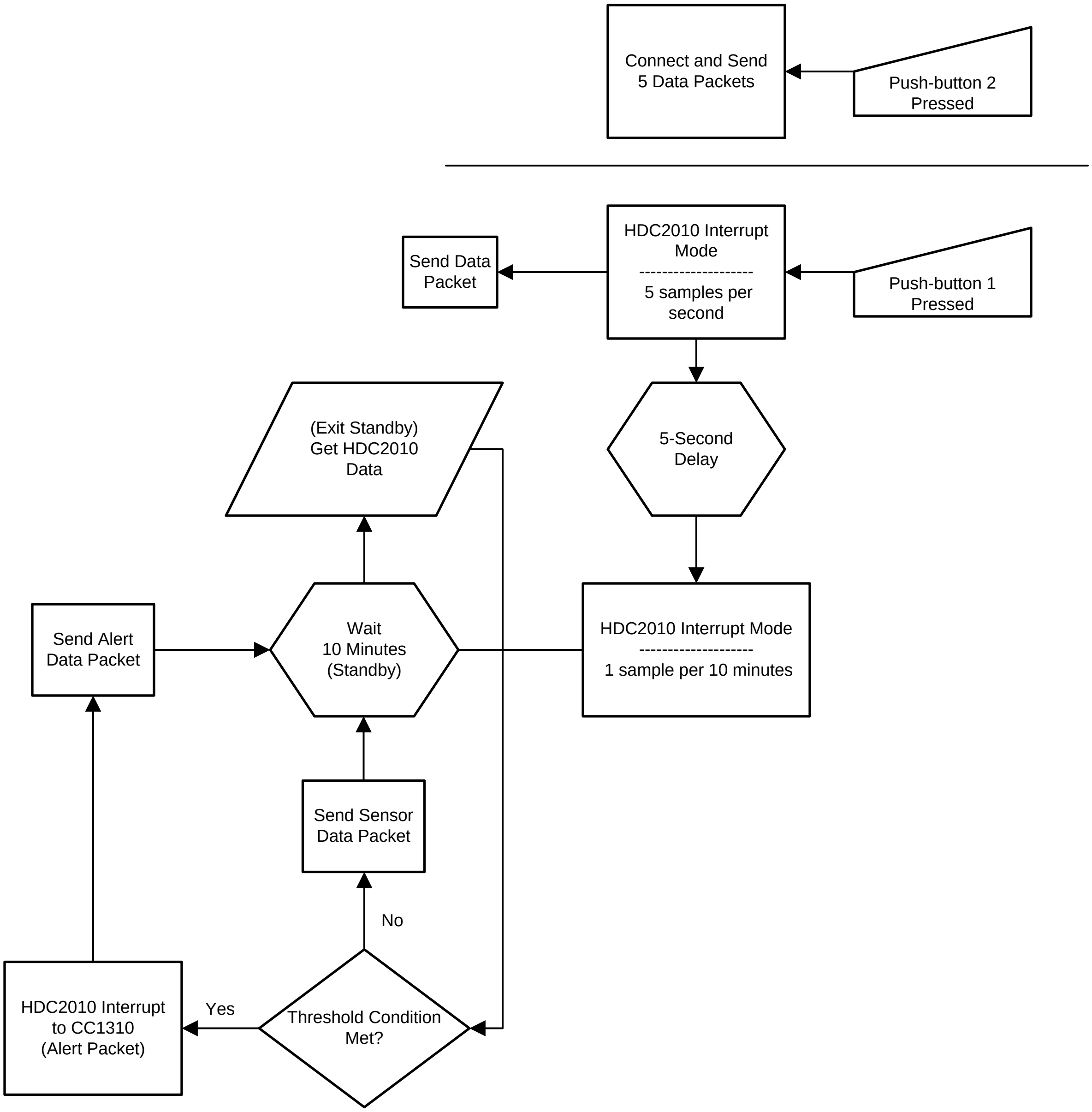


Figure 13. Software Flow Diagram of Main Thread

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

The following sections outline the necessary hardware and software needed to evaluate this reference design. These sections also provide instruction on how to get the board up and running quickly.

3.1.1 Hardware

Figure 14 shows the board overview for this reference design. The key features of the board are highlighted to allow the user to become familiar with the board components and their respective location on the board.

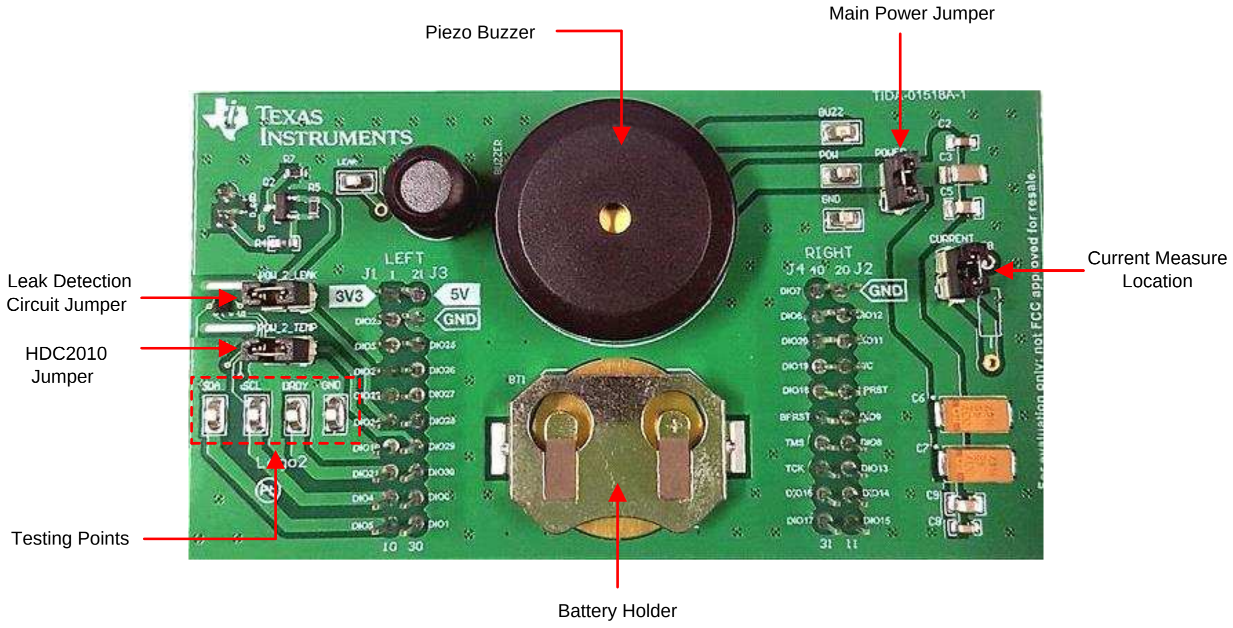


Figure 14. TIDA-01518 Board Overview

Figure 16 demonstrates the connection of the reference design board to the CC1310 LaunchPad evaluation module (EVM). The device is connected through the use of the CC1310 daughterboard header pins, located on the top of the LaunchPad. Find more information on the specific nets shared between the two devices in the TIDA-01518 schematic.

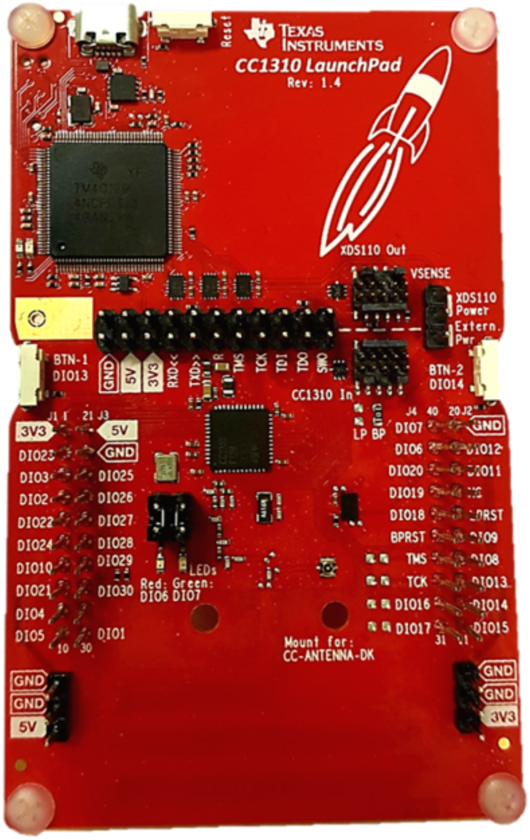


Figure 15. CC1310 LaunchPad Board

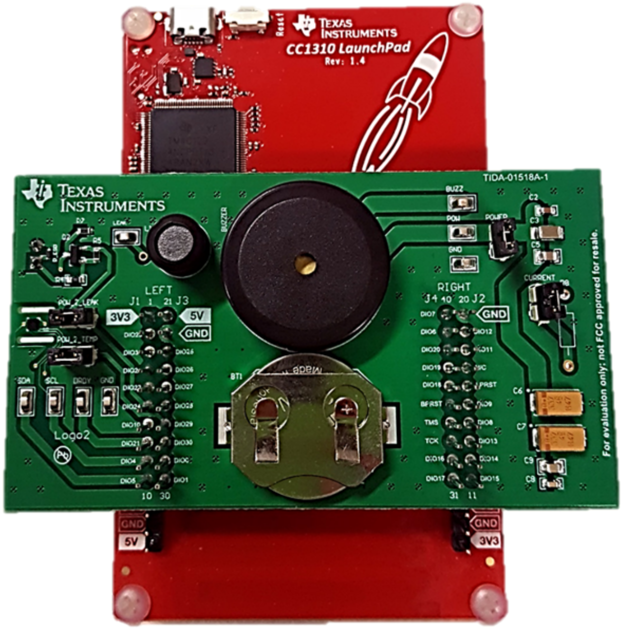


Figure 16. TIDA-01518 Board Using CC1310 LaunchPad Headers

3.1.2 Software

The following section is an overview of the software deployment to the LaunchPad as well as instructions on how to get the wireless capabilities of the CC1310 up and running.

3.1.2.1 Initial Firmware Deployment

Figure 17 shows the setup used to deploy the software developed in CCS to the CC1310 LaunchPad EVM. Before connecting the USB cable to the LaunchPad, ensure the this reference design board is securely attached to the LaunchPad daughterboard headers.

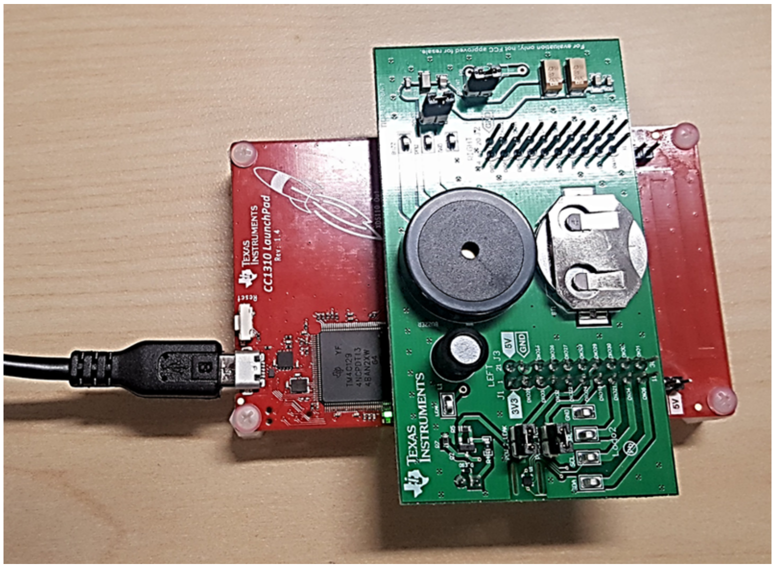
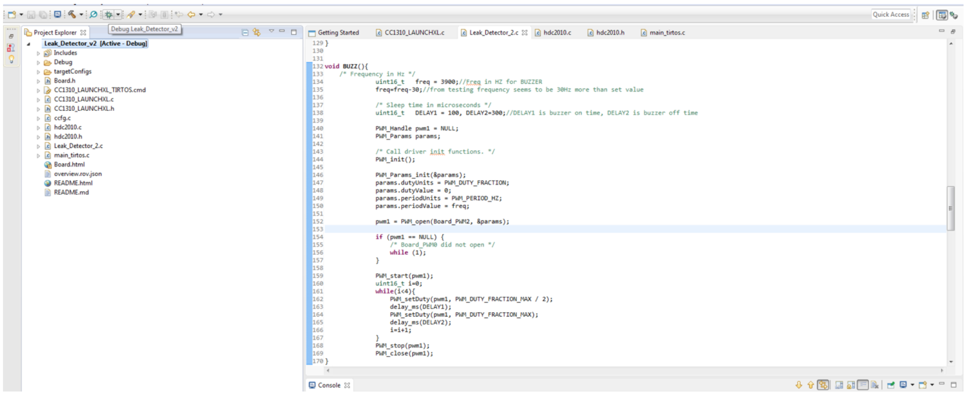


Figure 17. Firmware Deployment Configuration

After applying power to the LaunchPad through the USB cable attached to the computers COM port, a green indicator LED is activated to let the user know that there is power to the board. After downloading the TIDA-01518 firmware, the source code can be built in CCS using the build icon at the top. Once built to deploy the software to the LaunchPad, click the debug icon at the top of the CCS development environment.



```
}


void BUZZ(){
    /* Frequency in Hz */
          uint16_t   freq = 3900;//Freq in HZ for BUZZER
          freq=freq-30;//from testing frequency seems to be 30Hz more than set value

          /* Sleep time in microseconds */
          uint16_t   DELAY1 = 100, DELAY2=300;//DELAY1 is buzzer on time, DELAY2 is buzzer off time

          PWM_Handle pwm1 = NULL;
          PWM_Params params;

          /* Call driver init functions. */
          PWM_init();

          PWM_Params_init(&params);
          params.dutyUnits = PWM_DUTY_FRACTION;
          params.dutyValue = 0;
          params.periodUnits = PWM_PERIOD_HZ;
          params.periodValue = freq;

          pwm1 = PWM_open(Board_PWM2, &params);

          if (pwm1 == NULL) {
              /* Board_PWM0 did not open */
              while (1);
          }

          PWM_start(pwm1);
          uint16_t i=0;
          while(i<4){
              PWM_setDuty(pwm1, PWM_DUTY_FRACTION_MAX / 2);
              delay_ms(DELAY1);
              PWM_setDuty(pwm1, PWM_DUTY_FRACTION_MAX);
              delay_ms(DELAY2);
              i=i+1;
          }
          PWM_stop(pwm1);
          PWM_close(pwm1);
}
```

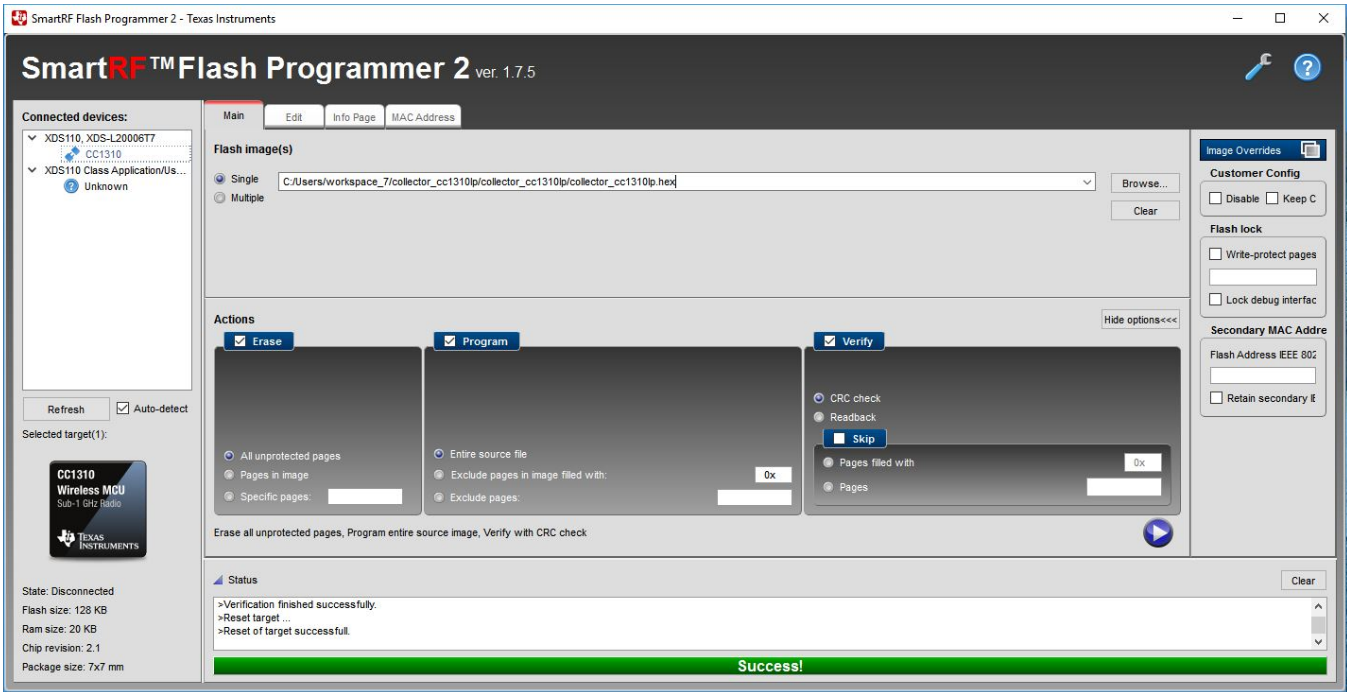
Figure 18. Building and Deploying of Firmware Through CCS

A quick way to test if the software is installed correctly is to place an index finger across the leak detection probes located underneath the board. Once the contact is made, the buzzer must begin sounding until the finger is removed from the pins. To fully verify the firmware functionality, the transmitted data packets from the CC1310 LaunchPad must be captured and analyzed by using a packet collector.

3.1.2.2 Programming the Collector

The SimpleLink SDK download includes a quick start guide to program and run the TI 15.4 Stack collector. The guide are in the SimpleLink SDK installation directory under docs (for example, "C:\ti\simplelink_cc13x0_sdk_1_30_00_06\docs\ti154stack"). Open the Software Developers Guide and navigate to Example Applications on the left side bar.

Flash Programmer 2 is the easiest way to program the collector if .hex files are already generated. CCS can be used to make changes to the example code. Figure 19 shows the Flash Programmer settings after plugging in the LaunchPad.



State: Disconnected
Flash size: 128 KB
Ram size: 20 KB
Chip revision: 2.1
Package size: 7x7 mm

● Single: C:/Users/workspace_7/collector_cc1310lp/collector_cc1310lp/collector_cc1310lp.hex
○ Multiple

Erase: ● All unprotected pages ○ Pages in image ○ Specific pages:

Program: ● Entire source file ○ Exclude pages in image filled with: 0x ○ Exclude pages:

Verify: ● CRC check ○ Readback

Skip: ○ Pages filled with 0x ○ Pages

Erase all unprotected pages, Program entire source image, Verify with CRC check

```
>Verification finished successfully.
>Reset target ...
>Reset of target successfull.
```

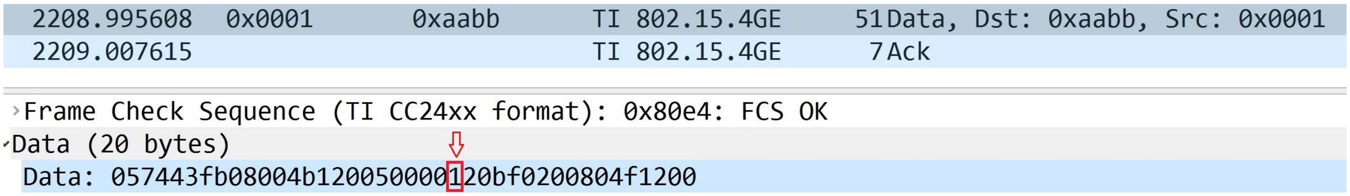
Success!

Figure 19. Flash Programmer 2 Setup

3.1.2.3 Receiving Data Packets

As this design guide previously described, this reference design is programmed to send data packets in the event of a leak or temperature or humidity issue. The CC1310 broadcasts three possible action values:

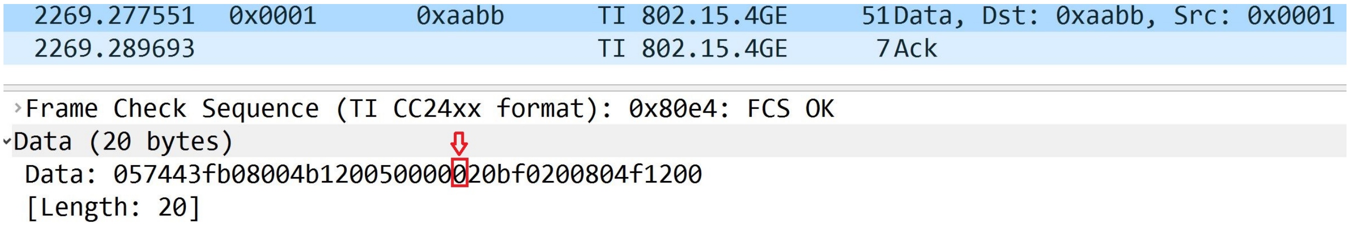
- Leak detected
- A temperature or humidity issue detected Figure 20)
- User button sensor data broadcast



```
2208.995608  0x0001      0xaabb      TI 802.15.4GE     51 Data, Dst: 0xaabb, Src: 0x0001
2209.007615                          TI 802.15.4GE      7 Ack

›Frame Check Sequence (TI CC24xx format): 0x80e4: FCS OK
⌄Data (20 bytes)
 Data: 057443fb08004b120050000120bf0200804f1200
```

Figure 20. Leak Detected Packet Data

- A leak detected packet after a leak is detected (see Figure 21)



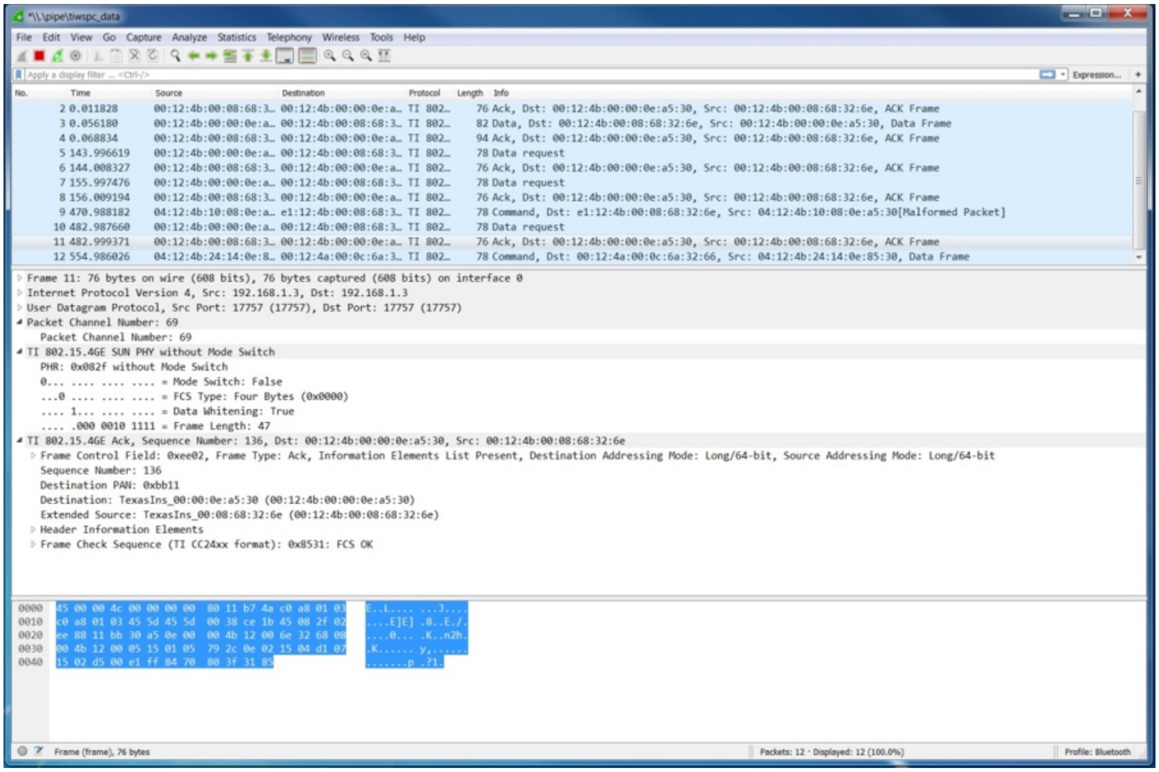
```
2269.277551  0x0001      0xaabb      TI 802.15.4GE     51 Data, Dst: 0xaabb, Src: 0x0001
2269.289693                          TI 802.15.4GE      7 Ack

›Frame Check Sequence (TI CC24xx format): 0x80e4: FCS OK
⌄Data (20 bytes)
 Data: 057443fb08004b120050000020bf0200804f1200
 [Length: 20]
```

Figure 21. Temperature Threshold Reached Packet Data

To verify the proper operation of the radio transmission, a CC1350 or CC1310 LaunchPad board can be used as a packet sniffer device for TI 15.4-Stack radio packets. This feature enables easier development and debugging for those developing products with the TI 15.4-Stack. The TI 15.4-Stack installs the TiWsPc2, which uses TI hardware to capture OTA data before sending the packets to Wireshark® or a PCAP file, and provides .dll files to dissect packets that follow the TI 802.15.4ge protocol to Wireshark. Figure 22 is an example of TI 15.4-Stack-based application OTA traffic being presented as a Wireshark capture.

3.1.2.3.1 CC1310 LaunchPad Sniffer

The SimpleLink SDK download includes quick start guides to install, program, and run the TI 15.4 Stack sniffer (for example, "C:\ti\simplelink_cc13x0_sdk_1_30_00_06\docs\ti154stack"). Open the *Software Developers Guide* and navigate to Example Applications on the left side bar. All the required software except for Wireshark is downloaded within the SimpleLink SDK.



```
No.   Time        Source                Destination           Protocol Length Info
    2 0.011828    00:12:4b:00:08:68:3…  00:12:4b:00:00:0e:a…  TI 802…  76 Ack, Dst: 00:12:4b:00:00:0e:a5:30, Src: 00:12:4b:00:08:68:32:6e, ACK Frame
    3 0.056180    00:12:4b:00:00:0e:a…  00:12:4b:00:08:68:3…  TI 802…  82 Data, Dst: 00:12:4b:00:08:68:32:6e, Src: 00:12:4b:00:00:0e:a5:30, Data Frame
    4 0.068834    00:12:4b:00:08:68:3…  00:12:4b:00:00:0e:a…  TI 802…  94 Ack, Dst: 00:12:4b:00:00:0e:a5:30, Src: 00:12:4b:00:08:68:32:6e, ACK Frame
    5 143.996619  00:12:4b:00:00:0e:a…  00:12:4b:00:08:68:3…  TI 802…  78 Data request
    6 144.008327  00:12:4b:00:08:68:3…  00:12:4b:00:00:0e:a…  TI 802…  76 Ack, Dst: 00:12:4b:00:00:0e:a5:30, Src: 00:12:4b:00:08:68:32:6e, ACK Frame
    7 155.997476  00:12:4b:00:00:0e:a…  00:12:4b:00:08:68:3…  TI 802…  78 Data request
    8 156.009194  00:12:4b:00:08:68:3…  00:12:4b:00:00:0e:a…  TI 802…  76 Ack, Dst: 00:12:4b:00:00:0e:a5:30, Src: 00:12:4b:00:08:68:32:6e, ACK Frame
    9 470.988182  04:12:4b:10:08:0e:a…  e1:12:4b:00:08:68:3…  TI 802…  78 Command, Dst: e1:12:4b:00:08:68:32:6e, Src: 04:12:4b:10:08:0e:a5:30[Malformed Packet]
   10 482.987660  00:12:4b:00:00:0e:a…  00:12:4b:00:08:68:3…  TI 802…  78 Data request
   11 482.999371  00:12:4b:00:08:68:3…  00:12:4b:00:00:0e:a…  TI 802…  76 Ack, Dst: 00:12:4b:00:00:0e:a5:30, Src: 00:12:4b:00:08:68:32:6e, ACK Frame
   12 554.986026  04:12:4b:24:14:0e:8…  00:12:4a:00:0c:6a:3…  TI 802…  78 Command, Dst: 00:12:4a:00:0c:6a:32:66, Src: 04:12:4b:24:14:0e:85:30, Data Frame
```

```
▷ Frame 11: 76 bytes on wire (608 bits), 76 bytes captured (608 bits) on interface 0
▷ Internet Protocol Version 4, Src: 192.168.1.3, Dst: 192.168.1.3
▷ User Datagram Protocol, Src Port: 17757 (17757), Dst Port: 17757 (17757)
◢ Packet Channel Number: 69
    Packet Channel Number: 69
◢ TI 802.15.4GE SUN PHY without Mode Switch
    PHR: 0x082f without Mode Switch
    0... .... .... .... = Mode Switch: False
    ...0 .... .... .... = FCS Type: Four Bytes (0x0000)
    .... 1... .... .... = Data Whitening: True
    .... .000 0010 1111 = Frame Length: 47
◢ TI 802.15.4GE Ack, Sequence Number: 136, Dst: 00:12:4b:00:00:0e:a5:30, Src: 00:12:4b:00:08:68:32:6e
  ▷ Frame Control Field: 0xee02, Frame Type: Ack, Information Elements List Present, Destination Addressing Mode: Long/64-bit, Source Addressing Mode: Long/64-bit
    Sequence Number: 136
    Destination PAN: 0xbb11
    Destination: TexasIns_00:00:0e:a5:30 (00:12:4b:00:00:0e:a5:30)
    Extended Source: TexasIns_00:08:68:32:6e (00:12:4b:00:08:68:32:6e)
  ▷ Header Information Elements
  ▷ Frame Check Sequence (TI CC24xx format): 0x8531: FCS OK
```

```
0000  45 00 00 4c 00 00 00 00  80 11 b7 4a c0 a8 01 03   E..L.... ...J....
0010  c0 a8 01 03 45 5d 45 5d  00 38 ce 1b 45 08 2f 02   ....E]E] .8..E./.
0020  ee 88 11 bb 30 a5 0e 00  00 4b 12 00 6e 32 68 08   ....0... .K..n2h.
0030  00 4b 12 00 05 15 01 05  79 2c 0e 02 15 04 d1 07   .K...... y,......
0040  15 02 d5 00 e1 ff 84 70  80 3f 31 85               .......p .?1.
```

Figure 22. Wireshark Packet Sniffer Software

Choose a packet to get detailed information on the data in that packet. The installed .dll file lets Wireshark dissect the information in a TI 802.15.4GE packet for easy debugging.

3.2 Testing and Results

3.2.1 Test Setup

The following subsections explain the testing done on the TIDA-01519 board, along with detailed setup instructions, allowing the user to easily replicate the results.

3.2.1.1 Test Setup of Sub-1 GHz Range

The range of the Wireless Sub-1 GHz RF is measured using the CC1111 USB dongle. For this test, the PIR PCB remained at a stationary location as a laptop with the CC1111 USB dongle attached and listening was moved away from the PIR PCB. While the CC1111 is on the move, the PIR design is being reset at regular short intervals to make sure there are radio packets constantly being transmitted. The distance at which packets are no longer received is then measured.

Different orientations of the PCB and the CC1111 USB dongle with respect to one another are used during the test. No discernable change in the wireless RF range is observed.

3.2.1.2 Test Setup of Leak Detection and Frequency Response

Figure 23 shows the setup for testing of the leak detection circuitry of this reference design. A Styrofoam™ cup is filled with water to simulate a leak situation. The probes of the leak detection circuit can be extended through the use of two male-to-female jumpers, allowing the probes to be placed in the cup of water.

Figure 23. Test Setup of Water Leak Detection

3.2.1.3 Test Setup of Temperature Threshold

To test the HDC2010 temperature threshold, the board is placed in a thermal test box, where the temperature is programmed to reach 32°F (0°C). This test box simulates a frozen evaporator coil, allowing the verification of proper functionality with respect to the HDC2010 communicating with the CC1310. As the temperature approaches the target threshold, the data transmission is monitored by a packet sniffer in order to intercept the sensor board packet information.

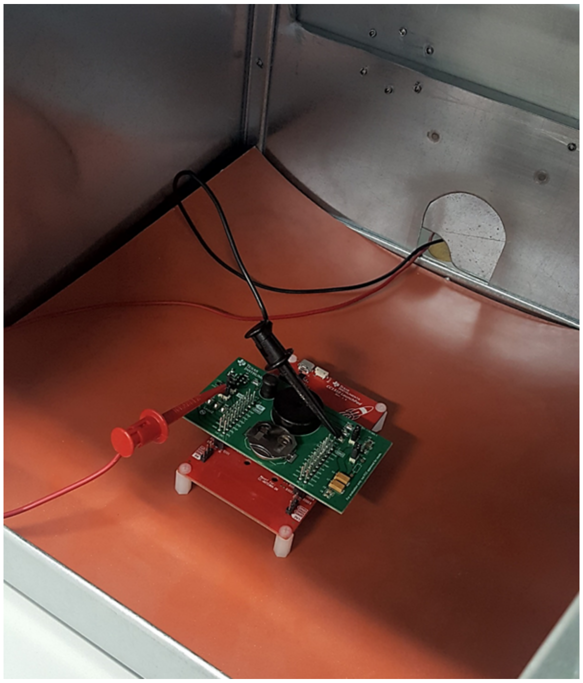


Figure 24. Test Setup of HDC Temperature and Humidity Threshold

3.2.1.4 Test Setup of Current Consumption

For the current consumption test setup, the current jumper and the main PWR jumper are removed from the headers. The current probes are next attached in series with the main power—the battery—to monitor the current being drawn by the remainder of the devices for particular events. The data is acquired through the use of a digital multimeter with mathematical processing capability. The current measurement for each standby mode test case is based off the average current over the duration of the event (for this test, 10 minutes standby).

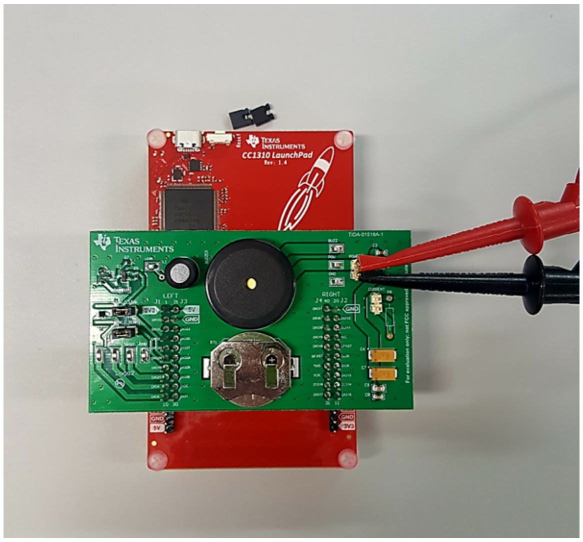


Figure 25. Test Setup of Main Supply Current Consumption

The current consumption for the packet transmission and the leak alarm functionality is acquired by using a 3.293-Ω current sense resistor in series with an isolated DC power supply. The oscilloscope probe is placed across the resistor to measure the voltage drop across it. The oscilloscope waveform captured during the target event can then be analyzed using the onboard waveform measurement tools for accurate consumption results.

3.2.2 Test Results

The following subsections outline the results from the reference design testing described in Section 3.2.1.

3.2.2.1 Test Results of Sub-1 GHz Range

The wireless RF range is measured to be 220 meters in a typical office environment with partial line of sight. The measured signal strength at this distance is less than –100 dBm as measured by the CC1111 packet sniffer dongle.

While this distance is outstanding considering the small footprint of the PCB antenna, there are ways to increase this distance even further. Use of a whip antenna with gain instead of the passive PCB antenna could offer improvements in the wireless RF range. Another option would be to increase the transmit power of the CC1310 to its maximum level at the expense of increased supply current during the radio transmission intervals.

3.2.2.2 Test Results of Leak Detection and Frequency Response

For the leak detection testing, the alarm successfully alerts as one of the probes are placed in liquid.

Table 4. Leak Detection Water Depth Testing

DEPTH	ALARM SOUNDS
On surface of water	Yes
Middle of cup	Yes
Bottom of cup	Yes

Figure 26 shows the output waveforms of the design board when the leak detection probes are introduced to water. As shown from the waveforms, once the input pin is pulled high, the buzzer begins sounding for the duration of the detected leak.

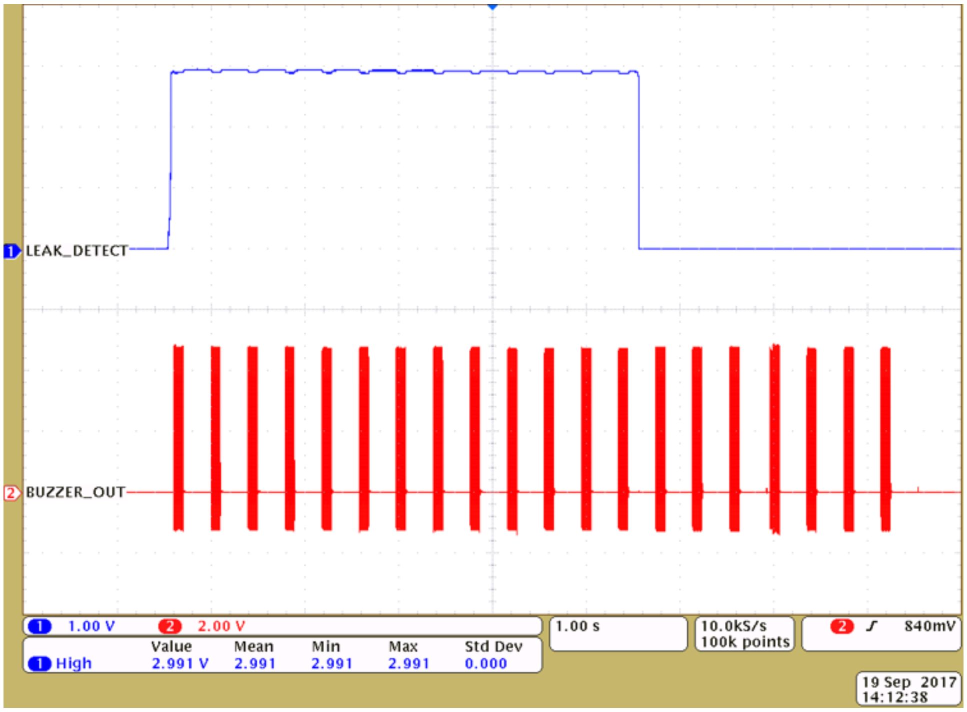


Figure 26. Leak Detection Response

Figure 23 and Figure 24 show the frequency response test results for the alarm at 1 ft and 5 ft, respectfully. As shown from these plots, there is a significant frequency magnitude peak at 3.9 kHz. For both alarm detection distances, there is relatively no change in dB magnitude.

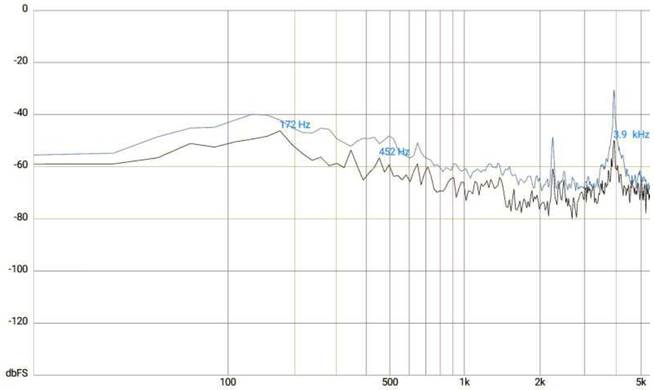


Figure 27. Frequency Response at 1 ft From Buzzer

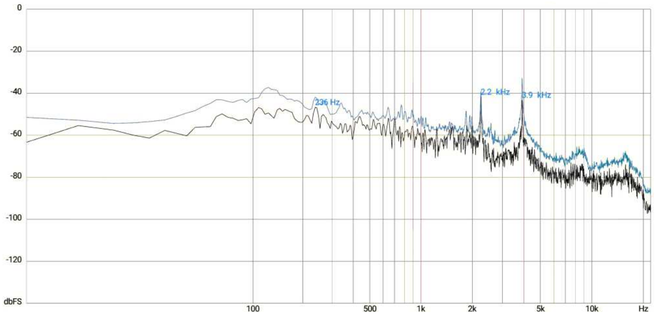
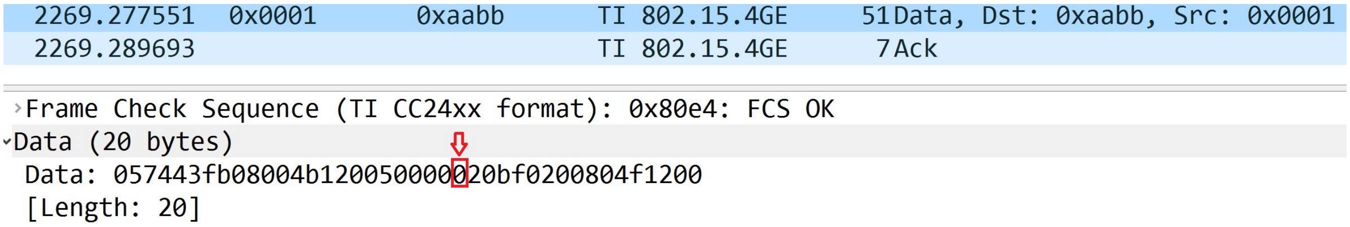


Figure 28. Frequency Response at 5 ft From Buzzer

3.2.2.3 Test Results of Temperature Threshold

For the temperature threshold testing, the temperature is brought down to around 32°F (0°C). The temperature threshold in this particular case is set to 40°F (≈ 4°C). Figure 29 shows the data packet received from the CC1310 once the temperature threshold is crossed.



```
2269.277551  0x0001      0xaabb      TI 802.15.4GE     51Data, Dst: 0xaabb, Src: 0x0001
2269.289693                          TI 802.15.4GE      7Ack

›Frame Check Sequence (TI CC24xx format): 0x80e4: FCS OK
⌄Data (20 bytes)
 Data: 057443fb08004b12005000020bf0200804f1200
 [Length: 20]
```

Figure 29. Temperature Threshold Reached Packet

3.2.2.4 Test Results of Current Consumption

Figure 30 shows the resulting current sensing waveform during a single humidity and temperature reading or transmission. The voltage across the resistor goes up slightly during the transaction between the HDC2010 and the CC1310. After approximately 86 ms, the data is transmitted to the collector board. This results in an initial voltage spike followed by a sharp attenuation back to the steady state. For this event, the data in the target area is averaged to provide a more accurate consumption value. The total acquisition and transmission time for the single HDC2010 packet from the sensor to the collector is measured to be 150 ms.

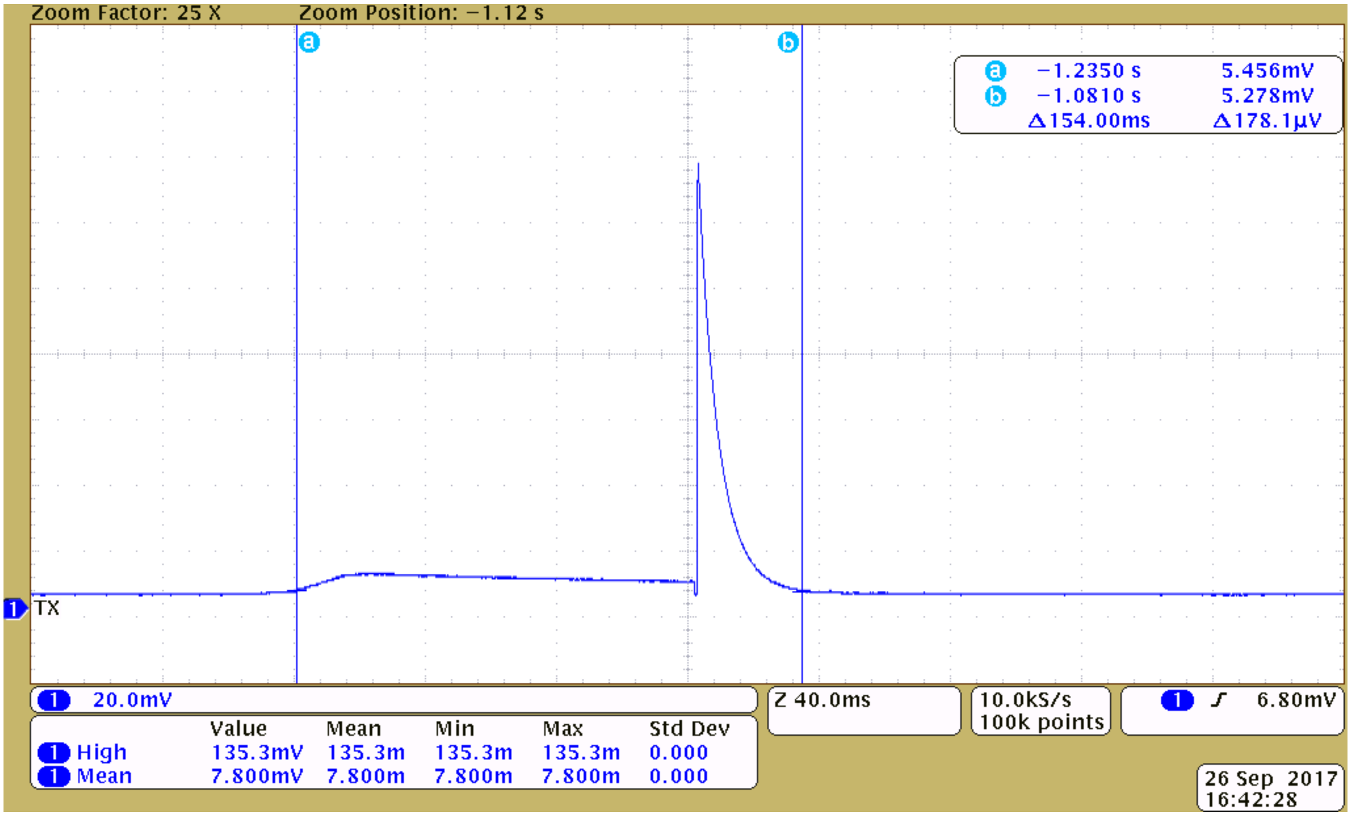
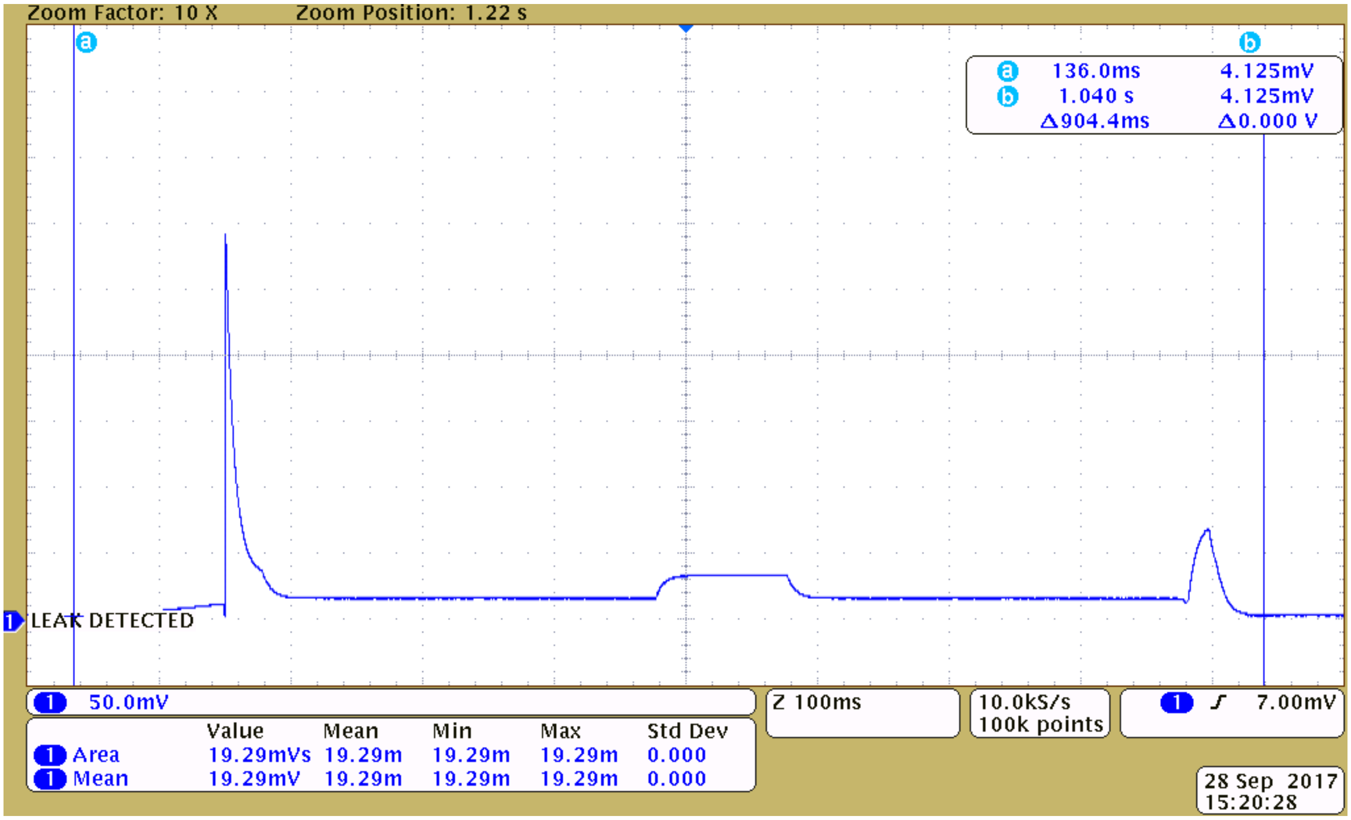


Figure 30. Temperature and Humidity Packet TX Waveform

The leak detection alert current consumption test result is shown in Figure 31. For this test, a leak alert packet is sent in addition to activating the piezoelectric buzzer. The duration of the sequence neglecting the repetition of the buzzer is measured to be 904.4 ms. This also includes the sensor data acquisition period as well. The first peak represents the leak alert transmission and the remaining voltage level shifts are due to the buzzer.



	Value	Mean	Min	Max	Std Dev
1 Area	19.29mVs	19.29m	19.29m	19.29m	0.000
1 Mean	19.29mV	19.29m	19.29m	19.29m	0.000

Figure 31. Leak Detected Packet TX With Active Buzzer Alert

Table 5 represents the collective test results with respect to current consumption of the sensor board (TIDA-01519). The initial boot-up current consumption is measured as well for the users reference, but this is not included in the battery life calculations because this is considered to be a one-time event, which becomes negligible in the estimated battery life calculations.

Table 5. Test Results of TIDA-01518 Current Consumption

BOARD STATUS	AVERAGE MEASURED CURRENT CONSUMPTION
Initial boot-up	35.97 µA
Sleep mode	1.37 µA
Temperature and humidity sensor TX	2.369 mA
Leak detected buzzer and TX	5.85 mA
Configuration packet RX	9.08 mA at 21.52-ms duration

3.2.3 Calculating Battery Life

The main parameters that affect the estimated battery life of the entire system are:

- Capacity rating of the battery in milliamp-hours (mAh)
- Average standby-state current consumption (μA)
- Standby-state duration (s)
- Average packet current consumption (mA)
- Packet transmission duration (ms)
- Polling rate

Using these parameters, the estimated battery life of the system can be calculated using Equation 16:

$$\text{Battery Lifetime}(\text{yr}) = \frac{\text{Battery Capacity}(\text{mAh})}{\left(\frac{I_{\text{Standby}}(\mu\text{A}) \times t_{\text{Standby}}(\text{s}) + I_{\text{Data}}(\mu\text{A}) \times t_{\text{Data}}(\text{s}) + I_{\text{Poll}}(\mu\text{A}) \times t_{\text{Poll}}(\text{s})}{t_{\text{Total}}(\text{s})}\right)} \times \frac{1\,\text{year}}{8760\,\text{hours}} \times \text{Derating Factor} \tag{16}$$

where:

- t_{Total} is an arbitrary time interval
- t_{Data} is the amount of time spent transmitting data packets. In this case, the data packet timing calculations are split into $t_{\text{Data(leak)}}$ and $t_{\text{Data(HDC2010)}}$ to account for the differences in reporting intervals.
- t_{Poll} is the amount of time transmitting poll packets which are used for configuration between the sensor and the collector.

The number of leak threshold events depends entirely on the end-use case. However, for the purpose of this reference design, the following use-case is defined:

- One leak detection event every month
- Polling interval of 30 minutes for configuration packet (t_{Total})

Converting this into the standard form shown in Equation 16 yields:

$$t_{\text{Data(leak)}} = 1\left(\frac{\text{Event}}{\text{Month}}\right) \times \frac{1\,\text{month}}{30\,\text{days}} \times \frac{1\,\text{day}}{24\,\text{hrs}} \times \frac{1\,\text{hr}}{3600\,\text{s}} \times t_{\text{LeakPkt}} \times t_{\text{Total}} \tag{17}$$

Plugging in the duration values found in Section 3.2.2.4, the total time taken to transmit a leak packet over the given interval is:

$$t_{\text{Data(leak)}} = \frac{t_{\text{LeakPkt}}}{1440} = 628.1\,\mu\text{s} \tag{18}$$

Because t_{Total} is set equal to the polling interval (30 min), then t_{Poll} equals the time it takes to send a single poll packet, 21.52 ms. $T_{\text{Data(HDC2010)}}$ can now be calculated as:

$$t_{\text{Data (HDC2010)}} = 6\left(\frac{\text{Events}}{\text{hr}}\right) \times \frac{1\,\text{hr}}{3600\,\text{s}} \times t_{\text{SensorPkt}} \times t_{\text{Total}} \tag{19}$$

where:

- 6 is the number of update event packets per hour, equating to a temperature and humidity reading every 10 minutes
- $t_{\text{SensorPkt}}$ is the amount of time it takes to acquire and send a status update data packet, 154 ms

Using these requirements, the total sensor data acquisition and TX time over the 30-minute interval is:

$$t_{\text{Data (HDC2010)}} = 6\left(\frac{1}{2}\right) \times 154\,\text{ms} = 462\,\text{ms} \tag{20}$$

Inserting these calculated times into Equation 16 yields:

$$\frac{240\,\text{mAh}}{\left(\frac{1.37\,\mu\text{A} \times 1800\,\text{s} + 2.37\,\text{mA} \times 462\,\text{ms} + 9.08\,\text{mA} \times 21.52\,\text{ms} + 5.83\,\text{mA} \times 628.1\,\mu\text{s}}{1800\,\text{s}}\right)} \times \frac{1\,\text{year}}{8760\,\text{hrs}} \times 0.85 \tag{21}$$

Finally, solving for the estimated battery life:

$$\text{Estimated Battery Life} = 11.15 \text{ Years} \tag{22}$$

This yields an estimated battery life that is longer than the shelf life of most coin cell batteries. Because the estimated battery life for this reference design system is above the specified shelf life of typical coin cell batteries, it is possible to increase the transmit power of the CC1310 device to increase range. Alternatively, more processing of the sensor data can be done on the sensor end-node to decrease the burden on the up-stream data processing units.

Another available knob in the optimization of battery life for this reference design is the sensor value acquisition interval for temperature and humidity sensor readings. The default value in the firmware is 10 minutes, but because this value can be modified, the battery life can be improved slightly more if the designer so wishes.

NOTE: To increase battery life, this reference design does not currently implement a frequency hopping scheme. A frequency hopping device loses synchronization if it does not get any collector data/ACK within about 20 minutes for the default 250-ms dwell interval. In frequency hopping mode, an end device tracks the slot boundaries of collector and the synchronization is maintained based on timing information on received Data/ACK. For the default 250-ms dwell time parameter, it is imperative that a data/ACK from collector is received at least once within 20 minutes. It is recommended to either transmit a poll (and received ACK/Data from collector) or data (and receive ACK) within this period.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01518.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01518.

4.3 PCB Layout Recommendations

4.3.1 PCB Antenna Layout Guidelines

The antenna on this reference design is the miniature helical PCB antenna for 868 MHz or 915 MHz. See the application note *Miniature Helical PCB Antenna for 868 MHz or 915/920 MHz* for more details about layout and performance.

4.3.2 HDC2010 Layout Guidelines

The relative humidity sensor element is located on the top side of the package. It is recommended to isolate the sensor from the rest of the PCB by eliminating copper layers below the device (GND, V_{DD}) and creating a slot into the PCB around the sensor to enhance thermal isolation.

Because the relative humidity is dependent on the temperature, the HDC2010 must be positioned away from hot spots present on the board such as a battery, display, or MCU. Slots around the device can be used to reduce the thermal mass for a quicker response for environmental changes.

4.3.3 TPD1E10B06DPYR Layout Guidelines

- The optimum placement is as close to the connector as possible.
  - EMI during an ESD event can couple from the trace being struck to other nearby unprotected traces, resulting in early system failures.
  - The PCB designer must minimize the possibility of EMI coupling by keeping any unprotected traces away from the protected traces, which are between the TVS and the connector.
- Route the protected traces as straight as possible.
- Eliminate any sharp corners on the protected traces between the TVS and the connector by using rounded corners with the largest radii possible.
  - Electric fields tend to build up on corners, increasing EMI coupling.
- If pin 1 or pin 2 is connected to ground, use a thick and short trace for this return path

4.3.4 Layout Prints

To download the layer plots, see the design files at TIDA-01518.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01518.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01518.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01518.

5 Software Files

To download the software files, see the GIT repository of TIDA-01518.

6 Related Documentation

1. Texas Instruments, *Sub-1 GHz Sensor to Cloud Industrial IoT Gateway Reference Design*, TIDEP-0084 Design Guide (TIDUCI9)
2. Texas Instruments, *Reverse Current/Battery Protection Circuits*, Application Report (SLVA139)
3. Texas Instruments,*Coin Cells and Peak Current Draw*, WP001 White Paper (SWRA349)
4. Texas Instruments, *Miniature Helical PCB Antenna for 868 MHz or 915/920 MHz*, DN038 Application Report (SWRA416)
5. Texas Instruments, WEBENCH® Design Center (http://www.ti.com/webench)

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