TI Designs

Humidity and Temperature Sensor Node for Star Networks Enabling 10+ Year Coin Cell Battery Life

TI Designs

TI Designs provide the foundation that you need including methodology, testing and design files to quickly evaluate and customize the system. TI Designs help *you* accelerate your time to market.

Design Resources

TIDA-00374	Tool Folder Containing Design Files
HDC1010	Product Folder
CC2650	Product Folder
TPL5110	Product Folder
TS5A3160	Product Folder
TPD1E10B06	Product Folder

TI E2E™ Community

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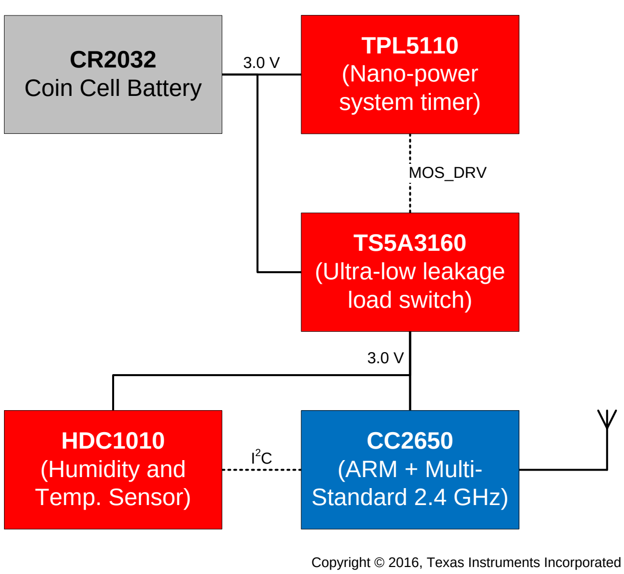
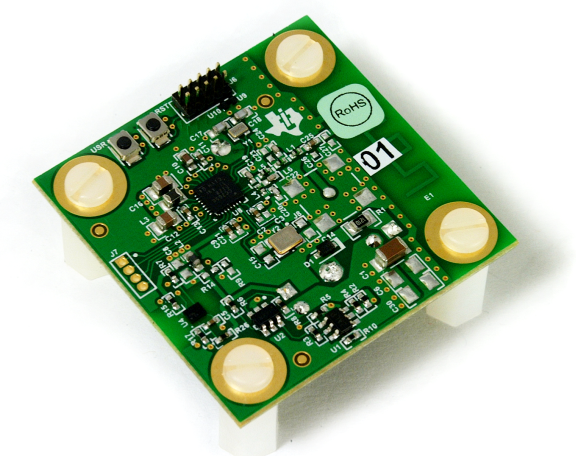
Design Features

- Use of Nano-Power System Timer to Duty-Cycle the System Results in 10+ Year Battery Life from CR2032 Coin Cell
- Configurable System Wakeup Interval
- Extremely Low Off-State Current (183 nA for 59.97 seconds)
- Ultra-Low On-State Current Due to Low Active Processor and Radio Transmit Currents (4.04 mA for 30 ms)
- ±2% Relative Humidity Accuracy
- ±0.2°C Temperature Accuracy

Featured Applications

- Industrial
- Internet of Things (IoT)
- Building Automation
- Intrusion Detection
- HVAC Sensors
- Smart Thermostats and Room Monitors
- Battery Powered Systems





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1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATION	DETAILS
Input power source	CR2032 Lithium-ion coin cell battery (3.0-V nominal voltage)	Section 2.5
Sensor type	Humidity and temperature	Section 2.1
Measurement interval	One measurement per minute	Section 2
Average on-state current consumption	4.04 mA	Section 6.2.1
On-state duration	30.0 milliseconds	Section 6.2.1
Average off-state current consumption	183.01 nA	Section 6.2.2
Off-state duration	59.97 seconds	Section 6.2.2
Estimated battery life	10.58 years	Section 6.2.3
Radio transmission range	430 feet (see DETAILS for test conditions)	Section 6.5
Operating temperature	–30°C to 60°C (limited by CR2032 coin cell operating range)	Section 2.5
Working environment	Indoor and outdoor	Section 2.5
Form factor	1.5×1.5-inch square PCB	Section 5.1

2 System Description

Many industrial, building automation, and IoT systems require increasing numbers of wireless sensor end-nodes. However, one of the major constraints of adding many wireless sensor end-nodes to a system is power. Typical sensor end nodes are powered by batteries, which last from several months to several years, depending on the power consumption of the end node. Replacing batteries can be a very expensive system-level cost, because each end node would require a periodic manual battery replacement.

Enabled by Texas Instruments' nano-power system timer, SimpleLink™ ultra-low power wireless microcontroller (MCU) platform, and humidity sensing technologies, the Humidity and Temperature Sensor Node for Star Networks Enabling 10+ Year Coin Cell Battery Life TI Design demonstrates an ultra-low power method to duty-cycle sensor end nodes leading to extremely long battery life.

At a high level, this TI Design system consists of a CR2032 coin cell battery, a nano-power system timer, an ultra-low power wireless MCU, and a combined humidity and temperature sensor. The nano-power system timer, which consumes tens of nanoamps when operating, controls power to all the remaining circuitry. The nano-power system timer will switch on power to the system at a programmable interval (one measurement per minute in this system), and when the wireless MCU has finished reading and transmitting the sensor data, a signal to the system timer shuts down the entire system. By duty-cycling the entire system in this manner, this TI Design achieves more than ten years of battery life from a CR2032 coin cell.

This design guide addresses component selection, design theory, and test results of the TI Design system. The scope of this design guide gives system designers a head-start in integrating TI's nano-power system timer, SimpleLink ultra-low power wireless MCU platform, and humidity sensing technologies into their end-equipment systems.

The following sub-sections describe the various blocks within the TI Design system and what characteristics are most critical to best implement the corresponding function.

2.1 Humidity and Temperature Sensor

In this TI Design, a digital humidity sensor with an integrated temperature sensor was chosen to demonstrate the ultra-low power duty-cycling power scheme. Humidity and temperature are both common measurements required in many industrial and building automation end-equipment systems. For example, home heating and cooling systems of the future will likely include humidity and temperature measurements in each individual room. With the wireless functionality of the system, this environmental information is sent back to a smart thermostat, which will then control the various air ducts going to each room, providing a much more intelligent home environment by providing individual comfort settings and increasing energy savings.

With a relative humidity accuracy of ±2% and a temperature accuracy of ±0.2°C, the HDC1010 device from Texas Instruments is ideally suited to accurately sense environmental information. The innovative placement of the HDC1010 sensing element on the bottom of the device provides resistance to dust, dirt, and other environmental contaminants, which improves system reliability for applications like heating, ventilation, and air conditioning (HVAC) systems, smart thermostats, and room monitors. Furthermore, the power consumption of the HDC1010 is extremely low, averaging 1.2 µA at one sample per second measurement rate and interfacing to the device is straightforward with any microcontroller platform using the I^2C communication protocol.

2.2 Ultra-Low Power Wireless MCU

In this TI Design, it is necessary to transmit the sensor information to some central location for processing. 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.

With TI's SimpleLink ultra-low power wireless MCU platform, low power with a combined radio and MCU enables extremely long battery life for sensor end nodes. Furthermore, the CC2650 device is a multi-standard device, targeting Bluetooth® Smart, ZigBee® and 6LoWPAN, and ZigBee RF4CE remote control applications. In this TI Design, Bluetooth Smart is the protocol of choice, but the hardware as built can work with other protocols as well.

2.3 Nano-Power System Timer

This TI Design is able to achieve extremely long battery life by means of a nano-power system timer. This type of device is intended to replace the internal timer of any standard microcontroller with a discrete analog system timer that consumes much less power than the microcontroller's internal timer. A nano-power system timer can be used either to bring an MCU out of sleep mode by means of a pin interrupt, or to completely shut off power to the system, in whole, or in part.

In this TI Design, the TPL5110 device was chosen to shut off power completely to the entire system, which reduces the off-state current drawn from the battery to the tens and hundreds of nanoamps. The timer interval is user-selectable by means of a resistor, and can range from 100 ms up to two hours with a typical time base accuracy of 1%. The TPL5110 device controls a low leakage analog switch, described in Section 2.4.

2.4 Low Leakage Analog Switch

In conjunction with a nano-power system timer, described in Section 2.3, this TI Design uses a low leakage analog switch to shut off power to the entire system. The most important characteristic of this switch is the off-state leakage, because that leakage will affect the overall battery life of the system significantly.

In this TI Design, the TS5A3160 device was chosen as the switch used to disconnect the system from the battery. The TS5A3160 has a rated leakage current of ±20 nA at 25°C, which enables extremely long battery life in this system.

2.5 Coin Cell Battery

The power source for this TI Design is a CR2032 lithium-ion coin cell. The selection of the CR2032 coin cell battery as the power source was due to the ubiquity of that battery type, particularly in small form factor systems, such as a sensor end node.

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. At that time, the output voltage drops off relatively quickly.

The temperature characteristics of lithium-ion batteries are also superior to that of alkaline cells, particularly at lower temperatures. This is due to lithium-ion cells having a non-aqueous electrolyte that performs better than aqueous electrolytes commonly found in alkaline batteries.

However, the CR2032 coin cell battery is still the limiting component in terms of operating temperature range; all of the integrated circuits and other electrical components are specified to operate at a wider temperature range than the battery. Therefore, the specified operating temperature range of the TI Design system is –30°C to 60°C. Given an appropriate weather-proof enclosure, this TI Design system is suited for both indoor and outdoor use.

Immediately following the battery is a low forward voltage Schottky diode, a current limiting resistor, and a bulk capacitor. The Schottky diode prevents damage to the hardware if the coin cell battery is inserted backwards. The current limiting resistor in conjunction with the bulk capacitor reduces the current spikes drawn from the battery when the system transitions from off-state to on-state. The bulk capacitor is also sized to prevent too much voltage from being dropped across the current limiting resistor during the on-state.

3 Block Diagram

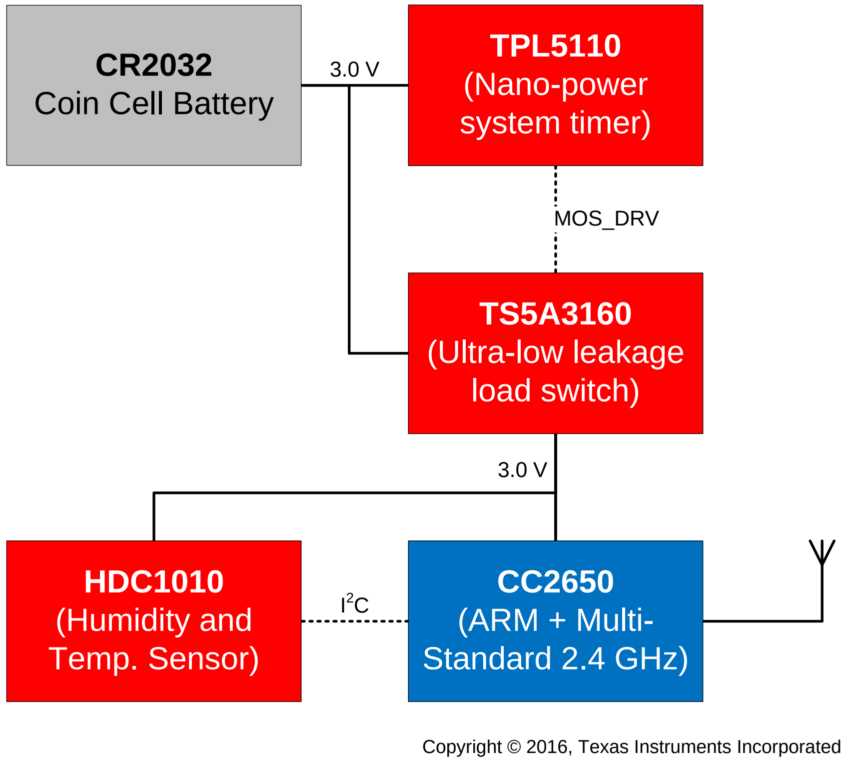

Figure 1. System Block Diagram

3.1 Highlighted Products

The Humidity and Temperature Sensor Node for Star Networks Enabling 10+ Year Coin Cell Battery Life Reference Design features the following devices:

- HDC1010 (Section 3.1.1): Low power, high accuracy digital humidity sensor with integrated temperature sensor
- CC2650 (Section 3.1.2): SimpleLink multi-standard 2.4 GHz ultra-low power wireless MCU
- TPL5110 (Section 3.1.3): Ultra–low-power timer with MOS driver and MOSFET Power ON
- TS5A3160 (Section 3.1.4): 1-Ω SPDT analog switch 5-V/3.3-V single-channel 2:1 multiplexer/demultiplexer
- TPD1E10B06 (Section 3.1.5): Single-channel ESD in a 0402 package with 10-pF capacitance and 6-V breakdown

For more information on each of these devices, see the respective product folders at www.ti.com.

3.1.1 HDC1010

The HDC1010 is a digital humidity sensor with integrated temperature sensor that provides excellent measurement accuracy at very low power. The HDC1010 operates over a wide supply range, and is a low cost, low power alternative to competitive solutions in a wide range of common applications. The innovative Wafer Level Chip Scale Package (WLCSP) simplifies board design with the use of an ultra-compact package. The sensing element of the HDC1010 is placed on the bottom part of the device, which makes the HDC1010 more robust against dirt, dust, and other environmental contaminants. The humidity and temperature sensors are factory calibrated and the calibration data is stored in the on-chip non-volatile memory.

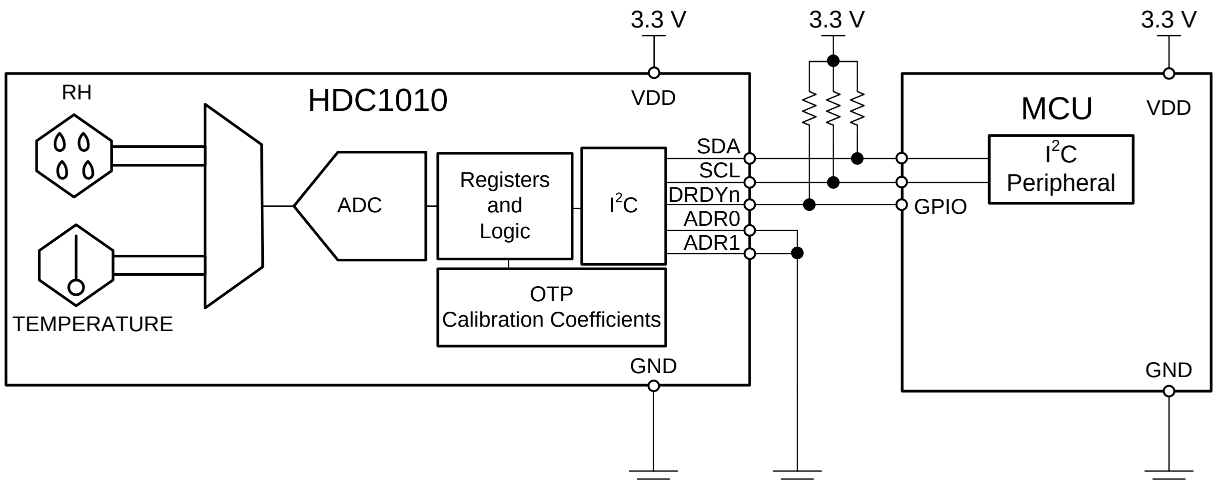

Figure 2. HDC1010 Functional Block Diagram

Features:

- Relative humidity accuracy ±2% (typical)
- Temperature accuracy ±0.2°C (typical)
- Excellent stability at high humidity
- 14-bit measurement resolution
- 100-nA sleep mode current
- Average supply current:
  - 710 nA at 1 sps, 11-bit RH measurement
  - 1.3 µA at 1 sps, 11-bit RH and temperature measurement
- Supply voltage 2.7 to 5.5 V
- Tiny 2-mm×1.6-mm device footprint
- I^{2}C interface

3.1.2 CC2650

The CC2650 is a wireless MCU targeting Bluetooth Smart, ZigBee and 6LoWPAN, and ZigBee RF4CE remote control applications.

The device is a member of the CC26xx family of cost-effective, ultra-low power, 2.4-GHz RF devices. Very low active RF and MCU current and low-power mode current consumption provides excellent battery lifetime and allows operation on small coin cell batteries and in energy-harvesting applications.

The CC2650 contains a 32-bit ARM Cortex®-M3 running at 48-MHz as the main processor and a rich peripheral feature set, including a unique ultra-low power sensor controller, ideal for interfacing external sensors or collecting analog and digital data autonomously while the rest of the system is in sleep mode.

This makes the CC2650 ideal for applications within a whole range of products including industrial, consumer electronics, and medical.

The Bluetooth Low Energy controller and the IEEE 802.15.4 MAC are embedded into ROM and are partly running on a separate ARM Cortex-M0 processor. This architecture improves overall system performance and power consumption and frees up flash memory for the application.

The Bluetooth Smart and ZigBee stacks are available free of charge from www.ti.com.

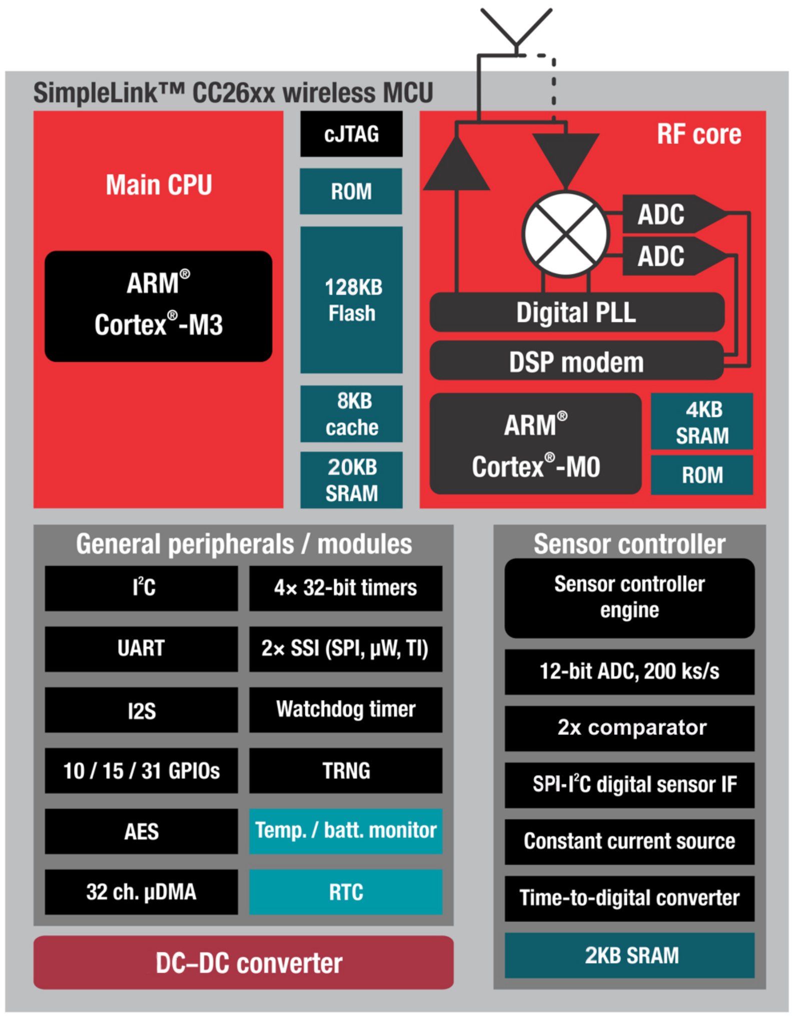

Figure 3. CC2650 Functional Block Diagram

Features:

- Microcontroller
  - Powerful ARM Cortex-M3
  - EEMBC CoreMark® score: 142
  - Up to 48-MHz clock speed
  - 128 KB of in-system programmable flash
  - 8-KB SRAM for cache
  - 20-KB ultra-low leakage SRAM
  - 2-Pin cJTAG and JTAG debugging
  - Supports over-the-air (OTA) upgrade
- Ultra-low power sensor controller
  - Can run autonomous from the rest of the system
  - 16-bit architecture
  - 2-KB ultra-low leakage SRAM for code and data
- Efficient code size architecture, placing drivers, Bluetooth low energy controller, IEEE 802.15.4 MAC, and bootloader in ROM
- RoHS-compliant packages
  - 4×4-mm RSM QFN32 (10 GPIOs)
  - 5×5-mm RHB QFN32 (15 GPIOs)
  - 7×7-mm RGZ QFN48 (31 GPIOs)
- Peripherals
  - All digital peripheral pins can be routed to any GPIO
  - 4 general-purpose timer modules (8 × 16-bit or 4 × 32-bit timer, PWM each)
  - 12-bit ADC, 200-k samples per second, 8-channel analog MUX
  - Continuous time comparator
  - Ultra-low power analog comparator
  - Programmable current source
  - UART
  - 2× SSI (SPI, µW, TI)
  - I^2C
  - I2S
  - Real-time clock (RTC)
  - AES-128 security module
  - True random number generator (TRNG)
  - 10, 15, or 31 GPIOs, depending on package option
  - Support for eight capacitive sensing buttons
  - Integrated temperature sensor
- External system
  - On-chip internal DC-DC converter
  - Very few external components
  - Seamless integration with the SimpleLink CC2590 and CC2592 range extenders
  - Pin compatible with the SimpleLink CC13xx in 4×4-mm and 5×5-mm QFN packages

- Low power
  - Wide supply voltage range
    - Normal operation: 1.8 to 3.8 V
    - External regulator mode: 1.7 to 1.95 V
  - Active-mode RX: 5.9 mA
  - Active-mode TX at 0 dBm: 6.1 mA
  - Active-mode TX at 5 dBm: 9.1 mA
  - Active-mode MCU: 61 µA/MHz
  - Active-mode MCU: 48.5 CoreMark/mA
  - Active-mode sensor controller: 8.2 µA/MHz
  - Standby: 1 µA (RTC running and RAM/CPU retention)
  - Shutdown: 100 nA (wakeup on external events)
- RF section
  - 2.4-GHz RF transceiver compatible with BLE 4.1 specification and IEEE 802.15.4 PHY and MAC
  - Excellent receiver sensitivity (–97 dBm for BLE and –100 dBm for 802.15.4), selectivity, and blocking performance
  - Programmable output power up to 5 dBm
  - Single-ended or differential RF interface
  - Suitable for systems targeting compliance with worldwide radio frequency regulations
    - ETSI EN 300 328 (Europe)
    - EN 300 440 Class 2 (Europe)
    - FCC CFR47 Part 15 (US)
    - ARIB STD-T66 (Japan)
- Tools and development environment
  - Full-feature and low-cost development kits
  - Multiple reference designs for different RF configurations
  - Packet sniffer PC software
  - Sensor controller studio
  - SmartRF™ studio
  - SmartRF flash programmer 2
  - IAR Embedded Workbench® for ARM®
  - Code Composer Studio™

3.1.3 TPL5110

The TPL5110 Nano-Power System Timer is a low power timer with an integrated MOSFET driver ideal for power gating in duty cycled or battery powered applications. Consuming only 35 nA, the TPL5110 can enable the power supply line and drastically reduce the overall system stand by current during the sleep time. Such power savings enable the use of significantly smaller batteries making it well suited for energy harvesting or wireless sensor applications. The TPL5110 provides selectable timing intervals from 100 ms to 7200 s and is designed for power gating applications. In addition, the TPL5110 has a unique one-shot feature where the timer will only power the MOSFET for one cycle. The TPL5110 is available in a 6-pin SOT23 package.

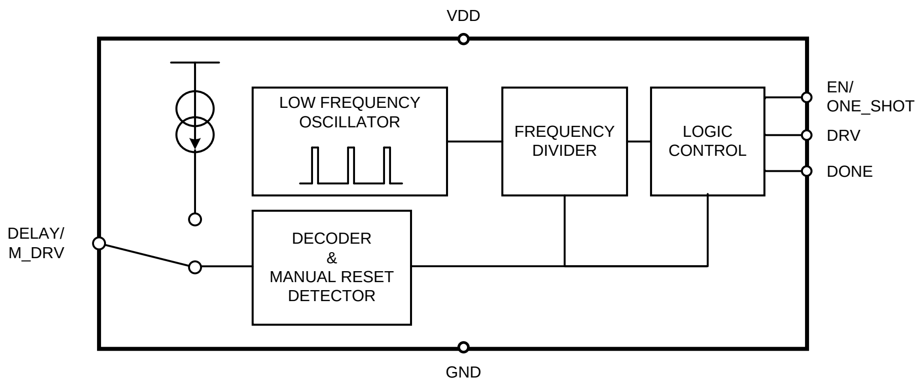

Figure 4. TPL5110 Functional Block Diagram

Features:

- Supply voltage: 1.8 to 5.5 V
- Current consumption: 2.5 V, 35 nA (typ)
- Selectable time intervals: 100 ms to 7200 s
- Timer accuracy: 1% (typ)
- Resistor selectable time interval
- Manual MOSFET power on
- One-shot feature

3.1.4 TS5A3160

The TS5A3160 is a single-pole double-throw (SPDT) analog switch that is designed to operate from 1.65 to 5.5 V. The device offers a low ON-state resistance and an excellent channel-to-channel ON-state resistance matching. The device has excellent total harmonic distortion (THD) performance and consumes very low power. These features make this device suitable for portable audio applications.

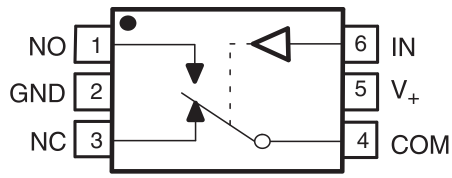

Figure 5. TS5A3160 Package Diagram

Features:

- Isolation in the powered-off mode, $V_+ = 0$
- Specified make-before-break switching
- Low ON-state resistance (1 Ω)
- Control inputs are 5.5-V tolerant
- Low charge injection
- Excellent ON-state resistance matching
- Low THD
- 1.65- to 5.5-V single-supply operation
- Latch-up performance exceeds 100 mA Per JESD 78, Class II
- ESD performance tested per JESD 22
  - 2000-V human-body model (A114-B, Class II)
  - 1000-V charged-device model (C101)

3.1.5 TPD1E10B06

The TPD1E10B06 is a single channel ESD protection device in a small 0402 package. The device offers over ±30-KV IEC air-gap, over ±30-KV contact ESD protection, and has an ESD clamp circuit with a back-to-back diode for bipolar or bidirectional signal support. The 10-pF line capacitance is suitable for a wide range of applications supporting data rates up to 400 Mbps. Typical application areas of the TPD1E10B06 include audio lines (microphone, earphone and speaker phone), SD interfacing, keypad or other buttons, and VBUS pins of USB ports (ID).

The 0402 package is industry standard and convenient for component placement in space saving applications. The TPD1E10B06 is characterized for operation over ambient air temperature of –40°C to 125°C.

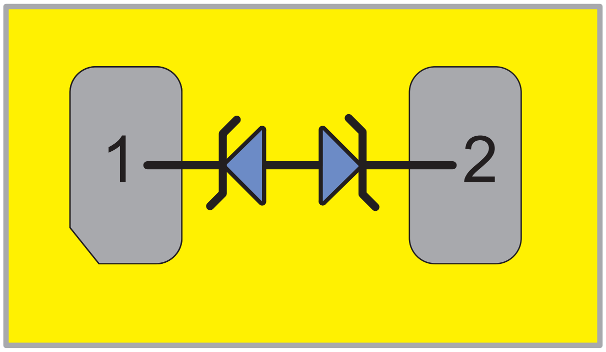

Figure 6. TPD1E10B06 Device Configuration

Features:

- Provides system-level ESD protection for low-voltage I/O interface
- IEC 61000-4-2 Level 4
  - >±30kV (air-gap discharge)
  - >±30kV (contact 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 (min)
- Ultra-low leakage current: 100 nA (max)
- 10-V clamping voltage (max at I_{PP} = 1 A)
- Industrial temperature range: –40°C to 125°C
- Space-saving 0402 footprint (1 × 0.6 × 0.5 mm)

4 System Design Theory and Considerations

The Humidity and Temperature Sensor Node for Star Networks Enabling 10+ Year Coin Cell Battery Life TI Design measures the ambient relative humidity and temperature and achieves an extremely long battery life through the use of duty-cycling with a nano-power system timer. The TPL5110 device controls when the TS5A3160 device switches the battery on and off to the entire system. Because the on-state, or the time when the CC2650 and HDC1010 have power, is very short, and the off-state current consumption from the coin cell battery is very low, the estimated battery life is very long.

4.1 Duty-Cycled Power Design Theory

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

- Capacity rating of the battery in milliamp-hours (mAh)
- Average off-state current consumption (nA)
- Off-state durations
- Average on-state current consumption (mA)
- On-state durations

Equation 1 describes the estimated battery life of the system in units most convenient to this TI Design:

$$\text{Battery life (years)} = \frac{\text{Battery capacity (mAh)}}{\left(\dfrac{I_{on}(\text{mA}) \times t_{on}(\text{s}) + I_{off}(\text{nA}) \times t_{off}(\text{s}) \times 10^{-6}}{\left(t_{on}(\text{s}) + t_{off}(\text{s})\right)}\right)} \times \frac{1\text{ year}}{8760\text{ hours}} \times 85\%\text{ derating factor} \quad (1)$$

Based on Equation 1, optimizing several factors will lead to a longer battery life:

- Longer t_{off}
- Shorter t_{on}
- Lower I_{on}
- Lower I_{off}

t_{off} is completely controllable by the end user. In this TI Design, a value of 1 minute was chosen for the TPL5110 wakeup interval, leading to T_{off} of the following form:

$$t_{off} = 1\text{ minute} - t_{on} \quad (2)$$

Equation 2 indicates that the system will wake up once a minute to measure the ambient relative humidity and temperature and transmit a Bluetooth Smart packet with that data.

t_{on} is somewhat less controllable, because there is some minimum amount of time required to power up the system, take the measurement from the HDC1010 device, transmit the packet, and shut down again. The HDC1010 device has a specified t_{wait} after power up before anything can be done, along with a t_{conv}, which is the time it takes to convert the humidity and temperature measurements. There is also the time required to perform the I^2C transactions between the CC2650 and HDC1010 devices as well as the time it takes to transmit the data packet from the CC2650 device.

I_{on} is defined as the average current consumed from the battery during the on-state. The majority of this current is attributed to the CC2650 device. The main processor core of the CC2650 device is running at 48 MHz. However, the CC26xx line of SimpleLink ultra-low power wireless MCUs is especially designed to consume very little current, even during radio transmission. At 0-dBm transmit power, the CC2650 is specified to consume a typical 6.1 mA of current, well below other available wireless microcontrollers. The HDC1010 device also consumes current during the on-state, but the amount is minimal compared to the CC2650 device.

I_{off} is defined as the average current consumed from the battery during the off-state. This current is comprised primarily of the leakage through the TS5A3160 analog switch, the operating current of the TPL5110 nano-power system timer, and the current required to re-charge the bulk capacitor that is placed near the CR2032 coin cell battery, as well as the steady-state leakage current through that same bulk capacitor.

In this TI Design, the bulk capacitor near the coin cell battery is required to prevent voltage sag during the on-state, and recharging itself from the battery during the off-state. However, this means that the bulk capacitor is connected to the coin cell battery all the time, and thus, must have a very low leakage current. The exact capacitor chosen for this system is manufactured by TDK Corporation (part number: C3216X5R1A107M160AC), and has a measured leakage current of 8.33 nA with 3.0-V applied voltage, as measured by TDK Corporation engineers. The value of 100 μF was chosen to provide adequate energy storage to handle the on-state current requirements of the CC2650 and HDC1010 devices.

Section 6.2 has more details about the battery life performance of this TI Design.

4.2 Wireless Network Design Theory

Because the power is completely cut off from the CC2650 wireless MCU, this TI Design is intended to be used in a star network configuration. This means that each sensor end-node connects directly to a central receiver, which receives the data from each end-node, and then performs any necessary processing and connection to the cloud. This implies that this TI Design is not intended for use in smart mesh networks, because the wireless microcontroller will not retain its state or have any control over when it wakes up.

The TI Design as released sends out non-connectable advertisement packets that contain four bytes of data: two bytes of temperature data and two bytes of relative humidity data. This data is transmitted directly as the HDC1010 device outputs it; no post-processing or correction is implemented on the CC2650 device itself.

The antenna on this TI Design is the small size 2.4-GHz PCB antenna. See the application note AN043 [6] for more details about layout and performance.

4.3 Firmware Control

The firmware for this TI Design is based on the packet error rate (PER) test software program. This program is demo software that is primarily used to perform radio power benchmarking, range testing, and multi-protocol testing. The PER test software is built on TI-RTOS, and has been modified to send out non-connectable *Bluetooth* Smart advertisement packets. These packets contain four bytes of data directly from the HDC1010 device. I^2C drivers have also been added to the PER test software to enable communication with the HDC1010 device.

Finally, after the packet with the HDC1010 data has been sent, the CC2650 device is programmed to pull a GPIO high; this GPIO is connected to the DONE pin of the TPL5110 device. When the TPL5110 device receives a high level on the DONE pin, the TS5A3160 device is signaled to open the connection between the coin cell battery and the rest of the circuit.

5 Getting Started

5.1 Hardware Overview

The Humidity and Temperature Sensor Node for Star Networks Enabling 10+ Year Coin Cell Battery Life TI Design hardware is shown in Figure 7 and Figure 8. The PCB is in a 1.5×1.5-inch square form factor, and comes with 0.5-inch nylon standoffs to ensure ease of use while performing lab measurements.

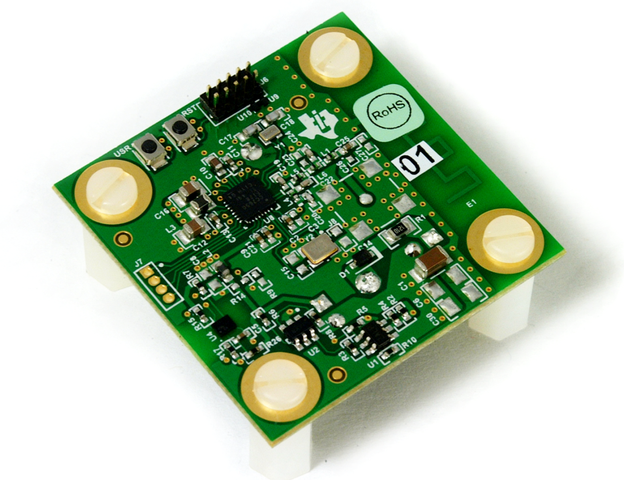

Figure 7. Humidity and Temperature Sensor Node for Star Networks Enabling 10+ Year Coin Cell Battery Life Reference Design Hardware (Top View)

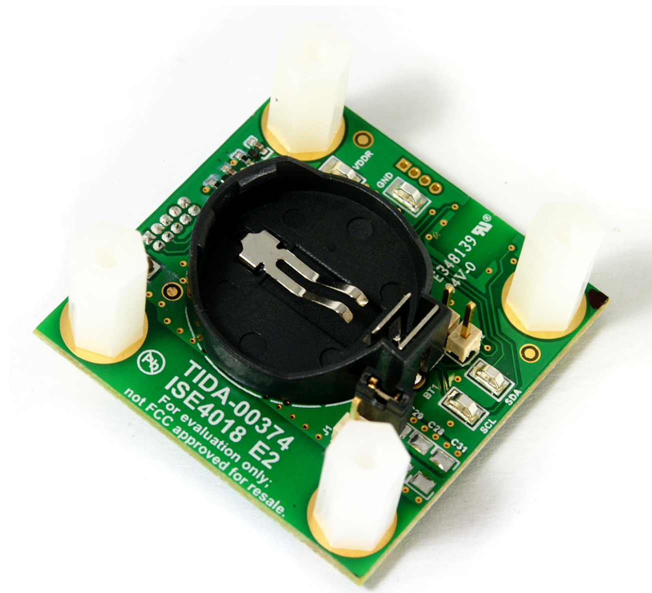

Figure 8. Humidity and Temperature Sensor Node for Star Networks Enabling 10+ Year Coin Cell Battery Life Reference Design Hardware (Bottom View)

All of the integrated circuits (CC2650, TPL5110, TS5A3160, and HDC1010) are located on the top side of the PCB. The 2.4-GHz antenna is also located on the top side of the PCB.

The bottom side of the PCB contains the CR2032 coin cell battery holder; several test points and jumpers as well as the ESD protection devices for the programming header.

There are four unused GPIOs that have been brought out from the CC2650 device to an unpopulated header to facilitate future prototyping and debugging.

5.2 Loading the Firmware

The firmware used on this TI Design was developed using TI's Code Composer Studio software (version 6.1.0). The IAR Embedded Workbench for ARM also supports the CC26xx line of SimpleLink products (www.iar.com).

To program or debug the TI Design hardware, it is necessary to close J2 with a jumper shunt; this bypasses the TS5A3160 analog switch. If J2 is left open, then the TPL5110 device will continue to control the power of the CC2650 device, preventing proper programming and debugging.

Also, it is necessary to power the board from 3.0 V, supplied at pin 2 of J1. Connecting the external power source at this location bypasses the Schottky diode and current limiting resistor. If power is supplied directly at the battery holder, either from a coin cell or a bench power supply, the CC2650 device will likely draw enough current during programming to drop the supply voltage because of the Schottky diode and current limiting resistor, which will likely result in the CC2650 device becoming "bricked" or unusable.

NOTE: For programming the TI Design hardware, shunt J2 and provide 3.0 V at pin 2 of J1. See Figure 9 for a photo of the correct setup for programming or debugging the TI Designs hardware.

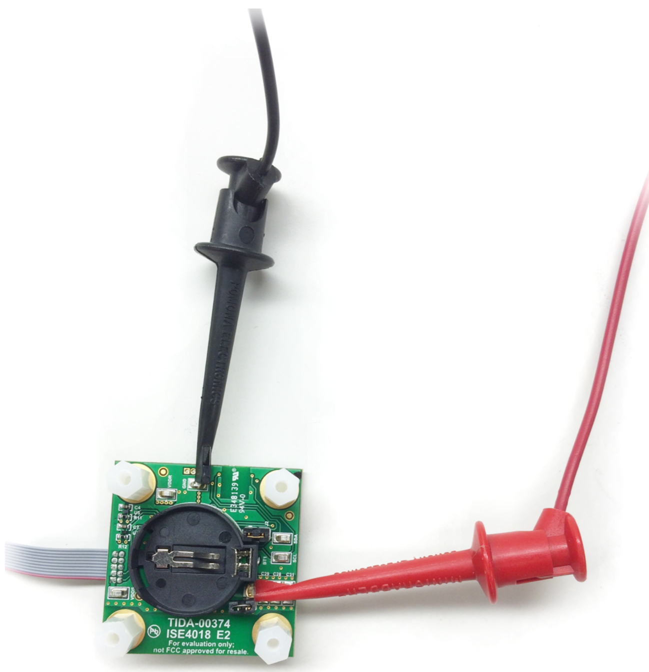

Figure 9. Configuration of Jumpers and Power for Programming and Debugging

The TI Design hardware is programmed by connecting the 10-pin mini ribbon cable from J6 to the SmartRF06 Evaluation Board (10-pin ARM Cortex Debug Connector, P418). See Figure 10 for a photo of the correct setup for connecting the TI Designs hardware to the SmartRF06 evaluation board.

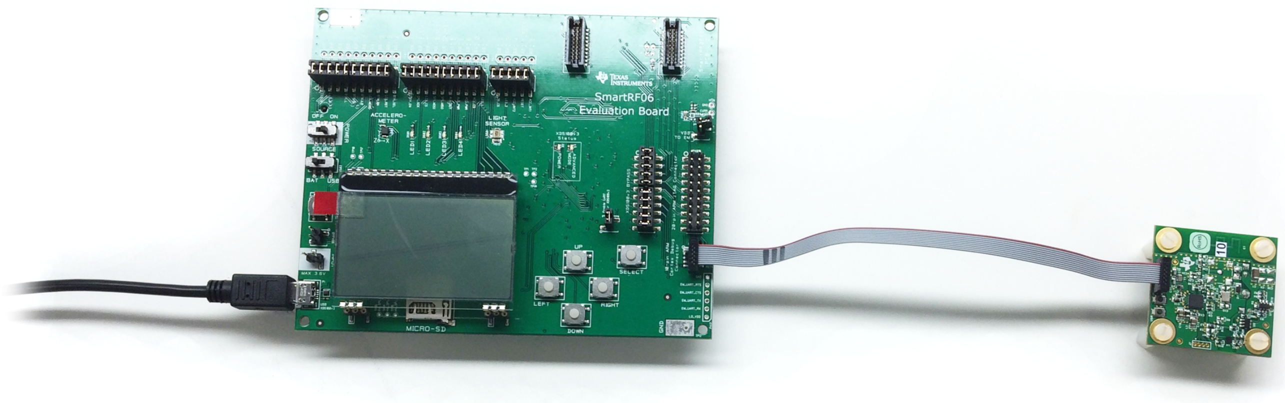

Figure 10. Connection of SmartRF06 Evaluation Board and TI Designs Hardware for Programming/Debugging

5.3 Receiving Data Packets Using CC2540EMK-USB and SmartRF Protocol Packet Sniffer

As described elsewhere, this TI Design is programmed to read the relative humidity and temperature data from the HDC1010 device, and then broadcast that data as a *Bluetooth* Smart non-connectable advertisement packet. The data payload consists of two bytes of temperature data, followed by two bytes of relative humidity data.

To verify the proper operation of the radio transmission, the CC2540EMK-USB CC2540 USB Evaluation Module Kit is used to "sniff" packets using the SmartRF Protocol Packet Sniffer software. After installing the Packet Sniffer software (v2.18.1 at the time of writing), the procedure is as follows to detect the data transmissions:

1. Plug the CC2540EMK-USB into an unused USB port on the computer with the Packet Sniffer software installed.
2. Open the Packet Sniffer software; choose "Bluetooth Low Energy" as the protocol and hit *Start*.

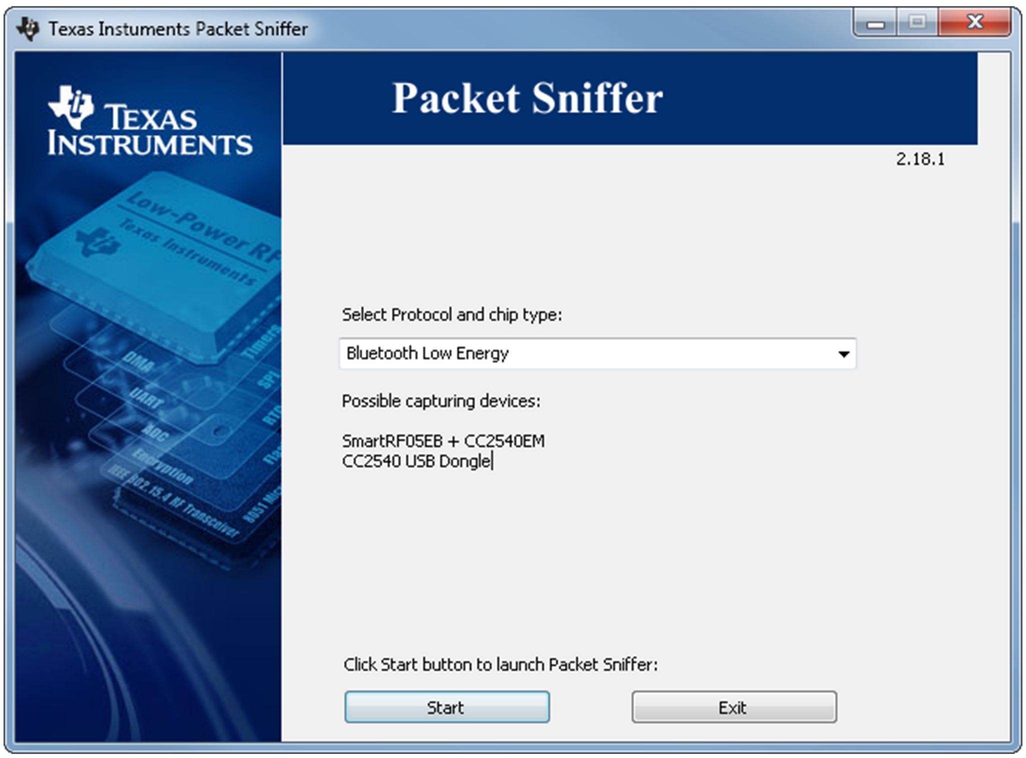

Figure 11. Packet Sniffer Start-up Dialog

3. Click the "Radio Configuration" tab on the bottom toolbar and select "39" for the Advertising Channel.
4. Press the *Play* button on the top toolbar to initiate the packet capture process.

5. There will likely be many other packets detected, probably from mobile phones and other devices that use the Bluetooth Smart protocol. To view only the packets sent from the TI Design hardware, apply a display filter. Figure 12 shows a sample display of what will be recorded with no filter applied. The highlighted row shows the desired data packet in the midst of other, undesired data packets.

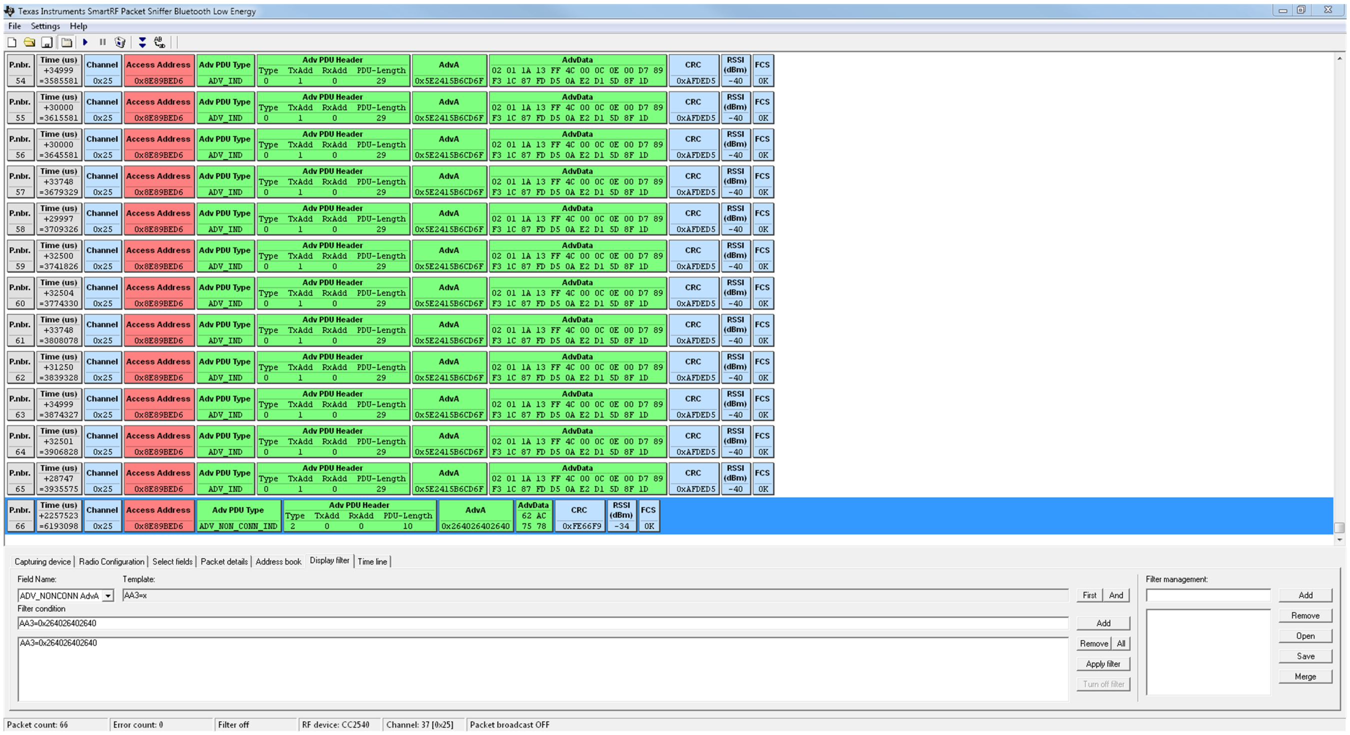

Figure 12. Packet Sniffer With No Display Filter Applied

6. The appropriate filter checks for non-connectable advertisement packets with ADV_NONCONN AdvA field equal to 0x264026402640. In *Field Name*, select "ADV_NONCONN AdvA" from the drop down options. Click the *First* button. Modify the filter condition to the correct address, hit *Add*, and then click *Apply filter*. Figure 13 shows an example filtered view.

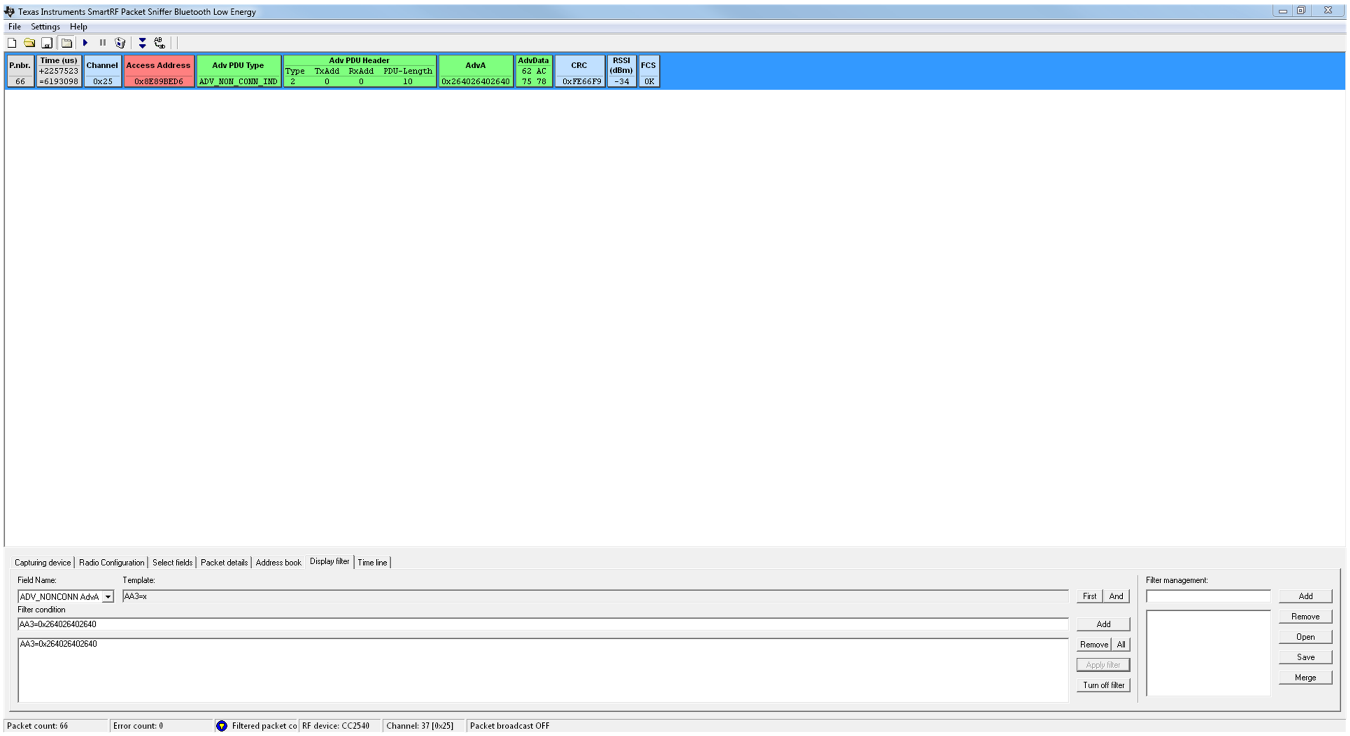

Figure 13. Packet Sniffer With Appropriate Display Filter Applied

7. To export the captured, filtered packets, press the *Save the current session* button on the toolbar, or pause the packet capture and click *File → Save data…*; either of these choices will prompt to save the displayed data as a packet sniffer data (.psd) file.
8. Using the HxD (http://mh-nexus.de/en/hxd/) hex editor software, open the .psd file. Click *View → Bytes per Row*, and enter "271"; click *Ok*. A different hex editor may perform this function as well; however, the authors of this document have not verified any other options.
9. Click *File → Export → Editor View*; this produces a text file that can then be imported into Microsoft® Excel® for further analysis. For more information on the sniffer data packet format, click *Help → User Manual* on the Packet Sniffer software.

6 Test Data

NOTE: Unless otherwise noted, the test data in the following sections was measured with the system at room temperature.

NOTE: All of the measurements in this section were measured with calibrated lab equipment.

6.1 Overview

The Humidity and Temperature Sensor Node for Star Networks Enabling 10+ Year Coin Cell Battery Life TI Design has been characterized for functional usage including power consumption, relative humidity performance, temperature performance, and radio transmission range.

The results of testing and characterization are shown in the following sections. Any plots of the HDC1010 device's output data was produced using data packets captured using a CC2540EMK-USB evaluation module kit and SmartRF Protocol Packet Sniffer software, as described in Section 5.3, with data formatting and analysis performed using Microsoft Excel.

6.2 Power Consumption

Because the primary purpose of this TI Design is to showcase a power topology for battery-powered wireless sensor end-nodes, characterization of the system's power consumption is critical.

As described in Section 4.1, there are two states that this TI Design system is in: on-state and off-state. Both the duration and the average current of each state are factors in estimating the total battery life of the TI Design system.

The on-state consists of the timer interval of the TPL5110 expiring, resulting in the TS5A3160 analog switch connecting the battery to the rest of the system. The CC2650 device receives power, communicates with the HDC1010 device using I^2C, receives the current temperature and relative humidity information, transmits a non-connectable advertisement packet with that data, and then signals the TPL5110 that the system can be shut back down.

The off-state consists of the rest of the system (CC2650 and HDC1010) being completely disconnected from the coin cell battery by means of the TS5A3160 analog switch. The sources of off-state current consumption from the coin cell battery are the recharging and leakage currents due to the bulk capacitor near the coin cell, the operating current of the TPL5110 nano-power system timer device, and the leakage current due to the TS5A3160 analog switch.

6.2.1 On-State Power Characterization

The on-state duration and average current was characterized with the use of a Tektronix MDO3024 Mixed Domain oscilloscope and a Tektronix TCP0030A current probe. The oscilloscope was connected directly to a laptop through a USB cable with the corresponding software to directly export the recorded data points. Figure 11 shows the current drawn from the coin cell battery, as measured through jumper J1. Because there is the 100-µF bulk capacitor and 12.1-Ω resistor in series with the battery, the current profile has a slight low-pass filtered effect.

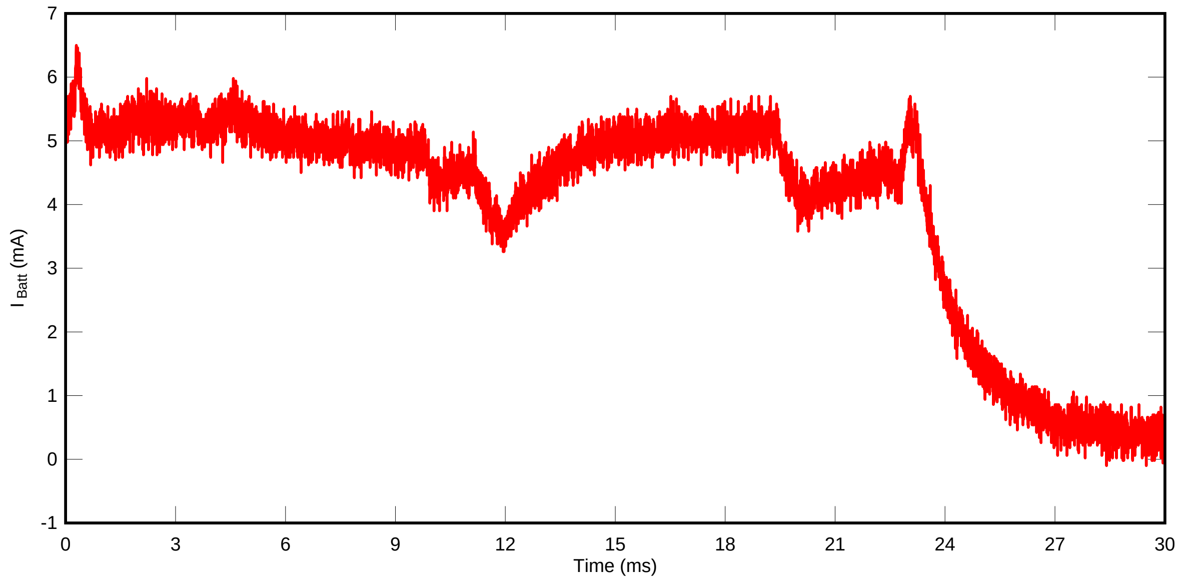

Figure 14. On-State Current versus Time

At time t = 0 ms, the TPL5110 device has activated, and immediately the current jumps up to about 6.5 mA. The current draw then quickly settles to approximately 5 mA for the remainder of the on-state.

At about time t = 24 ms, the current drawn from the battery starts to decay in an RC-sort of pattern, which is due to the recharging of the bulk capacitor, which has been providing energy to the CC2650 and HDC1010 devices during the on-state. This is the point at which the TPL5110 device has been given the DONE signal by the CC2650 device, indicating that the system has successfully transmitted the data packet containing the HDC1010 device output data.

The on-state is considered complete at 30 ms, when the current level drops below the accuracy of the current probe in use. By exporting the data into Excel for analysis, it was determined that the average current over the first 30 ms of system operation was 4.038 mA. This is considered the average on-state current of the TI Design system.

6.2.2 Off-State Power Characterization

The off-state duration and average current was characterized with the use of a Keysight (Agilent) 34401A Digital Multimeter (DMM) with 6½ digits of resolution. The DMM was connected directly to a laptop with the corresponding software to directly export the recorded data points. Figure 15 shows the current drawn from the coin cell battery as measured through jumper J1.

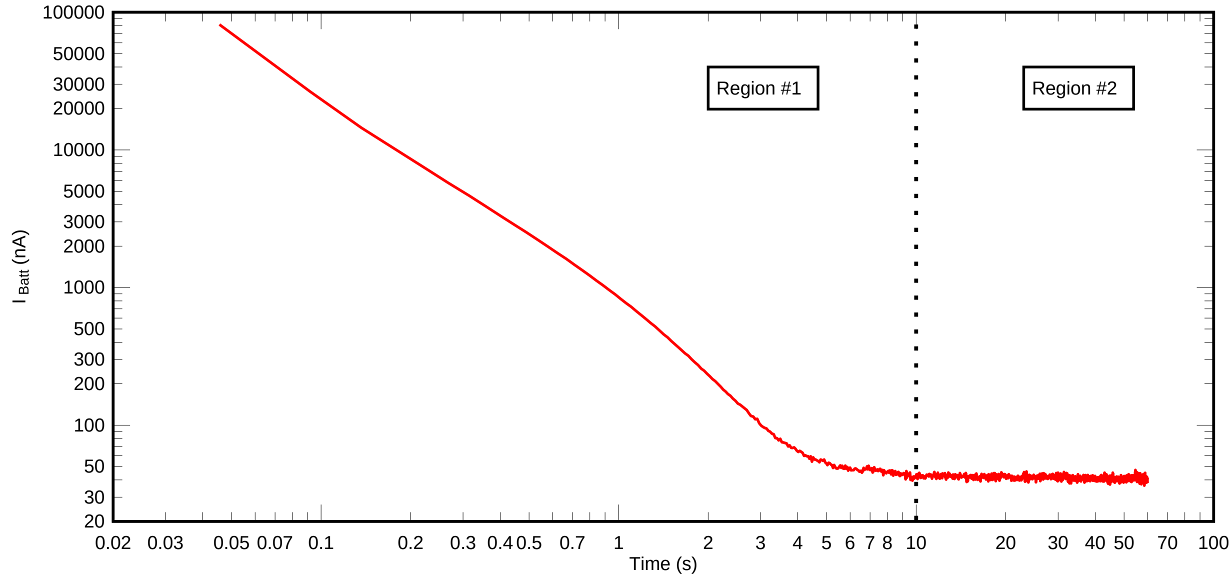

Figure 15. Off-State Current versus Time

The data has been plotted logarithmically on both the x and y axes because the first portion of the plot, labeled "Region 1", has a much higher current and shorter time duration than that of "Region 2".

Region 1 is actually the portion of the off-state where the bulk capacitor is continuing to recharge directly from the coin cell. The first data point occurs at approximately 45 ms after the system first powers up, and then is essentially complete after 10 seconds. The average current over Region 1 is 890.03 nA.

The off-state current during Region 2 is dominated by the operating current of the TPL5110 device, which is specified to have a typical value of 35 nA, and a maximum value of 50 nA with a supply current of 2.5 V. The supply current in this TI Design system is nominally 3.0 V, and in practice can be somewhat higher (3.2 to 3.3 V), depending on the age of the coin cell in use. As mentioned previously, the leakage current of both the bulk capacitor (~8.33 nA) and the TS5A3160 analog switch (±20 nA) will also contribute to the off-state current during Region 2. Given the expected values of the sources of off-state current, the measured average value of 41.60 nA during Region 2 is quite reasonable.

Averaged over the entire duration of Regions 1 and 2, the off-state current is equal to 183.01 nA, and lasts for a duration of 1 minute – 30 ms = 59.970 seconds.

6.2.3 Estimated Battery Life Calculations

As shown in Section 4.1, Equation 1, used for estimating battery life of the TI Design system, has five parameters:

- Capacity rating of the battery in milliamp-hours (mAh)
- Average off-state current consumption (nA)
- Off-state duration (s)
- Average on-state current consumption (mA)
- On-state duration (s)

The battery used in this TI Design, as stated previously, is a CR2032 lithium-ion coin cell, which has a capacity rating of 240 mAh. There is a built-in de-rating factor of 85%, which attempts to model the effects of varying temperatures, as well as battery self-leakage.

When using the measured values for the remaining parameters, the battery life calculation appears as Equation 3:

$$\text{Battery Life (years)} = \frac{240\ \text{mAh}}{\left(\frac{4.038\ \text{mA} \times 0.03\ \text{s} + 183.01\ \text{nA} \times 59.97\ \text{s} \times 10^{-6}}{0.03\ \text{s} + 59.97\ \text{s}}\right)} \times \frac{1\ \text{year}}{8760\ \text{hours}} \times 85\% = 10.58\ \text{years} \quad (3)$$

This battery calculation has one caveat: the estimated battery life uses the value of 240 mAh for battery capacity. According to the Energizer CR2032 datasheet, this lifetime is calculated by the capacity at which the battery voltage drops to 2.0 V. However, in the current system, the HDC1010 device has a minimum rated voltage of 2.7 V. Therefore, the actual capacity of this system is more approximately 200 mAh, which leads to an estimated battery life of 8.81 years.

The result of this finding is that it is most desirable to have all components, including the sensor and any required analog front-end work down to 1.8 V. This enables a complete depletion of the coin cell battery, ensuring the longest possible battery life.

6.2.4 Duty-Cycled System Tradeoffs

This TI Design is based around the concept that by duty-cycling the system with a nano-power system timer, the off-state current can be lowered beyond that of what any inherent sleep mode of the remaining components can achieve. It follows that a comparison between a system using this concept and one that does not use this concept would be valuable, because there are various situations where either system topology could make sense.

If it is assumed that the on-state current and duration remain fixed for both types of system topologies, it is possible to compare the two. By varying the wakeup interval, there will be certain scenarios where it makes more sense to use the built-in standby mode of the CC2650 device, rather than using the TPL5110 device. The assumption is that by using the built-in standby mode of the CC2650 device, the off-state current goes from 183.01 nA up to approximately 1 µA. Also, a reference line is displayed with a level of 10 years, a common shelf life of coin cell batteries.

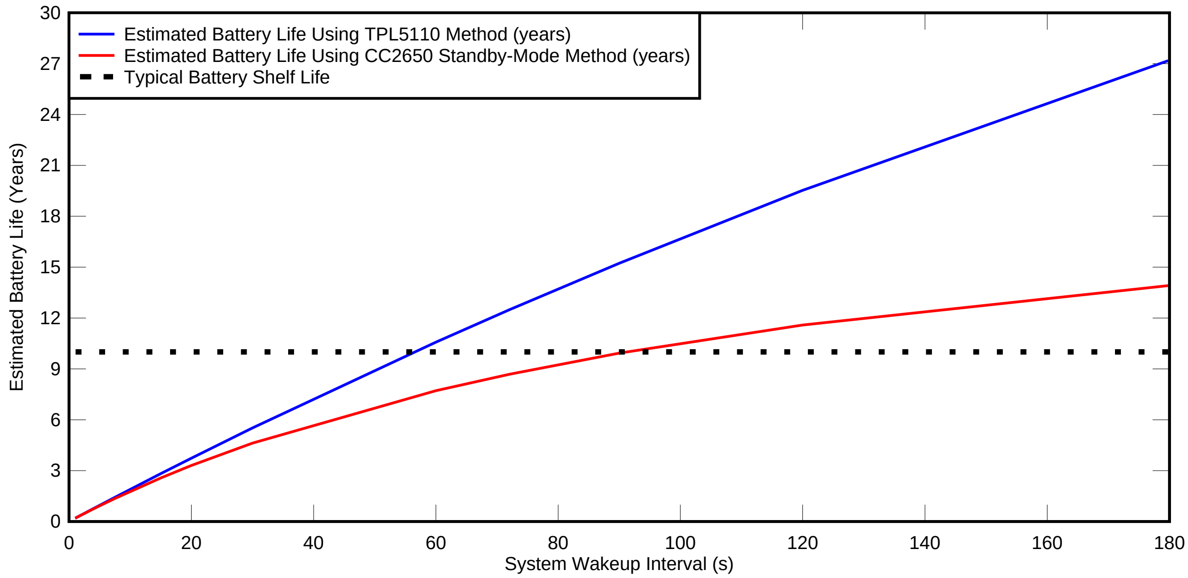

Figure 16. Estimated Battery Life Comparison: TPL5110 Nano-Power System Timer versus CC2650 Standby Mode

However, as Figure 16 shows, the system using the TPL5110 device to duty-cycle the system will always have a better estimated battery life. The only scenario where the use of a TPL5110 device to create a duty-cycled sensor end-node is not practical is if the wireless network is a sleeping mesh network. In this case, the CC2650 device would need to be in control of its own sleep state to maintain network communications. Furthermore, additional load switches would likely need to be added to the system to ensure that quiescent or standby currents of any other sensors or devices in the system are minimized during the off-state, which could potentially increase the system cost and complexity.

That being said, once the wakeup interval exceeds approximately two minutes, both methods should provide more than enough battery life to exceed the typical battery shelf life of 10 years, which is common to many coin cell vendors.

If the end-equipment system has different requirements for the on-state current and duration, this calculation could change significantly, and these calculations should be re-run to see what sort of system topology makes the most sense to achieve the longest battery life possible.

6.3 Relative Humidity Characterization

This TI Design exemplifies the concept of a duty-cycled sensor end node through the use of the HDC1010 device, which measures both relative humidity and temperature.

To get an idea of how the TI Design system responded to varying relative humidity levels, the hardware was placed in a Thunder Scientific Model 2500 Benchtop Humidity Generator (http://www.thunderscientific.com/) with a brand new Energizer® CR2032 lithium-ion coin cell battery. The CC2540EMK-USB CC2540 USB Evaluation Module Kit was plugged into a USB extension cord and placed next to the TI Design hardware for optimal data packet reception performance. A Rotronic© HC2-S precision humidity and temperature probe (http://www.rotronic.com) and Rotronic Hygro Flex HF53 transmitter was used to provide reference relative humidity and temperature measurements. The test setup is shown in Figure 17.

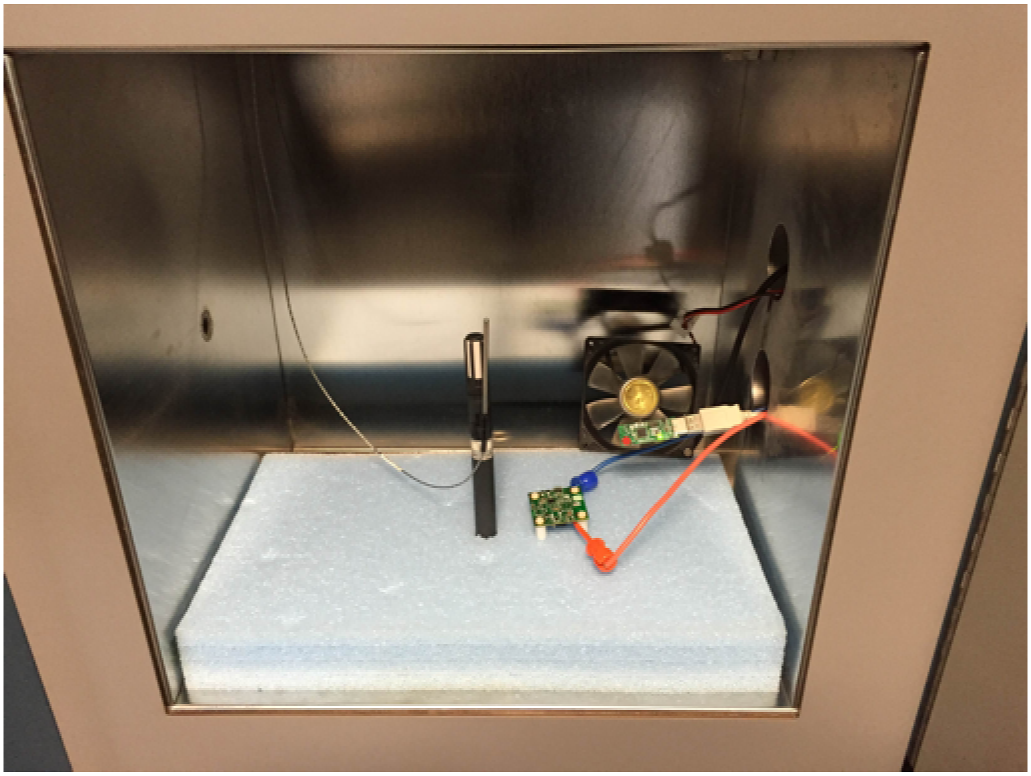

Figure 17. Relative Humidity Test Setup

The relative humidity was then programmed to run a pre-defined profile. This profile set the initial chamber humidity to 20% and soaked the TI Design hardware for an initial 40 minutes. The relative humidity was then ramped up to 30% at a controlled rate over 10 minutes and then soaked at that humidity level for 20 minutes. This process was repeated up to the maximum tested relative humidity of 70%, then decreased similarly to the minimum humidity level of 20%, and then soaked for 40 minutes to end the test. The temperature during this profile was held to a set point of 45°C.

Figure 18 shows the measured relative humidity from the HDC1000 device over the duration of the test as well as the reference relative humidity from the Rotronic HC2-S precision humidity and temperature probe. These results show the HDC1000 device tracks the reference relative humidity very closely.

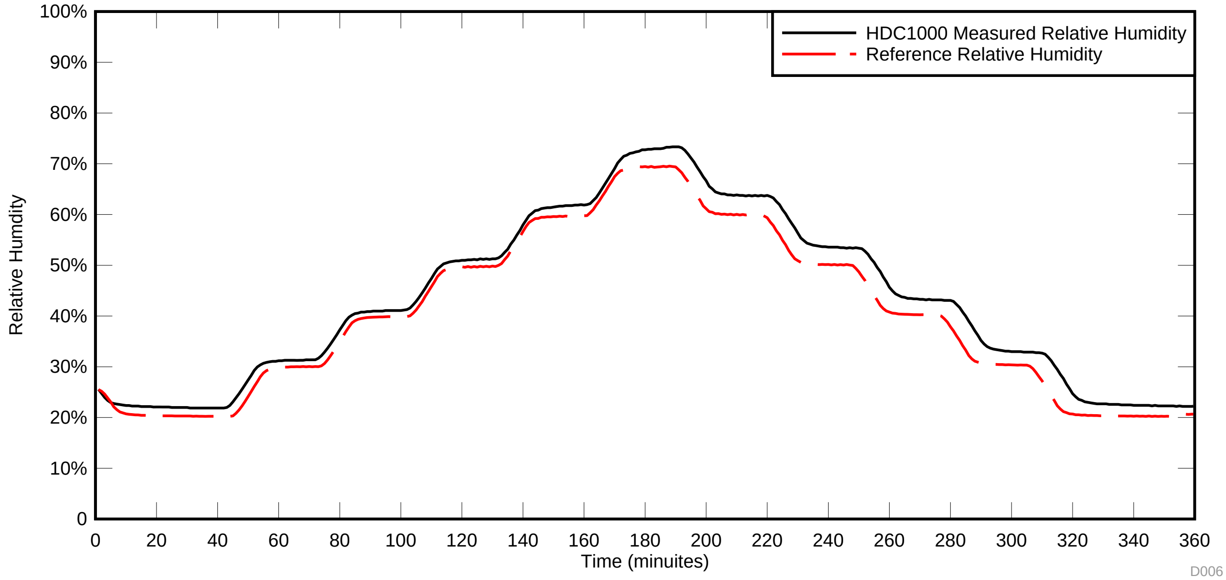

Figure 18. HDC1000 Measured Relative Humidity Data and Reference Relative Humidity Data

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NOTE: The HDC1000 was used for the Relative Humidity testing. The HDC1010 has the same functionality and pinout as the HDC1000 but is *not* an exact equivalent.

Testing using the HDC1010 will be done at a later date.

6.4 Temperature Characterization

This TI Design exemplifies the concept of a duty-cycled sensor end node through the use of the HDC1010 device, which measures both relative humidity and temperature.

To get an idea of how the TI Design system responded to varying temperatures, the hardware was placed in a TestEquity 1007H Temperature/Humidity Chamber (http://www.testequity.com/products/1104/) with a brand-new Energizer CR2032 lithium-ion coin cell battery. Two test wires were routed outside the chamber to a Keysight (Agilent) 34401A DMM with 6½ digits of resolution for monitoring of the V_BATT voltage net. The CC2540EMK-USB CC2540 USB Evaluation Module Kit was plugged into a USB extension cord and placed next to the TI Design hardware for optimal data packet reception performance. The test setup is shown in Figure 19.

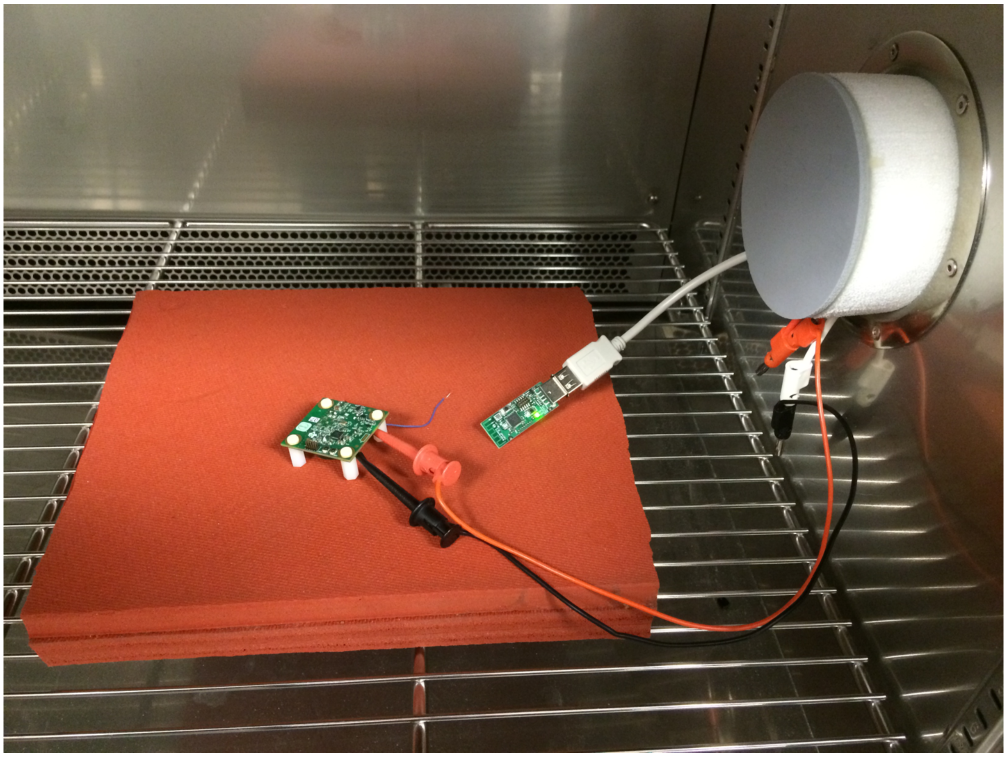

Figure 19. Temperature Test Setup

The temperature was then programmed to run a pre-defined profile. This profile set the initial chamber temperature to 25°C, and soaked the TI Design hardware for 10 minutes. The temperature then ramped up to 35°C at a controlled rate over five minutes, and then soaked at that temperature for 10 minutes. This process was repeated up to the maximum temperature of 60°C, and then decreased similarly to the minimum temperature of –30°C. Finally, the temperature was increased back to 25°C using the same controlled method. Relative humidity was allowed to vary during the temperature test, much as a real-world environment would respond.

The HDC1000 output data was recorded using the CC2540EMK-USB and Packet Sniffer software combination described in Section 5.3.

Figure 20 shows the environmental chamber set-point and the measured temperature from the HDC1000 device over the duration of the test. As is clearly seen, the HDC1000 device tracks the chamber temperature very closely.

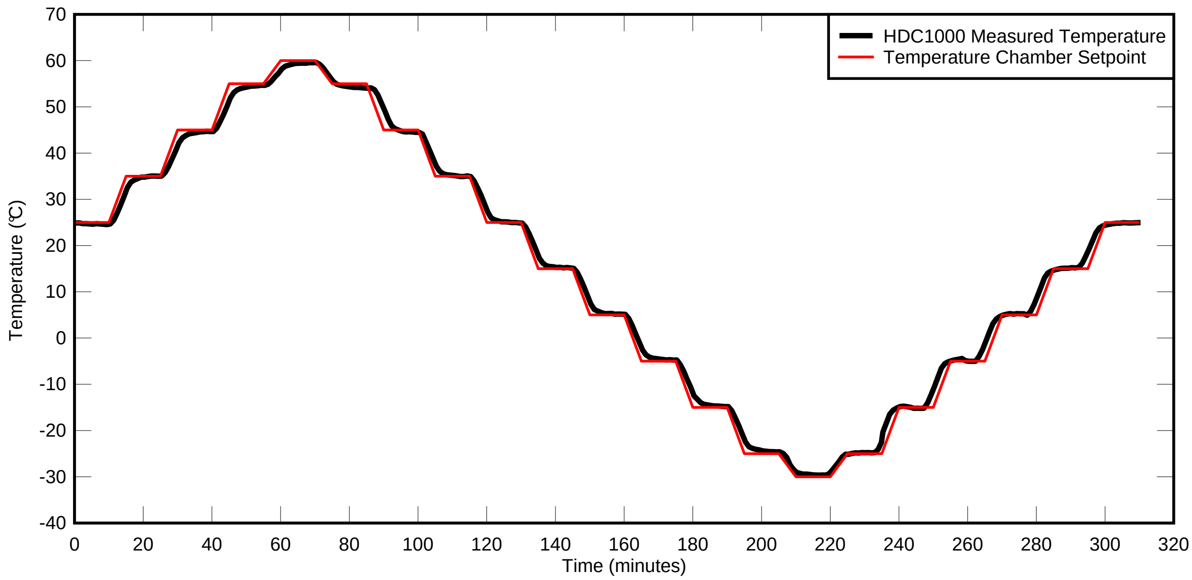

Figure 20. HDC1000 Measured Temperature Data and Environmental Chamber Set Point

NOTE: The HDC1000 was used for the relative humidity testing. The HDC1010 has the same functionality and pinout as the HDC1000 but is *not* an exact equivalent.

Testing using the HDC1010 will be done at a later date.

Due to the nature of CR2032 lithium ion coin cell battery chemistry, the output voltage can drop slightly (tens to hundreds of millivolts) at lower temperatures. However, if all components in the system work throughout the lifetime operating voltage of the coin cell, this should not be an issue for proper operation.

6.5 CC2650 Radio Transmission Range

A brief transmission range test was performed with the TI Design hardware to get a rough approximation of transmission range. The test was done inside a commercial office building hallway, with the TI Design hardware placed at one end of the hallway on top of a fabric-covered metal chair. The hallway is approximately 8 feet, 5 inches wide, a dropped ceiling 10 feet high, and a length of approximately 430 feet. There were not any significant obstacles in the hallway during the test.

A laptop with the CC2540EMK-USB and packet sniffer software was placed at varying intervals from the TI Design hardware to test if the data packet successfully receivable. During the test, there was an abundance of undesirable Bluetooth Smart packets received from the multitude of mobile phones in the vicinity. However, the display filter setting on the packet sniffer software was set to only show data packets from the TI Design hardware.

Packets received when the sniffer setup was in close proximity to the TI Design hardware were received with a received signal strength indication (RSSI) of approximately –30 to –35 dBm. Packets received when the sniffer setup was at the end of the hallway (~430 feet away) from the TI Design hardware were received reliably with an RSSI of approximately –65 to –75 dBm. Packets beyond the end of the hallway were not reliably received by the packet sniffer setup.

This TI Design was able to successfully transmit data packets down the entire length of a 430-foot hallway with minimal obstructions. However, radio performance will likely vary in the end-equipment environment, because obstructions in the RF transmit path will reduce range. For full verification of the TI Design hardware transmitting characteristics, further testing with end-equipment context is required.

7 Design Files

7.1 Schematics

To download the schematics, see the design files at TIDA-00374 Schematics.

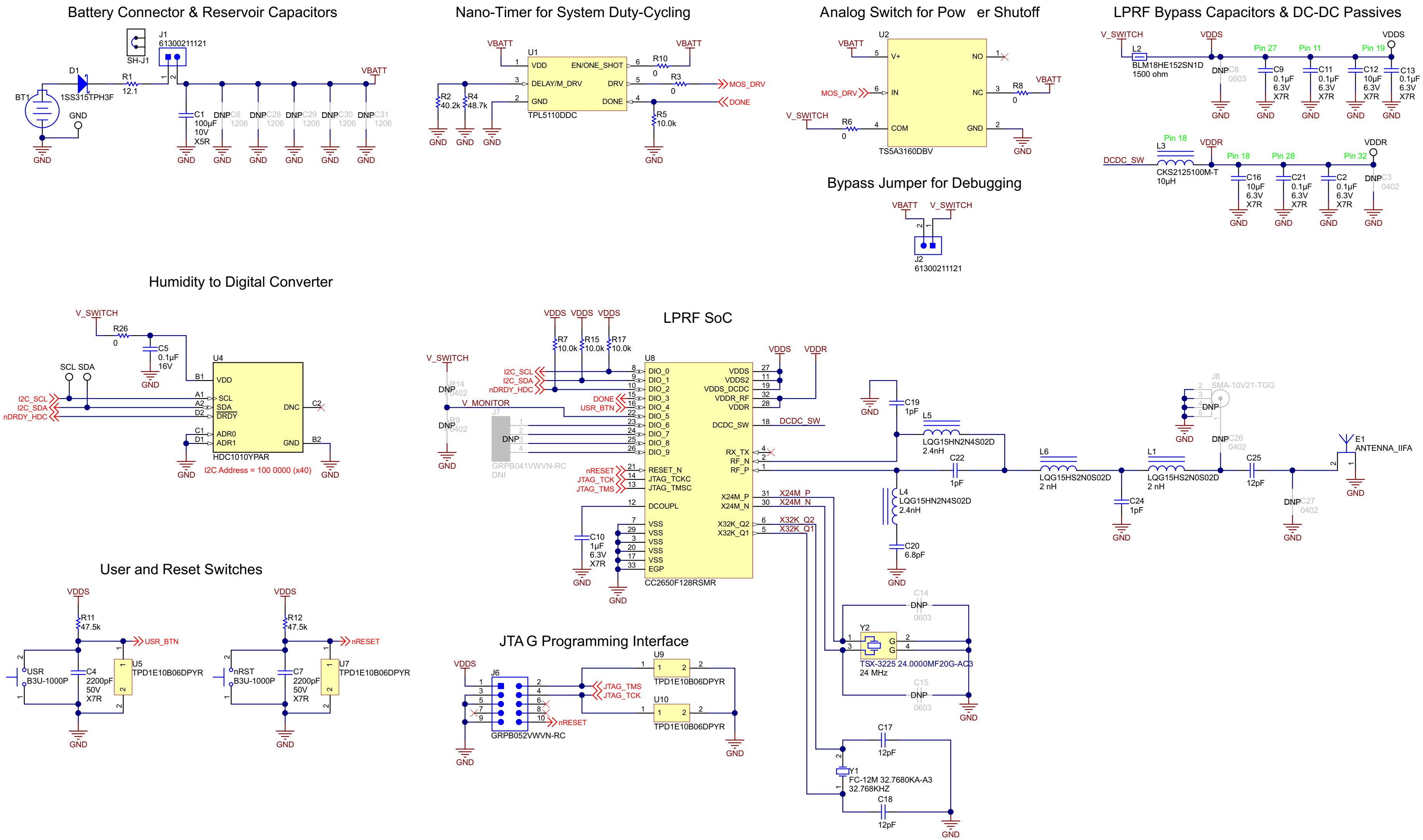

Figure 21. Humidity and Temperature Sensor Node for Star Networks Enabling 10+ Year Coin Cell Battery Life Schematic

7.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00374 BOM.

7.3 Layout Guidelines

To ensure high performance, the Humidity and Temperature Sensor Node for Star Networks Enabling 10+ Year Coin Cell Battery Life TI Design was laid out using a four-layer PCB. The second layer is a solid GND pour, and the third layer is used for power rail routing with GND fills in unused areas. The top and bottom layers are used for general signal routing and also have GND fills in unused areas.

For all of the TI products used in this TI Design, ensure that care is taken to adhere to the layout guidelines given in the respective datasheets.

7.3.1 Layer Plots

To download the layer plots, see the design files at TIDA-00374 Layer Plots.

7.4 Altium Project

To download the Altium project files, see the design files at TIDA-00374 Altium.

7.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00374 Gerber.

7.6 Assembly Drawing

To download the assembly drawing, see the design files at TIDA-00374 Assembly Drawing.

7.7 Software Files

To download the software files, see the design files at TIDA-00374 Firmware.

8 References

1. Texas Instruments, *HDC1010 Low Power, High Accuracy Digital Humidity Sensor with Temperature Sensor*, HDC1010 Datasheet, (SNAS685)
2. Texas Instruments, *CC2650 SimpleLink™ Multistandard Wireless MCU*, CC2650 Datasheet (SWRS158)
3. Texas Instruments, *TPL5110 Nano-power System Timer for Power Gating*, TPL5110 Datasheet (SNAS650)
4. Texas Instruments, *1-Ω SPDT ANALOG SWITCH 5-V/3.3-V SINGLE-CHANNEL 2:1 MULTIPLEXER/DEMULTIPLEXER*, TS5A3160 Datasheet (SCDS216)
5. Texas Instruments, *Single Channel ESD Protection Device in 0402 Package*, TPD1E10B06 Datasheet (SLLSEB1)
6. Texas Instruments, *Small Size 2.4 GHz PCB antenna*, Application Note AN043 (SWRA117)

9 About the Authors

EVAN D. CORNELL is a systems architect at Texas Instruments where he is responsible for developing reference design solutions for the industrial segment. Evan brings to this role experience in system-level analog, mixed-signal, and power management design. Evan earned his master of electrical and computer engineering (M.Eng.) and bachelor of science (BS) in electrical engineering from the Rose-Hulman Institute of Technology in Terre Haute, IN. Evan is a member of the Institute of Electrical and Electronics Engineers (IEEE).

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Revision D History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from C Revision (March 2016) to D Revision **Page**

Revision C History

Changes from B Revision (May 2015) to C Revision **Page**

Revision B History

Changes from A Revision (March 2015) to B Revision **Page**

Revision A History

Changes from Original (March 2015) to A Revision **Page**

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