TI Designs：TIDA-01477

支持低于 *1GHz* 技术和传感器到云网络的温湿度传感器节点参考设计

TEXAS INSTRUMENTS

说明

此参考设计演示了如何创建能够连接物联网 (IoT) 网络网关和云数据提供商的工业传感器到云端节点。此传感器节点采用了德州仪器 (TI) 毫微级功耗系统计时器、升压转换器、 SimpleLink™、超低功耗、低于 1GHz 无线微控制器 (MCU) 平台和湿度检测技术，展示了传感器终端节点占空比调节的超低功耗方法，可实现极长的电池寿命。

资源

TIDA-01477	设计文件夹
HDC2010	产品文件夹
CC1310	产品文件夹
TPL5111	产品文件夹
TPS61291	产品文件夹
TPS22860	产品文件夹
TPD1E10B06	产品文件夹

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特性
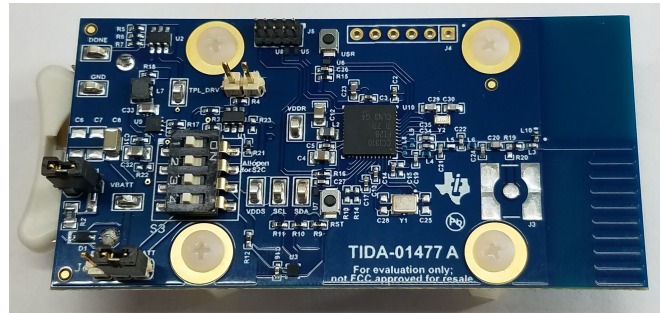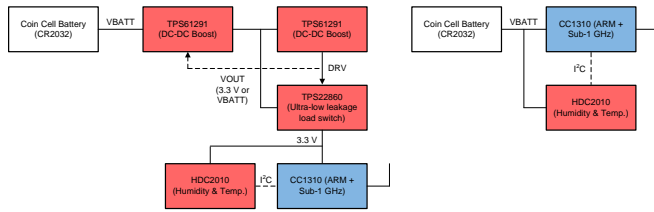
- 大型网络到云连接可实现远距离应用，支持长达 1km 的视线
- 采用 TI 15.4-Stack 且符合 IEEE 802.15.4e/g 标准的 Sub-1GHz 解决方案
- 可配置系统唤醒间隔
- 低待机电流 (1μA)
- ±2% 相对湿度精度
- ±0.2°C 温度精度

应用

- 无线环境传感器
- 恒温器
- 烟雾和热量探测器
- 空气质量和气体检测
- 楼宇自动化

该 TI 参考设计末尾的重要声明表述了授权使用、知识产权问题和其他重要的免责声明和信息。

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1 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 requires a periodic manual battery replacement.

At a high level, this reference design consists of a CR2032 coin cell battery, a nano-power system timer, a low I_Q boost converter, an ultra-low power wireless MCU, and a combined humidity and temperature sensor. The most simple use case employs the wireless MCU and the humidity + temperature sensor powered through the coin cell battery to create a simple sensor-to-cloud end node. Temperature and humidity data is collected and transmitted every five minutes to the sensor-to-cloud gateway. Customizable jumpers allow users to cover other use cases with the help of the nano-power system timer to wake up the system on longer intervals to further extend battery life.

Enabled by Texas Instruments' SimpleLink ultra-low power wireless microcontroller (MCU) platform, and humidity sensing technologies, this humidity and temperature sensor node reference design demonstrates an ultra-low-power method to collect environmental data on a sensor-to-cloud network.

This design guide addresses component selection, design theory, and test results of the reference design system. The scope of this design guide gives system designers a head-start in integrating TI's nano-power system timer, boost converter, the SimpleLink ultra-low-power wireless MCU platform along with a starting point for sensor-to-cloud software integration, and humidity sensing technologies into their end-equipment systems.

1.1 Key System Specifications

表 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Input power source	CR2032 Lithium-ion coin cell battery (3.0-V nominal voltage)	节 2.2.6
Sensor type	Humidity and temperature	节 2.2.1
Measurement interval	One temperature and humidity measurement every five minutes	1 节
Transmit state average current	14 mA	节 3.2.1.1
Transmit state duration	41 milliseconds	节 3.2.1.1
Average Standby Current	1 μA	节 3.2.1.2
Estimated battery life	8.31 Years	节 3.2.1.2
Operating temperature	–30°C to +60°C (limited by CR2032 coin cell operating range)	节 2.2.6
Working environment	Indoor and outdoor	节 2.2.6
Form factor	1.5 inch × 3.0 inch rectangular PCB	节 3.1.1

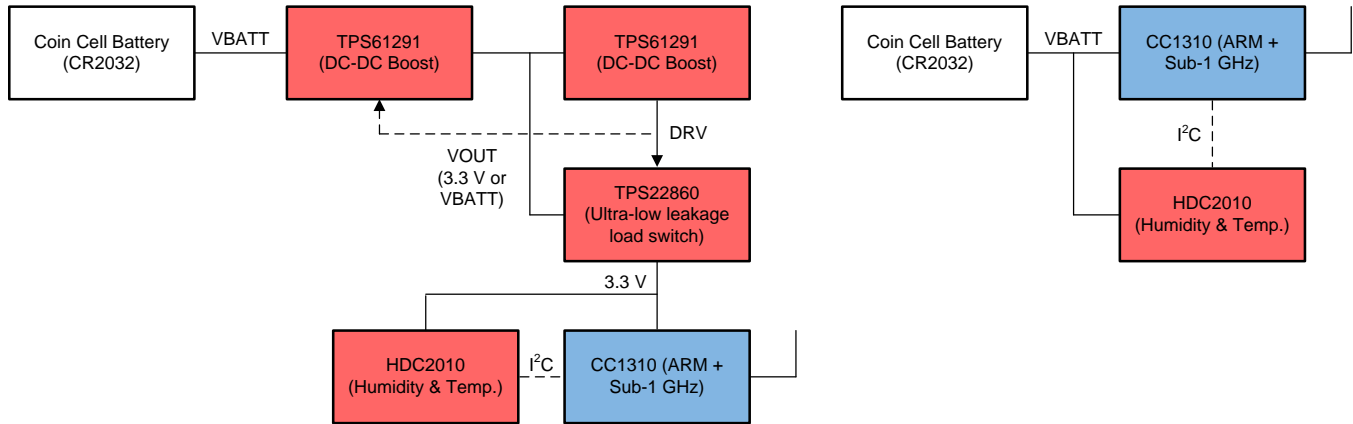# 2   System Overview

2.1   *Block Diagram*

图 **1. Block Diagram of Humidity and Temperature Sensor Node Reference Design**

2.2   *Design Considerations*

2.2.1   Humidity and Temperature Sensor

In this reference design, a digital humidity sensor with an integrated temperature sensor is chosen to demonstrate the ultra-low-power, duty-cycling power scheme. Humidity and temperature are both common measurements required for many end-equipment systems in industrial and building automation applications. For example, home heating and cooling systems of the future are likely to 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 then controls the various air ducts connecting 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 HDC2010 device from Texas Instruments is ideally suited to accurately sense environmental information. The innovative placement of the HDC2010 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 HDC2010 is extremely low, averaging 0.55 μA at a measurement rate of one sample per second. Interfacing to the device is straightforward with any MCU platform using the I^{2}C communication protocol.

2.2.2   Ultra-Low-Power Wireless Microcontroller (MCU)

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.

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 CC1310 device is a multi-standard device, with software stack support for wM-Bus and TI's SimpliciTI™ (star network) network protocol. In this reference design, a generic proprietary protocol is the protocol of choice, but the hardware as built can work with other protocols as well.

2.2.3 Nano-Power System Timer

This reference design is able to achieve extremely long battery life by means of a nano-power system timer. The use of this type of device replaces 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 reference design, the TPL5111 device is chosen to control both the boost converter mode and load switch, 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 TPL5111 device controls the operating mode of a boost converter, as the following 节 2.2.4 describes, and a low leakage load switch, as 节 2.2.5 describes.

2.2.4 Boost Converter

Some sensor end-nodes require a regulated voltage rail to operate at their highest levels of sensing performance. To provide a well-regulated voltage rail over the entire lifetime of the battery, a boost converter is necessary. However, to reduce the battery life loss due to converter inefficiency, an extremely high-efficiency boost converter is required.

In this reference design, the TPS61291 device is chosen to regulate the battery voltage to 3.3 V. With a battery voltage of 3.0 V, the TPS61291 maintains an efficiency level greater than 95% at the load currents typical of a sensor end-node: 1 mA to 100 mA. Even at the depleted coin cell voltage of 2.0 V, the TPS61291 device maintains an efficiency level greater than 90% over the typical load current range of 1 mA to 100 mA.

Furthermore, the TPS61291 device has a bypass mode that connects the input voltage source directly to the output pin, while bypassing the boost inductor. This low-loss bypass mode only consumes 15 nA (typical), which when combined with a low-leakage load switch, enables ultra-low off-state currents.

2.2.5 Low-Leakage Load Switch

In conjunction with a nano-power system timer (see 节 2.2.3), this reference design uses a low-leakage load switch to shut off power to the wireless MCU and humidity sensor. The most important characteristic of this switch is the off-state leakage, because that leakage significantly affects the overall battery life of the system.

In this reference design, the TPS22860 device is chosen as the switch used to disconnect the system from the battery. The TPS22860 has a rated leakage current of ±20 nA at 25°C, which enables extremely long battery life in this system.

2.2.6 Coin Cell Battery

The power source for this reference 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. When the remaining charge in the coin cell battery is nearly depleted, 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 superiority 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 the 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 reference design system is suited for both indoor and outdoor use.

Immediately following the battery is a low forward voltage Schottky diode and a bulk capacitor. The Schottky diode prevents damage to the hardware if the coin cell battery is inserted backwards. This reference design also uses a coin cell battery tray that prevents an end-user from inserting the battery backwards, which may eliminate the need for the Schottky diode. The bulk capacitor is sized to prevent too much voltage sag, particularly during the initial transition into the on-state.

2.3 Highlighted Products

The Humidity and Temperature Sensor Node Reference Design Enabling Sub-1 GHz and Sensor-to-Cloud Networks features the following devices:

- HDC2010: Low-power, high-accuracy, digital humidity sensor with integrated temperature sensor (节 2.3.1)
- CC1310: SimpleLink Sub-1 GHz ultra-low-power wireless MCU (节 2.3.2)
- TPL5111: Ultra-low-power timer with MOS driver and MOSFET power ON (节 2.3.3)
- TPS61291: Low I_Q boost converter with bypass operation (节 2.3.4)
- TPS22860: Ultra-low leakage load switch (节 2.3.5)
- TPD1E10B06: Single-channel electro-static discharge (ESD) in a 0402 package with 10-pF capacitance and 6-V breakdown (节 2.3.6)

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

2.3.1   HDC2010

Key features of this device include:

- 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: 550 nA

- Temperature range:
    - Operating: –40°C to +85°C
    - Functional: –40°C to +125°C

- Supply voltage: 1.62 to 3.6 V

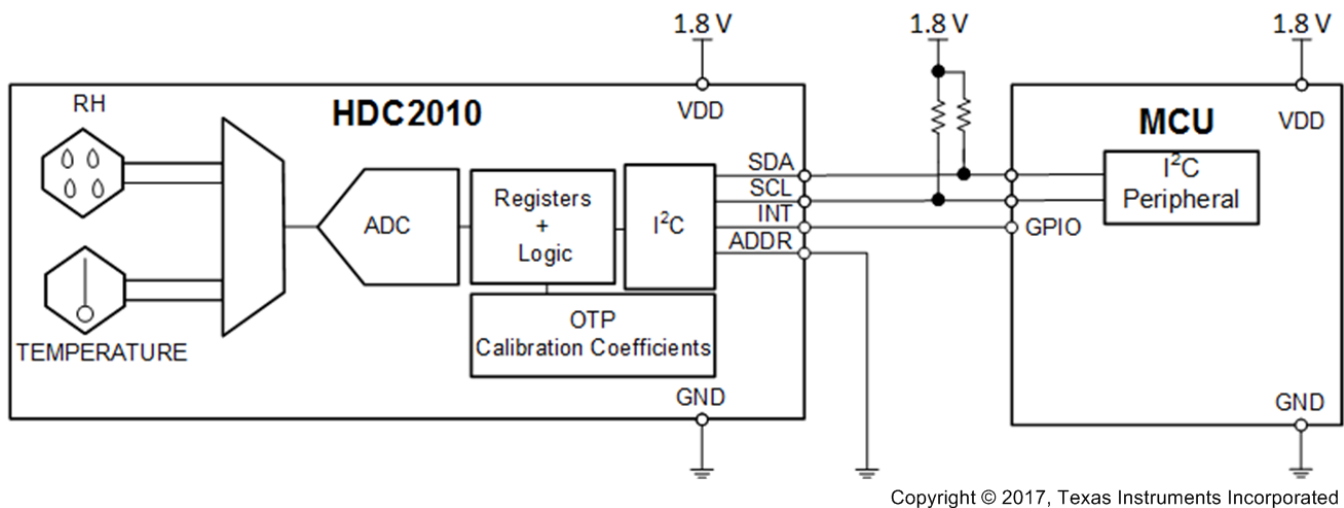- Automatic sampling rate (5 Hz, 2 Hz, 1 Hz, 0.2 Hz, 0.1 Hz, 1/60 Hz, 1/120 Hz) or on demand

- I²C interface

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图 **2. HDC1010 Functional Block Diagram**

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 a 1.8-V supply voltage, this makes 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.

2.3.2 CC1310

Key features of this device include:

- Microcontroller
  - Powerful Arm® Cortex®-M3
  - EEMBC CoreMark Score: 142
  - Up to 48-MHz clock speed
  - 128KB of in-system programmable flash
  - 8KB SRAM for cache
  - Up to 20-KB of ultra-low leakage SRAM
  - 2-pin cJTAG and JTAG debugging
  - Supports over-the-air upgrade (OTA)
- Ultra-low-power sensor controller
  - 16-bit architecture
  - 2KB of ultra-low leakage SRAM for code and data
- Efficient code size architecture, placing peripheral drivers, RTOS, RF drivers, and Bootloader in ROM
- RoHS-compliant packages
  - 4-mm × 4-mm RSM QFN32 (10 GPIOs)
  - 5-mm × 5-mm RHB QFN32 (15 GPIOs)
  - 7-mm × 7-mm RGZ QFN48 (30 GPIOs)
- Peripherals
  - All digital peripheral pins can be routed to any GPIO
  - Four general-purpose timer modules (8 × 16-bit or 4 × 32-bit timer, PWM each)
  - 12-bit ADC, 200-ksamples/s, 8-channel analog MUX
  - Continuous comparator
  - Ultra-low-power analog comparator
  - Programmable Current Source
  - UART
  - 2 × SSI (SPI, µW, TI)
  - I²C
  - 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
  - World's smallest Sub-1 GHz wireless MCU: 4 mm × 4 mm
  - On-chip internal DC-DC converter
  - Very few external components
  - Seamless integration with the SimpleLink CC1190 Range Extender
  - Pin compatible with the SimpleLink CC26xx
- Low power
  - Wide supply voltage range
    - Normal operation: 1.8 V to 3.8 V
    - External regulator mode: 1.65 V to 1.95 V
  - Active-Mode RX: 5.5 mA
  - Active-Mode TX at 10 dBm: 12 mA, 14 dBm: 25 mA
  - Active-Mode MCU: 61 µA/MHz
  - Active-Mode MCU: 48.5 CoreMark/mA
  - Active-Mode Sensor Controller: 8.2 µA/MHz
  - Standby: 0.7 µA (RTC running and RAM/CPU retention)
  - Shutdown: 100 nA (wakeup on external events)
- RF section
  - Excellent receiver sensitivity:
    - −121 dBm at 2.4 kbit/s
    - −111 dBm at 50 kbit/s
  - Very good selectivity and blocking performance
  - Data rate up to 4 Mbit/s
  - Modulation support: MSK, FSK, GFSK, OOK, ASK, 4GFSK, CPM (shaped-8 FSK)
  - Highly flexible RF modem (software-

defined radio) to also cover legacy and proprietary communication protocols

– Programmable output power up to 15 dBm with shared RX and TX RF pins (regulated power supply)

– Antenna diversity

– Coding gain

– Suitable for systems targeting compliance with worldwide radio frequency regulations

– ETSI EN 300 220, EN 303 131, EN 303 204 (Europe)

– FCC CFR47 Part 15 (US)

– ARIB STD-T108 (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™ (CCS)
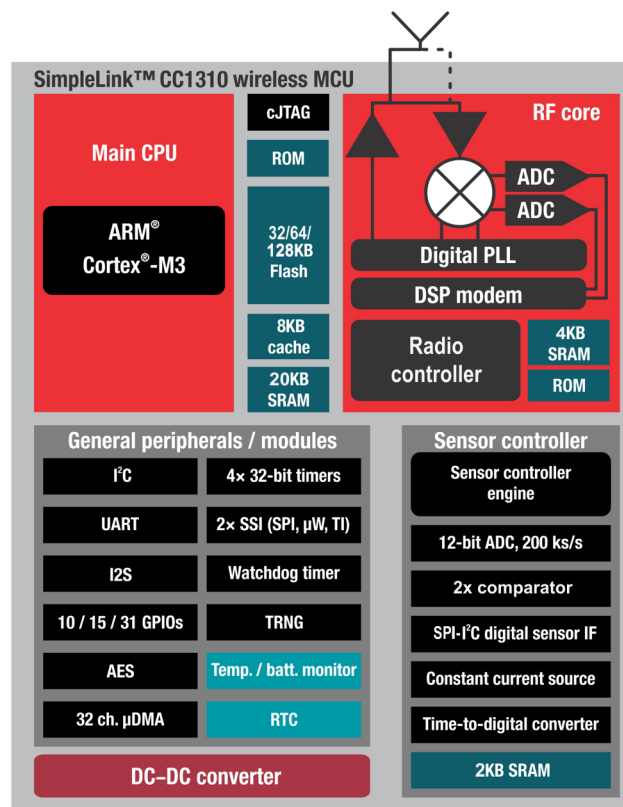
图 **3. CC1310 Functional Block Diagram**

The CC1310 device is the first part 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 Cortex-M0 MCU is handling 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 solution offering a complete RF system solution, which includes an on-chip DC-DC converter into a true single-chip solution down to a 4-mm × 4-mm package.

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) sleeps for as long as possible. Software stack support for this device is as follows:

- wM-Bus
- SimpliciTI (Star Network)

2.3.3   TPL5111

Key features of this device include:

- Selectable time intervals: 100 ms to 7200 s

- Timer accuracy: 1% (typ)

- Current consumption at 2.5 V: 35 nA (typ)

- Resistor selectable time interval

- Manual power-on input

- One-shot feature

- Supply voltage range: 1.8 V to 5.5 V

Key applications of this device include:

- Duty cycle control of battery powered systems

- Internet of Things (IoT)

- Intruder detection

- Tamper detection

- Home automation sensors

- Thermostats

- Consumer electronics

- Remote sensor

- White goods
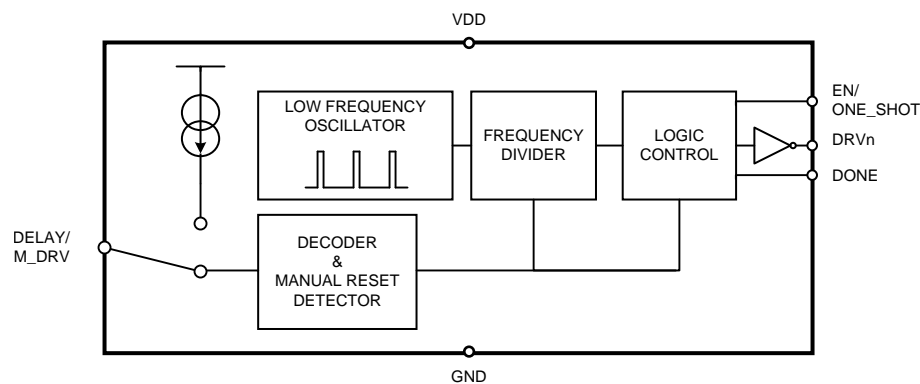
图 4. **TPL5111 Functional Block Diagram**

The TPL5111 Nano Timer is a low-power system timer, ideal for power gating in duty cycled or battery powered applications. Consuming only 35 nA, the TPL5111 can be used to enable and disable the power supply for an MCU or other system device, drastically reducing the overall system stand-by current during the sleep time. This power saving enables the use of significantly smaller batteries and makes the TPL5111 well suited for energy harvesting or wireless sensor applications. The TPL5111 provides selectable timing intervals from 100 ms to 7200 s. In addition, the TPL5111 has a unique One-shot feature where the timer only asserts its enable pulse for one cycle. The TPL5111 is available in a 6-pin SOT23 package.

2.3.4 TPS61291

Key features of this device include:

- Input voltage range: 0.9 V to 5 V

- Startup voltage: 1.5 V at 20-mA load

- Pin selectable output voltages: 3.3 V, 3 V, 2.5 V

- 15-nA typical quiescent current in bypass mode

- 5.7-µA typical quiescent current in boost mode

- Bypass switch from V_{IN} to V_{OUT}

- I_{OUT} > 200 mA at 3.3-V V_{OUT}, V_{IN} = 1.8 V

- Internal feedback divider disconnect (bypass mode)

- Controlled bypass transition prevents reverse current into battery

- Power-save mode at light loads

- Over temperature protection

- Redundant overvoltage protection

- Small 2-mm × 2-mm SON 6-pin package

Key applications of this device include:

- Metering (gas, water, smart meters)

- Remote controls

- Home security / home automation

- Single 3-V Li-MnO$_2$ or 2 × 1.5-V alkaline cell powered applications
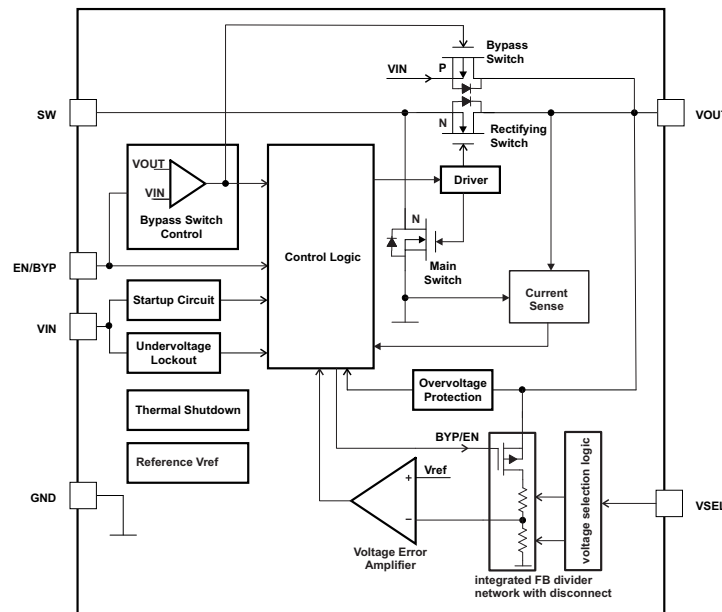

图 **5. TPS61291 Functional Block Diagram**

The TPS61291 is a boost converter with pin selectable output voltages and an integrated bypass mode. In bypass operation, the device provides a direct path from the input to the system and allows a low-power MCU such as the MSP430 to operate directly from a single 3-V Li-MnO2 battery or dual alkaline battery cells.

In bypass mode the integrated feedback divider network for boost mode operation is disconnected from the output and the quiescent current consumption drops down to only 15 nA (typical).

In boost mode, the device provides a minimum output current of 200 mA at 3.3-V V_{OUT} from 1.8-V V_{IN}. The boost mode is used for system components that require a regulated supply voltage and cannot directly operate from the input source. The boost converter is based on a current-mode controller using synchronous rectification to obtain maximum efficiency and consumes typically 5.7 µA from the output. During startup of the boost converter, the VSEL pin is read out and the integrated feedback network sets the output voltage to 2.5 V, 3 V, or 3.3 V.

Bypass mode or boost mode operation is controlled by the system via the EN/BYP pin. The device integrates an enhanced bypass mode control to prevent charge, stored in the output capacitor during boost mode operation, from flowing back to the input and charging the battery.

2.3.5 TPS22860

Key features of this device include:

- Integrated single channel load switch
- Bias voltage range (V_{BIAS}): 1.65 V to 5.5 V
- Input voltage range: 0 V to V_{BIAS}
- ON-resistance (R_{ON})
  - R_{ON} = 0.73 Ω at V_{IN} = 5 V (V_{BIAS} = 5 V)
  - R_{ON} = 0.68 Ω at V_{IN} = 3.3 V (V_{BIAS} = 5 V)
  - R_{ON} = 0.63 Ω at V_{IN} = 1.8 V (V_{BIAS} = 5 V)
- 200-mA maximum continuous switch current
- Ultra-low leakage current

  - V_{IN} leakage current = 2 nA
  - V_{BIAS} leakage current at 5.5 V = 10 nA
- 6-pin SOT-23 or SC70 package
- ESD performance tested per JESD 22
  - 2-kV HBM and 1-kV CDM

Key applications of this device include:

- Wearables
- IoT
- Wireless sensor networks
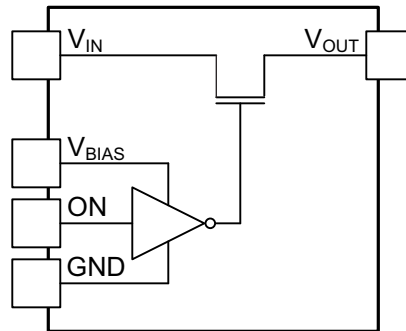
图 6. TPS22860 Functional Block Diagram

The TPS22860 is a small, ultra-low leakage current, single-channel load switch. The device requires a V_{BIAS} voltage and can operate over an input voltage range of 0 V to V_{BIAS}. The device can support a maximum continuous current of 200 mA. The switch is controlled by an on/off input (ON), which is capable of interfacing directly with low-voltage control signals. The TPS22860 is available in two small, space-saving 6-pin SOT-23 and SC70 packages. The device is characterized for operation over the free-air temperature range of –40°C to +85°C.

2.3.6   TPD1E10B06

Key features of this device include:

- 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)

Key applications of this device include:

- End equipment:
  - Tablets
  - Remote controllers
  - Wearables
  - Set-top boxes
  - Electronic point of sale (EPOS)
  - ebooks
- Interfaces:
  - Audio lines
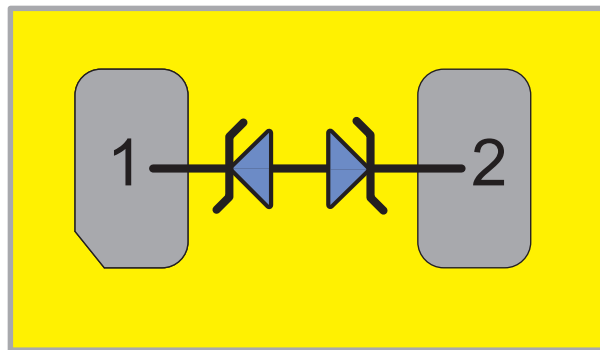 - Pushbuttons
  - General-purpose input/output (GPIO)

图 **7. TPD1E10B06 Functional Block Diagram**

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 speakerphone), SD interfacing, keypad or other buttons, VBUS 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 ebooks, tablets, remote controllers, wearables, set-top boxes, and EPOS equipment.

2.4   *System Design Theory and Considerations*

The Humidity and Temperature Sensor Node Reference Design Enabling Sub-1 GHz and Sensor-to-Cloud Networks measures the ambient relative humidity and temperature and achieves a long battery life by staying in sleep between sampling and transmitting states. The CC1310 wireless MCU sleeps for almost 5 minutes before measuring humidity and temperature and transmitting the data back to the sensor-to-cloud gateway.

The humidity and temperature sensor node reference design can be configured to support two different networking use cases, the sensor-to-cloud implementation and an ultra-low-power Sub-1 GHz star network topology. The sensor-to-cloud implementation requires the CC1310 to stay in time-sync with the gateway and therefore the wireless MCU can not be powered down between transmissions to save more energy. The sensor-to-cloud configuration includes only the CC1310 Wireless MCU, a CR2032 battery, and the HDC2010 humidity and temperature sensor.

The ultra-low-power sub-1 GHz star network configuration uses a nano-power timer, load switch and a boost converter to control when the wireless MCU powers up to take environment measurement and transmit data. The TPL5111 nano-power system timer controls when the TPS61291 boost converter enters and exits its bypass mode and when the TPS22860 load switch disconnects the CC1310 and HDC2010 devices from the output of the boost converter. Because the on-state is very short (the time when the CC1310 and HDC2010 have power), and the off-state current consumption from the coin cell battery is very low, the estimated battery life is very long. Duty-cycling with a nano-power system timer can extend battery life. For more information of the nano-power use case, see the Humidity and Temperature Sensor Node for Sub-1 GHz Star Networks Enabling 10+ Year Coin Cell Battery Life reference design.

2.4.1   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 standby current consumption (µA)
* Average transmit current consumption (mA)
* Transmit state duration (s)

Battery capacity is dependent on the size of the battery and the intended install location.

Average standby current is somewhat less controllable because there is a minimum number of devices that have to stay in standby or sleep between wakeups. The sensor-to-cloud implementation includes only the CC1310 in standby along with the HDC2010.

Average transmit current and duration is adjustable by changing transmit power and transmit packet properties. The current implementation transmits a total of 72 bytes with 59 bytes of payload data. The data fields can be adjusted depending on the sensor-to-cloud gateway implementation and what sensors are connected.

节 3.2.1 has more details about the battery life performance of this reference design.
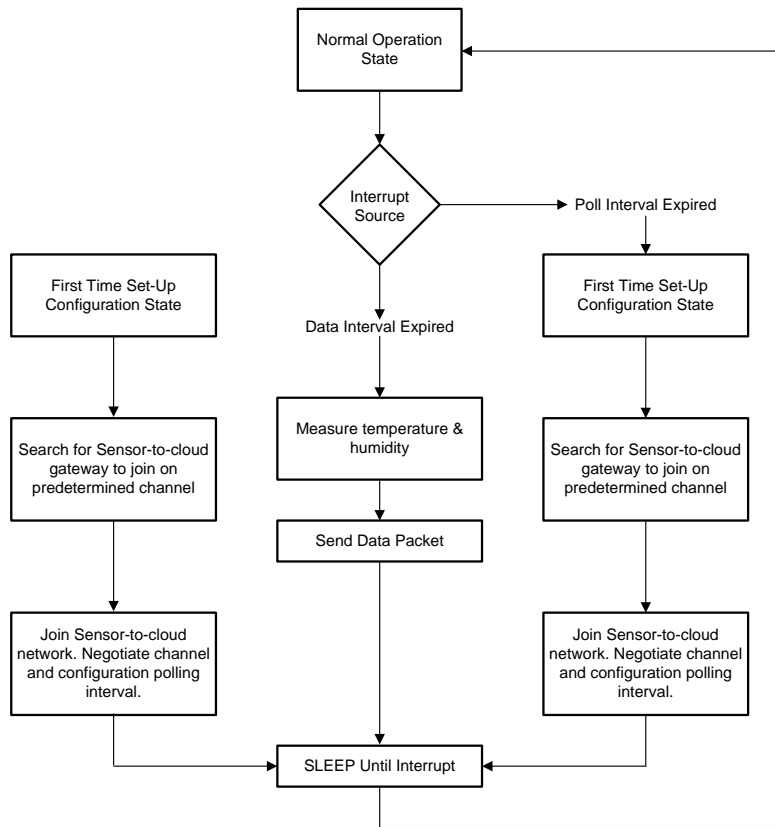
2.4.2 Firmware Control

图 **8. Firmware Flow Chart**

The flow chart shown in 图 8 describes the CC1310 operation in this reference design. The CC1310 first starts by checking the source of the wakeup. If the device is powered on for the first time, the CC1310 searches for the sensor-to-cloud gateway to join, then after joining the network the wireless MCU goes to sleep. To connect to a new or different gateway, hold the user button at the top of the board when resetting the board and keep it held down for at least 1 second during start-up to reset the network configurations.

The CC1310 stays in sleep mode until the environmental data timer has expired. At this time the MCU wakes up, triggers the HDC2010 to take temperature and humidity measurement, and then sends out the humidity and temperature data to the gateway. The software is currently configured to send environmental data to the sensor-to-cloud gateway every two minutes. Also as per the TI 15.4 stack, the CC1310 wakes up on the configuration polling interval set by the gateway to check if there are any messages from the gateway. During this time, the sensor and gateway can negotiate a new frequency when frequency hopping is enabled.

2.4.3   Polling Intervals and Frequency Hopping

To increase battery life, the humidity and temperature sensor node 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.

3 Hardware, Firmware, Testing Requirements, and Test Results

3.1 Required Hardware and Firmware

3.1.1 Hardware Overview

图 9 shows the hardware for the Humidity and Temperature Sensor Node Reference Design Enabling Sub-1 GHz and Sensor-to-Cloud Networks. The printed circuit board (PCB) is in a 1.5 × 3.0-inch rectangular form factor and comes with 0.5-inch nylon standoffs to ensure ease of use while performing lab measurements.
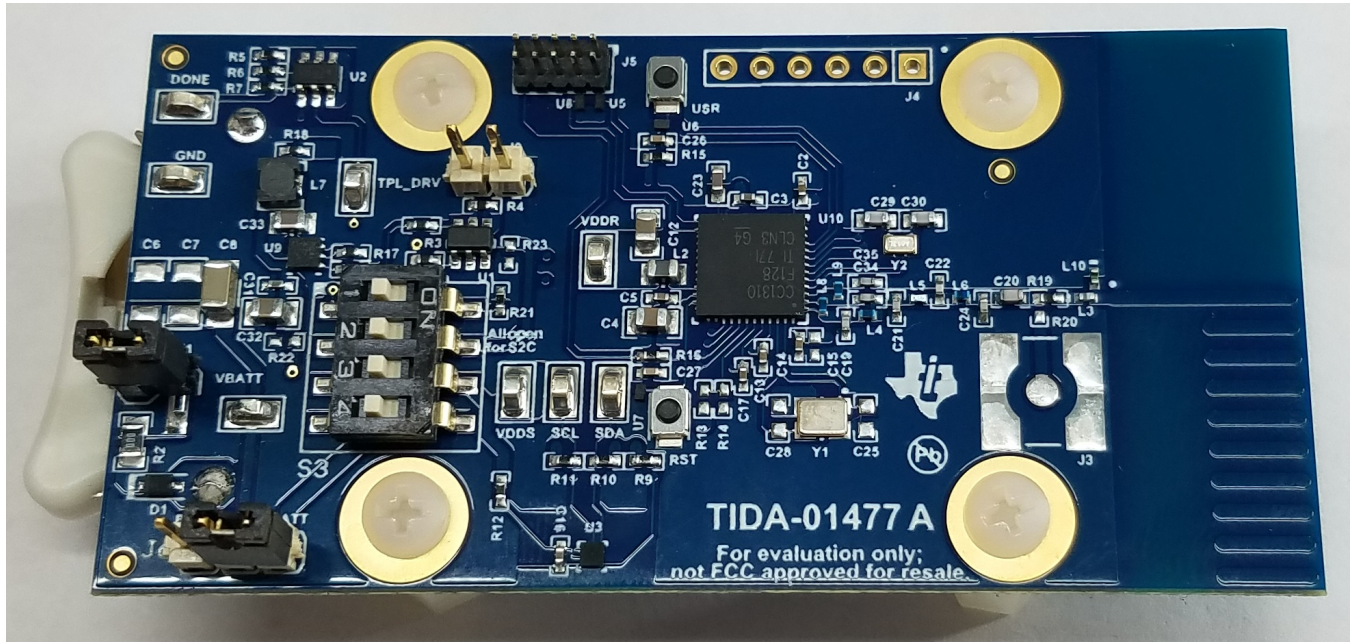

图 9. Humidity and Temperature Sensor Node Reference Design Enabling Sub-1 GHz and Sensor-to-Cloud Networks

All of the integrated circuits (CC1310, TPL5111, TPS22860, and HDC2010), several test points and jumpers, as well as the ESD protection devices for the programming header 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.

There are four unused GPIOs that have been brought out from the CC1310 device to an unpopulated header to facilitate future prototyping and debugging.

注**:** To connect to a new or different gateway, hold the user button at the top of the board while pressing the reset button.

3.1.1.1 Jumper and Switch Configuration

To facilitate measuring critical parameters, debugging, and enabling different use cases with this reference design, there are several jumpers and dip switches that must be in the proper position.

To run the sensor-to-cloud implementation described in 图 1 jumpers J1 = shorted, J2 = open, and J6 = shorted. Jumper J6 shorts pins 2 and 3, shorting the two rightmost pins. This connects the battery directly to the MCU and HDC2010. All DIP switches should be in the open (OFF) position and J2 = open.

To run the ultra-low-power nano-power timer implementation, J1 = shorted, J2 = open, and J6 = shorted (pins 1 and 2). The two leftmost pins of J6. Place all DIP switches to the closed (ON) position.

注**:** The device needs to be reprogrammed with the TIDA-00484 software.

3.1.1.2 *Gateway Hardware*

The first option for demonstrating the sensor-to-cloud system is to build TI's Sub-1 GHz Sensor to Cloud Industrial IoT Gateway Reference Design. The following items are required to build the sensor-to-cloud gateway:

- A CC1310 or CC1350 LaunchPad™ to run the MAC coprocessor application
- An AM335x-based BeagleBone Black board
- A 5-V power supply for the BeagleBone Black
- BeagleBone Black wireless connectivity cape to connect the gateway to the Internet
- An 8GB microSD card (the TI processor SDK image requires at least 8GB of space)
- A means to configure and set up the BeagleBone Black microSD card (Windows® or Linux machine)
- A PC to host and run the web browser used to view the web application
- A USB cable to connect the BeagleBone Black with the CC1310 or CC1350 LaunchPad
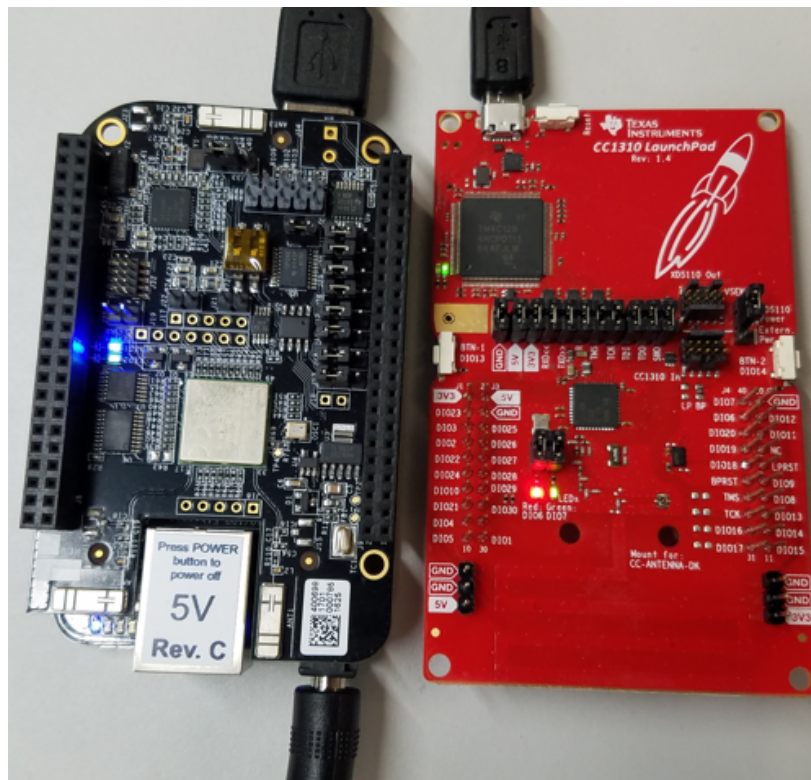

图 **10. BeagleBone Gateway Hardware Setup**

3.1.1.3   *Collector Hardware*

The second and easier option for demonstrating the sensor-to-cloud system is to use a CC1310 or CC1350 LaunchPad running the Collector Example Application featured in the SimpleLink SDK to act as the gateway device. The LaunchPad creates the TI 15.4-Stack network, allows sensor devices to join the network, collects sensor information sent by devices running the sensor example application, and tracks if the devices are on the network or not by periodically sending tracking request messages. The only hardware required is the LaunchPad and a PC to view the UART output.

3.1.2 Firmware

3.1.2.1 Loading Firmware

The firmware used on this reference design is developed using TI's CCS software (version 7.1.0). The IAR Embedded Workbench for Arm also supports the CC13xx line of SimpleLink products.

Powering the board from 3.0 V is also necessary and is supplied at the test point labeled VBATT. Connecting the external power source at this location bypasses the Schottky diode.

The reference design hardware is programmed by connecting the 10-pin mini ribbon cable from J5 to the SmartRF06 EVM (10-pin Arm Cortex Debug Connector, P410). See 图 11 for a photo of the correct setup for connecting the reference design hardware to the SmartRF06 EVM.
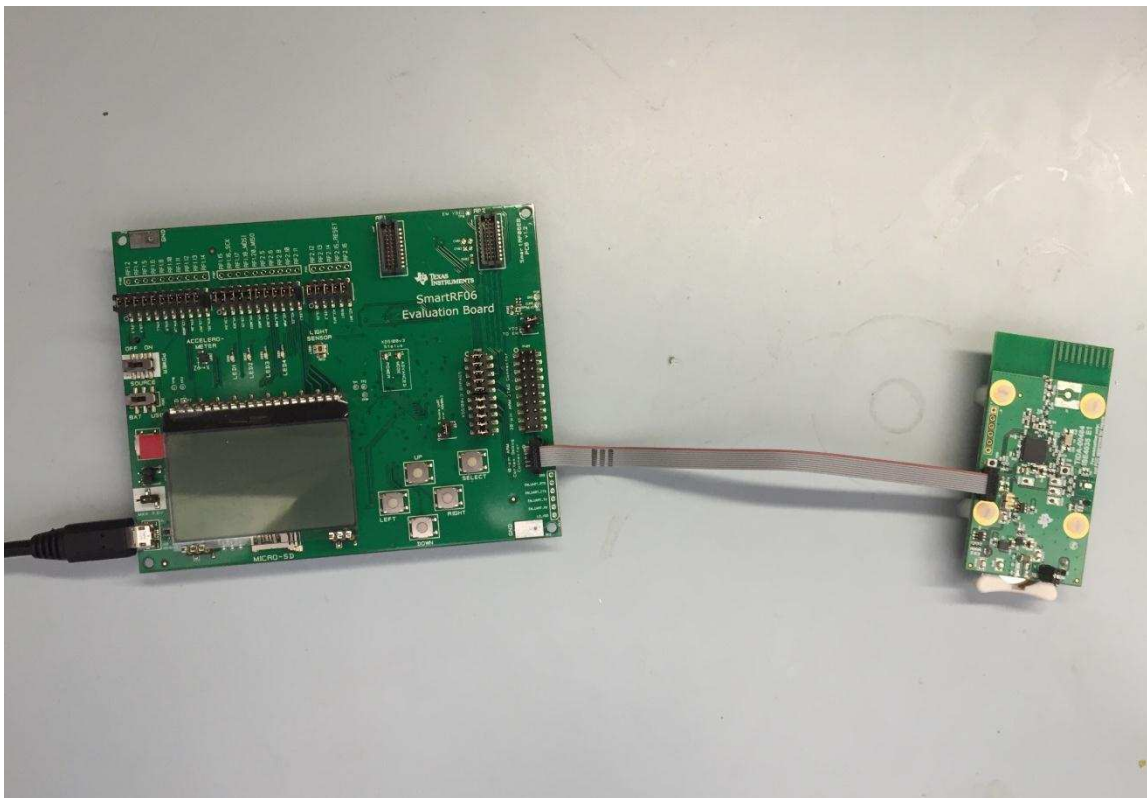
图 11. Connection of SmartRF06 Evaluation Board and Reference Design Hardware for Programming and Debugging

To run the LaunchPad collector, connect the CC13xx LaunchPad to the PC and open a serial connection to the application UART. To restart the collector, hold BTN-2 while pressing the reset button. Press the BTN-2 button on the LaunchPad collector to allow new devices to join the network. Press the BTN-2 a second time to close the network, which does not allow new devices to join the network.

图 **12. CC1310 LaunchPad Collector UART Output**

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. 图 13 shows the Flash Programmer settings after plugging in the LaunchPad.
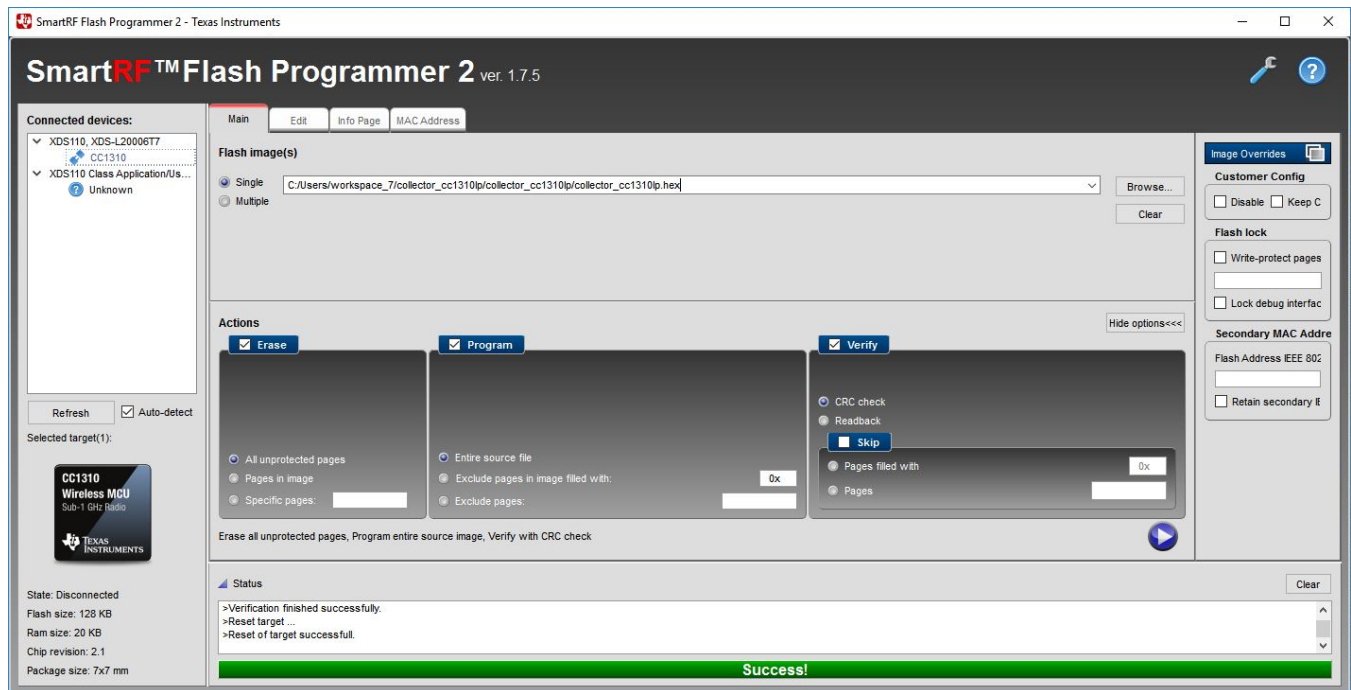

图 **13. Flash Programmer 2 Setup**

3.1.2.3 Receiving Data Packets

As this reference guide previously describes, this reference design is programmed to periodically wake up and measure the temperature and humidity. The CC1310 then sends the data to the sensor-to-cloud gateway. The packet data is shown in 图 14. The data is stored with the first two bytes representing the temperature data and the last two bytes are the humidity. Converting hex format to decimal 0x18 converts to 24°C and the humidity reads 0x2F, which converts to 47% relative humidity.

```
        81 1451.588970              0x0001      0xaabb   TI 802.15.4GE                   72 Data, Dst: 0xaabb, Src: 0x0001
        82 1451.604356                                   TI 802.15.4GE                    7 Ack

> Frame 81: 101 bytes on wire (808 bits), 101 bytes captured (808 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: 0
> TI 802.15.4GE SUN PHY without Mode Switch
> TI 802.15.4GE Data, Dst: 0xaabb, Src: 0x0001
∨ Data (59 bytes)
   Data: 051c77fb08004b12001c0018002f00010000000000000000...
   Text: \005\034w\357\277\275\b
0000  45 00 00 65 00 00 00 00  80 11 b7 31 c0 a8 01 03   E..e.... ...1....
0010  c0 a8 01 03 45 5d 45 5d  00 51 6c c6 00 08 48 61   ....E]E] .Ql...Ha
0020  88 0d 01 00 bb aa 01 00  05 1c 77 fb 08 00 4b 12   ........ ..w...K.
0030  00 1c 00 18 00 2f 00 01  00 00 00 00 00 00 00 00   ...../.. ........
0040  00 00 00 00 00 01 00 01  00 01 00 00 00 00 00 00   ........ ........
0050  00 00 00 00 00 00 00 00  00 00 00 c0 d4 01 00 80   ........ ........
0060  4f 12 00 ee 80                                     O....
```

图 14. Temperature and Humidity Data Packet Capture

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. 图 15 is an example of TI 15.4-Stack-based application OTA traffic being presented as a Wireshark capture.

3.1.2.3.1 *CC13xx 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.
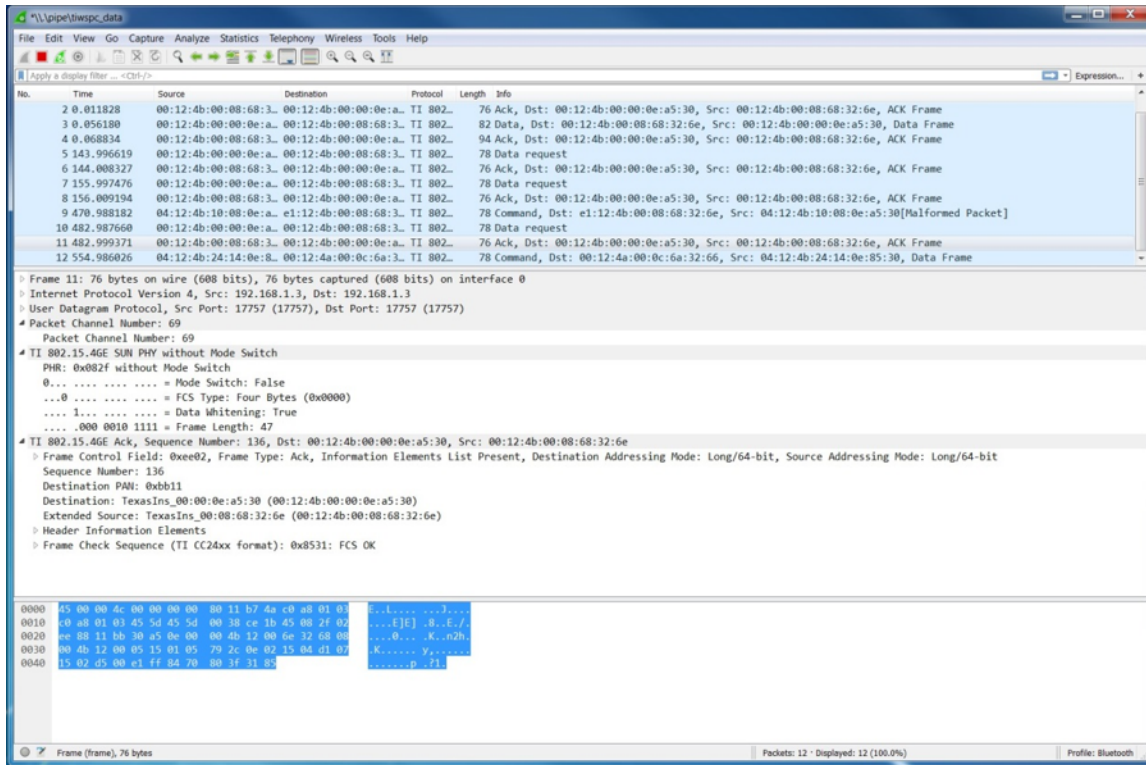

图 **15. Wireshark Packet Sniffer Software**

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*

注**:** Unless otherwise noted, the test data in the following sections is measured with the system at room temperature.

All of the measurements in this section are measured with calibrated lab equipment.

The Humidity and Temperature Sensor Node Reference Design Enabling Sub-1 GHz and Sensor-to-Cloud Networks has been characterized for functional usage including power consumption, relative humidity performance, and temperature performance.

3.2.1 Power Consumption

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

Further characterization is done on the reference design hardware over the voltage range of the design. The test setup for the supply current measurements is illustrated in 图 16.
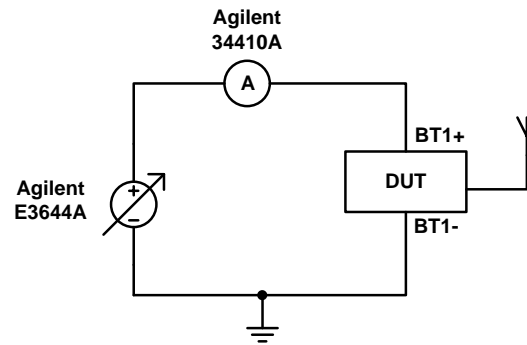
图 **16. Test Circuit Used for Measuring Supply Current**

To compute the battery life, the radio transmission intervals also need to be characterized as these intervals have brief periods of high peak currents before settling to the low microamp current levels measured using the setup in 图 16. The measurement of the radio transmission interval involves using a sense resistor that interfaces to an oscilloscope, which can then be used to trigger on the high current events. Data from this interval is then exported to Microsoft® Excel® to analyze the data. This setup is illustrated in 图 17. A 3.293-Ω sense resistor is placed in series with the power supply on the positive battery terminal. Oscilloscope probes are then attached to each side of the resistor to capture the current waveform during transmission.
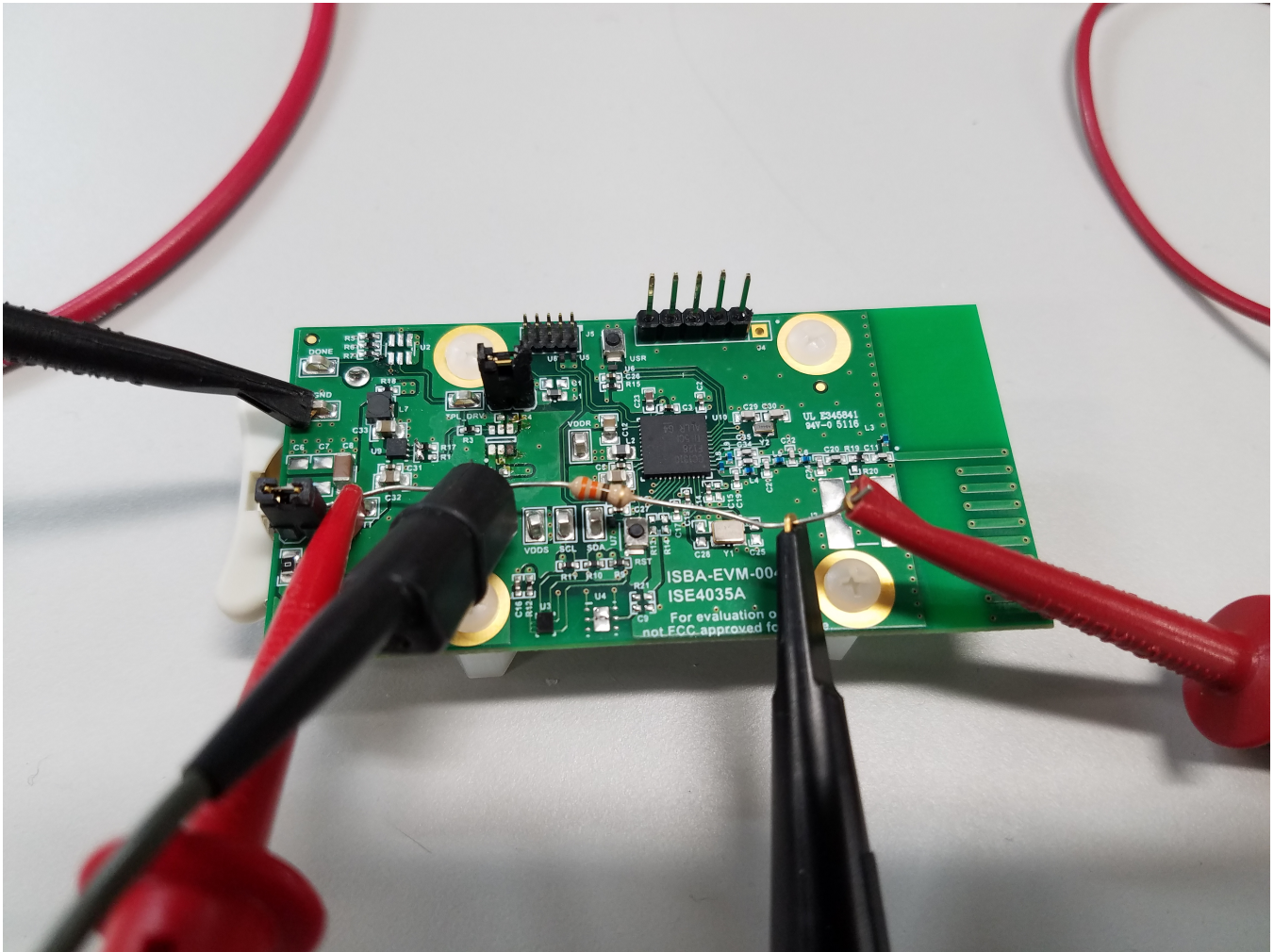
图 **17. Sense Resistor Used to Measure Supply Current During Radio Transmission Intervals**

3.2.1.1   *Power Characterization*

The supply current for the different circuit paths in this design is measured using an initial prototype design. This information is used early in the design process to balance the battery lifetime with motion sensitivity specifications and the sensor bias. This data is also compared to measurements made on the reference design hardware to make sure there is a good correlation between initial results and final results.

The connection events contribute to the majority of the current consumption and therefore influence battery life the most. On first power-up, the reference design must search for and join the network as discussed in 节 2.4.2. The connection event is approximately 51.6 ms long with an average current of 12.84 mA as shown in 图 18. This is quite a bit of current, but this only happens on initial start-up of the device or when the reference design is connected to a new network.
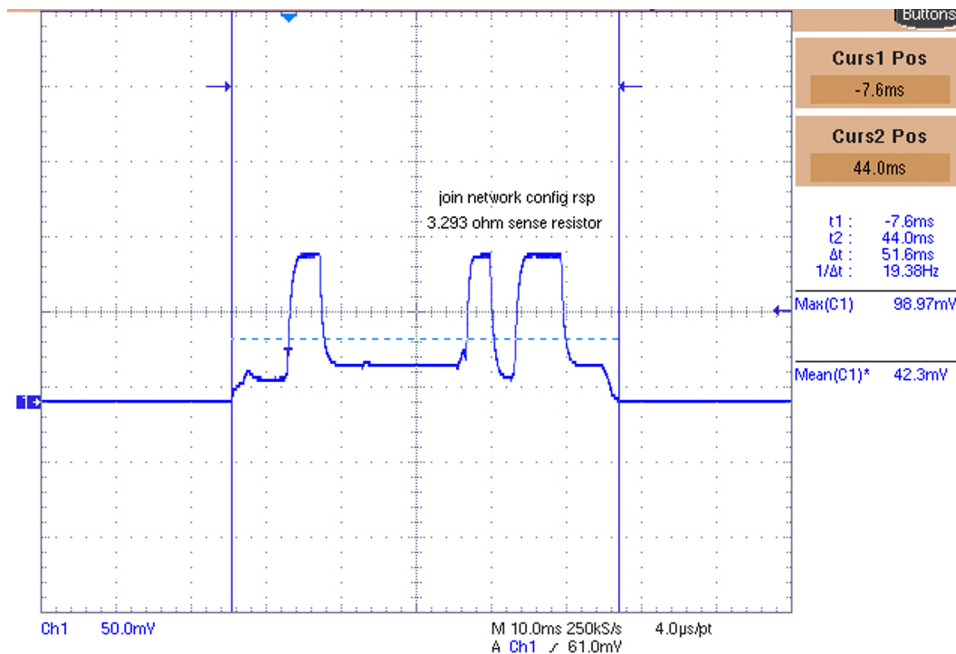

图 **18. Join Sensor-to-Cloud Network Transmission**

图 19 shows the packet sniffer capture of the joining network transmission. The transmission consists of a 14-byte data request packet from the sensor (0x0001), followed by an ACK from the gateway (0xaabb). The gateway sends data and the sensor node acknowledges. After that, the sensor sends the gateway its own data.

1666.381816	0x0001	0xaabb	TI 802.15.4GE	14 Data request
1666.387928			TI 802.15.4GE	7 Ack
1666.392069	0xaabb	0x0001	TI 802.15.4GE	42 Data, Dst: 0x0001, Src: 0xaabb
1666.402686			TI 802.15.4GE	7 Ack
1666.409112	0x0001	0xaabb	TI 802.15.4GE	44 Data, Dst: 0xaabb, Src: 0x0001
1666.420019			TI 802.15.4GE	7 Ack

图 **19. Join Network Packet Sniffer Capture**

The next connection event occurs when the environmental data interval has expired, to optimize battery life the sensor data is sent every 5 minutes. The interval is configurable and battery life can be lengthened by increasing the time between data transmissions. The HDC trigger causes the first little spike and then the MCU must wait for the temperature and humidity conversion before building and sending the data packet. The HDC sensor reading and the transmission takes approximately 41.42 ms with an average current of 11.89 mA as shown in 图 20.
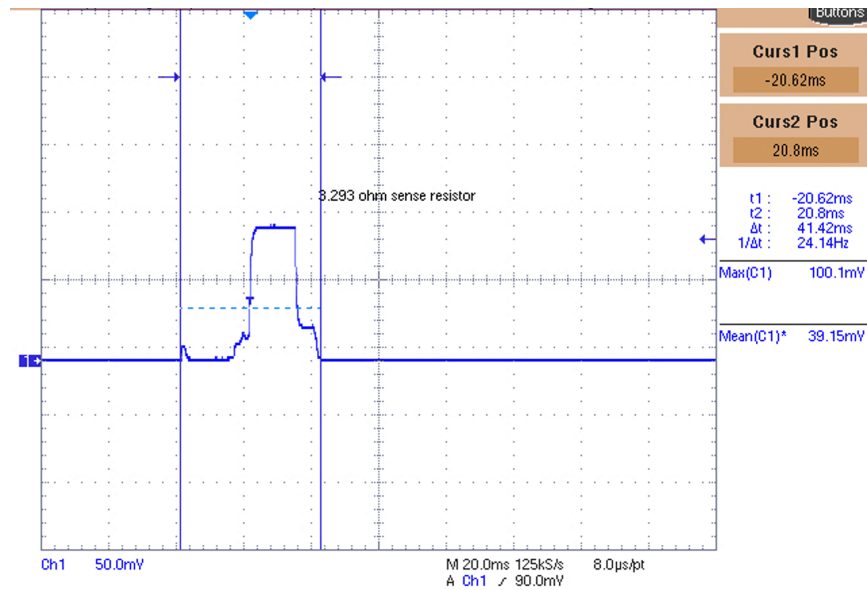
图 **20. Environmental Data Reading and Packet Transmit**

The last connection event is the configuration transmission between the gateway and the sensor node. This occurs on the Configuration Polling interval discussed in 节 2.4.2. 图 21 shows the single packet transmit and the following ACK being received. Other packets follow if there are messages from the gateway or if frequency hopping is enabled because a new frequency is negotiated on each configuration interval. To save power, frequency hopping is disabled and the configuration polling interval was set to 20 minutes. The configuration polling event takes approximately 15 ms with an average current of 12.87 mA as shown in 图 21. This scope capture also shows the HDC sampling and transmit after the configuration polling.
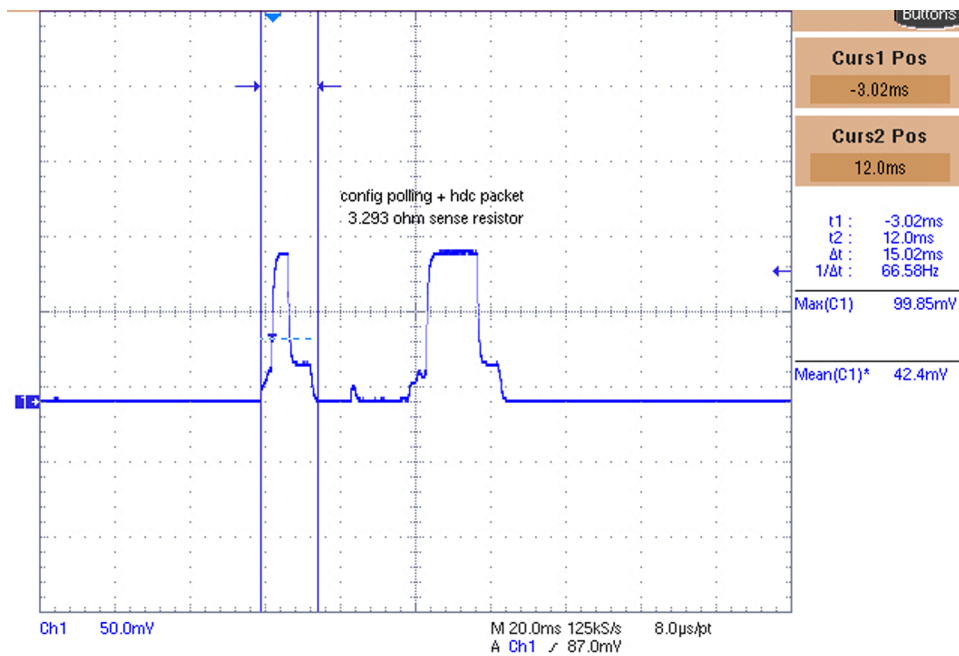

图 **21. Configuration Polling Packet Transmission**

The data values highlighted in this section are used in the following section to calculate the expected battery life for expected use conditions.

3.2.1.2 *Battery Life Calculations*

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

公式 1 describes the estimated battery life of the system:

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

(1)

where:

- t_{Total} is an arbitrary time interval

- t_{Data} is the amount of time spent transmitting data packets

- t_{Poll} is the amount of time transmitting poll packets

If t_{Total} is set equal to the polling interval (20 min or 1200 seconds), then t_{Poll} equals the time it takes to send a single poll packet, 15 ms. The value for t_{Data} is calculated as:

$$t_{Data} = n\left(\frac{Events}{hr}\right) \times \frac{1\,hr}{3600\,s} t_{Total} \times t_{DataPkt}$$

(2)

where:

- *n* is the number of environmental data packets per hour

- $t_{DataPkt}$ is the amount of time it takes to send an environmental data update packet, 41.42 ms

The number of environmental data packets per hour depends entirely on the end-use case. However, for the purpose of this reference design, the following use-case is defined:

- Sensor node installation

- 12 data packet events per hour = Five minute environmental data reporting interval

- Polling interval of 20 minutes

Using these requirements, the t_{Data} can be calculated as follows:

$$t_{Data} = 12\left(\frac{Events}{hr}\right) \times \frac{1\,hr}{3600\,s} \times 41.42\,ms \times t_{Total}$$

(3)

$$t_{Data} = 138.1 \times 10^{-6} \times t_{Total} = 165.68\,ms$$

The equation for the expected battery life for the use case in consideration are as follows.

General lifetime equation:

$$\text{Battery Lifetime}(yr) = \cfrac{240\,mAh}{\left(\cfrac{1.0\,\mu A \times (1200\,s) + 11.89\,mA \times 165.68\,ms + 12.87\,mA \times 15\,ms}{1200\,s}\right)} \times \cfrac{1\,year}{8760\,hours} \times 0.85 = 8.31\,years$$

(4)

The derating factor in these equations accounts for self aging of the battery. Based on these equations, 表 2 and 图 22 show the average expected battery lifetime for this reference design with a 5-minute environmental data reporting interval and the polling interval from 1 minute to 1 hour.

表 2. Battery Lifetime versus Polling Interval

| T_{Poll} (min)	T_{Poll} (s)	$I_{Standby}$ (A)	$t_{Standby}$ (s)	I_{Poll} (A)	t_{Poll} (s)	I_{Data} (A)	t_{Data} (s)	I_{Avg} (A)	BATT CAP (Ah)	DERATING	BATT LIFE (yrs)
1.0E+0	60.0E+0	1.00E-6	59.98E+0	12.87E-3	15.02E-3	11.89E-3	8.28E-3	5.86E-6	240.0E-3	0.85	3.97
2.0E+0	120.0E+0	1.00E-6	119.97E+0	12.87E-3	15.02E-3	11.89E-3	16.57E-3	4.25E-6	240.0E-3	0.85	5.48
5.0E+0	300.0E+0	1.00E-6	299.94E+0	12.87E-3	15.02E-3	11.89E-3	41.42E-3	3.29E-6	240.0E-3	0.85	7.09
10.0E+0	600.0E+0	1.00E-6	599.90E+0	12.87E-3	15.02E-3	11.89E-3	82.84E-3	2.96E-6	240.0E-3	0.85	7.86
20.0E+0	1.2E+3	1.00E-6	1.20E+3	12.87E-3	15.02E-3	11.89E-3	165.68E-3	2.80E-6	240.0E-3	0.85	8.31
21.0E+0	1.3E+3	1.00E-6	1.26E+3	12.87E-3	15.02E-3	11.89E-3	173.96E-3	2.79E-6	240.0E-3	0.85	8.33
24.0E+0	1.4E+3	1.00E-6	1.44E+3	12.87E-3	15.02E-3	11.89E-3	198.82E-3	2.78E-6	240.0E-3	0.85	8.39
27.0E+0	1.6E+3	1.00E-6	1.62E+3	12.87E-3	15.02E-3	11.89E-3	223.67E-3	2.76E-6	240.0E-3	0.85	8.44
30.0E+0	1.8E+3	1.00E-6	1.80E+3	12.87E-3	15.02E-3	11.89E-3	248.52E-3	2.75E-6	240.0E-3	0.85	8.47
33.0E+0	2.0E+3	1.00E-6	1.98E+3	12.87E-3	15.02E-3	11.89E-3	273.37E-3	2.74E-6	240.0E-3	0.85	8.50
36.0E+0	2.2E+3	1.00E-6	2.16E+3	12.87E-3	15.02E-3	11.89E-3	298.22E-3	2.73E-6	240.0E-3	0.85	8.53
39.0E+0	2.3E+3	1.00E-6	2.34E+3	12.87E-3	15.02E-3	11.89E-3	323.08E-3	2.72E-6	240.0E-3	0.85	8.55
42.0E+0	2.5E+3	1.00E-6	2.52E+3	12.87E-3	15.02E-3	11.89E-3	347.93E-3	2.72E-6	240.0E-3	0.85	8.57
45.0E+0	2.7E+3	1.00E-6	2.70E+3	12.87E-3	15.02E-3	11.89E-3	372.78E-3	2.71E-6	240.0E-3	0.85	8.58
48.0E+0	2.9E+3	1.00E-6	2.88E+3	12.87E-3	15.02E-3	11.89E-3	397.63E-3	2.71E-6	240.0E-3	0.85	8.60
51.0E+0	3.1E+3	1.00E-6	3.06E+3	12.87E-3	15.02E-3	11.89E-3	422.48E-3	2.70E-6	240.0E-3	0.85	8.61
54.0E+0	3.2E+3	1.00E-6	3.24E+3	12.87E-3	15.02E-3	11.89E-3	447.34E-3	2.70E-6	240.0E-3	0.85	8.62
57.0E+0	3.4E+3	1.00E-6	3.42E+3	12.87E-3	15.02E-3	11.89E-3	472.19E-3	2.70E-6	240.0E-3	0.85	8.63
60.0E+0	3.6E+3	1.00E-6	3.60E+3	12.87E-3	15.02E-3	11.89E-3	497.04E-3	2.70E-6	240.0E-3	0.85	8.64
64.0E+0	3.8E+3	1.00E-6	3.84E+3	12.87E-3	15.02E-3	11.89E-3	530.18E-3	2.69E-6	240.0E-3	0.85	8.65
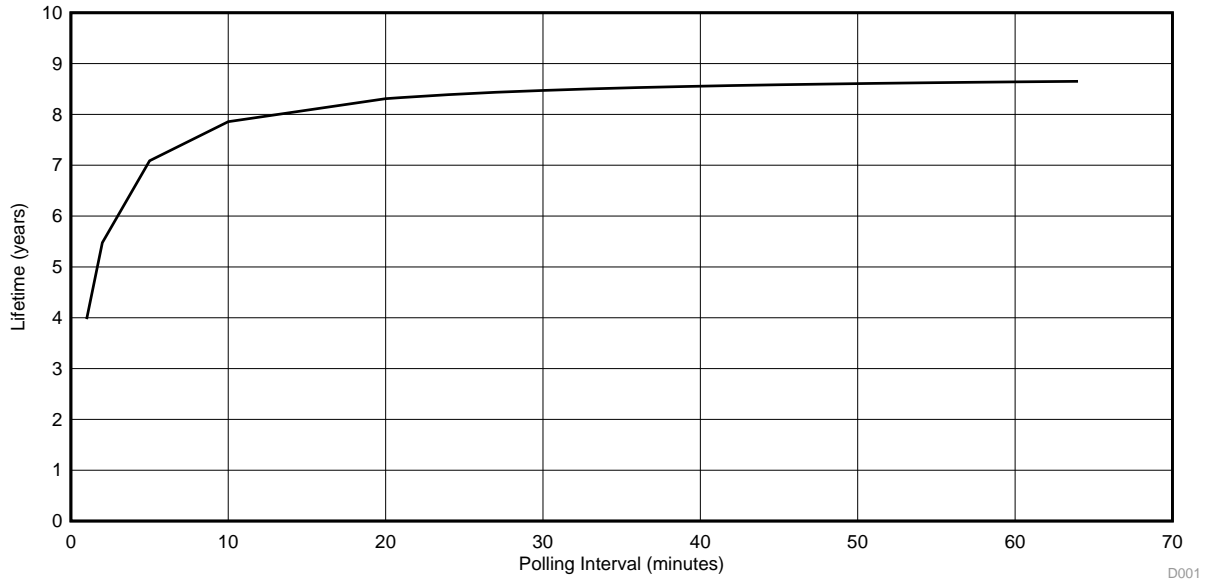
图 **22. Battery Lifetime versus Polling Interval**

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01477.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01477.

4.3 PCB Layout Recommendations

To ensure high performance, the Humidity and Temperature Sensor Node Reference Design Enabling Sub-1 GHz and Sensor-to-Cloud Networks is 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 reference design, take care to adhere to the layout guidelines detailed in the respective data sheets.

4.3.1 Layer Plots

To download the layer plots, see the design files at TIDA-01477.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01477.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01477.

4.6 Assembly Drawings

To download the assembly drawing files, see the design files at TIDA-01477.

5 Software Files

To download the software files, see the GIT repository of TIDA-01477.

6 Related Documentation

1. Texas Instruments, *HDC2010 Low Power, High Accuracy Digital Humidity Sensor with Temperature Sensor Data Sheet*
2. Texas Instruments, *TIDEP-0084 Sub-1 GHz Sensor to Cloud Industrial IoT Gateway Reference Design*
3. Texas Instruments, *CC1310 Simplelink™ Ultra-Low Power Sub-1GHz Wireless MCU Data Sheet*
4. Texas Instruments, *TPL5111 Nano-power System Timer for Power Gating Data Sheet*
5. Texas Instruments, *TPS61291 Low IQ Boost Converter with Bypass Operation Data Sheet*
6. Texas Instruments, *TPS22860 Ultra-Low Leakage Load Switch Data Sheet*
7. Texas Instruments, *TPD1E10B06 Single-Channel ESD Protection Diode in 0402 Package Data Sheet*
8. Texas Instruments, *DN038 Miniature Helical PCB Antenna for 868 MHz or 915/920 MHz Application Report*

6.1 商标

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7   About the Author

JARROD KREBS is a systems designer at Texas Instruments, where he is responsible for developing reference designs in the industrial segment. Jarrod has experience with software and embedded applications implemented on Arm-based microcontrollers and TI's MSP430™ platforms. Jarrod earned his bachelor of science in computer engineering from Kansas State University in Manhattan, KS. Jarrod is also a member of the Institute of Electrical and Electronics Engineers (IEEE).

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