*TI Designs*リファレンス・デザイン

*Bluetooth® Low Energy*接続を搭載し、*4～20mA*の電流ループで駆動されるフィールド・トランスミッタのリファレンス・デザイン

TEXAS INSTRUMENTS

概要

TIDA-00666 TI Designにより*Bluetooth*® low energyを使用し2線式の4～20mAループで駆動される通信が実現します。

TIDA-00666リファレンス・デザインは、Bluetooth Low Energyによりセンサ・データを送信する湿度および温度センサです。TIDA-00666設計はループを電源とし、ループの電流値は湿度に応じて変化します(0%では4mA、100%では20mA)。
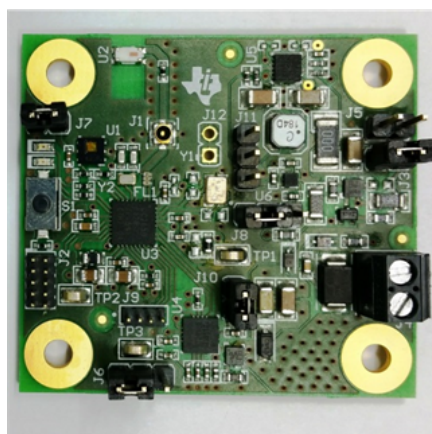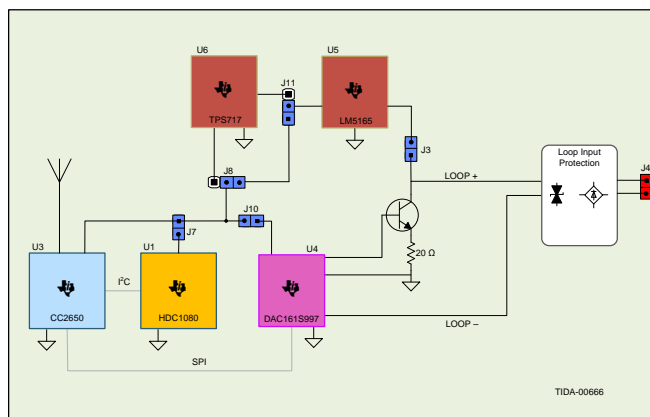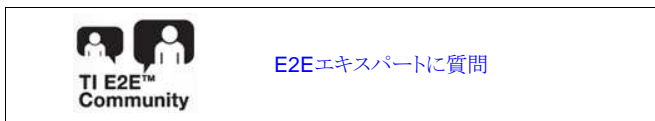
リソース

TIDA-00666	デザイン・フォルダ
CC2650	プロダクト・フォルダ
DAC161S997	プロダクト・フォルダ
LM5165	プロダクト・フォルダ
TPS717	プロダクト・フォルダ
HDC1080	プロダクト・フォルダ

TI E2E™ Community

E2Eエキスパートに質問

特長

- 4～20mAの電流ループ出力信号
- 8～33Vの入力電圧範囲
- 16ビットのループ電流分解能
- 4～20mAのループでBLE通信を駆動
- オンボードの湿度および温度センサ

アプリケーション

- 産業用
- ファクトリ・オートメーションとプロセス制御
- センサおよびフィールド・トランスミッタ
- フィールド・アクチュエータ
- ビルディング・オートメーション
- モノのインターネット(IoT)

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1 System Overview

1.1 System Description

In this TIDA-00666 TI-Design, a digital humidity sensor with an integrated temperature sensor was chosen to demonstrate *Bluetooth* low energy (BLE) communication powered from a 4- to 20-mA current loop. Humidity and temperature are both common measurements required in many industrial systems. Monitoring and maintaining process variables at the appropriate levels is extremely critical in industrial automation and process control. A sensor in the industrial environment either continuously or periodically measures vital parameters such as temperature, pressure, humidity, and so on. The primary challenge of sensing in industrial environments is conditioning low-signal levels in the presence of high-noise and high-surge voltage.

For industrial process control instruments, analog 4- to 20-mA current loops are commonly used for analog signaling, with 4 mA representing the lowest end of the range and 20 mA the highest. The key advantages of the current loop are that the accuracy of the signal is not affected by voltage drop in the interconnecting wiring and the loop can supply the operating power to the device. Even if significant electrical resistance exists in the line, the current loop transmitter maintains the proper current, up to its maximum voltage capability. Such instruments are used to measure pressure, temperature, level, humidity, pH, or other process variables. A 4- to 20-mA current loop can also be used to control a valve positioner or other output actuator.

With TI's SimpleLink™ ultra-low-power wireless MCU platform, low power with a combined radio and MCU enables the Bluetooth low energy communication powered from a 4- to 20-mA current loop. Furthermore, the CC2650 is a multi-standard device, targeting Bluetooth, ZigBee®, 6LoWPAN, and also 802.15.4-based applications. In this TI Design, Bluetooth is the protocol of choice, but the hardware as built can work with other protocols as well.

The design files include schematics, bill of materials (BOM), layer plots, Altium files and Gerber files.

1.2 Key System Specifications

表 1. Key System Specifications

PARAMETERS	SPECIFICATIONS AND FEATURES
Output signal	2-wire 4- to 20-mA current loop according to NAMUR NE43
Power supply voltage range on loop interface terminals	8 to 33 V
Compliance voltage	8 V
Supply current consumption	< 3.3 mA (to power all the functional blocks of the transmitter)
Error output currents	Low: 3.375 mA (typical) High: 21.75 mA (typical)
Reverse polarity protection	Continuous
Input current limit	< 50 mA
Surge transient immunity	Designed to meet IEC 61000-4-5: ±1-kV line-line (DM)
Operating temperature	–40°C to 85°C
Interface connector	2-pin TH Terminal Block, 6 A, 3.5 mm for loop interface
Sensor type	Humidity and temperature

1.3 Block Diagram
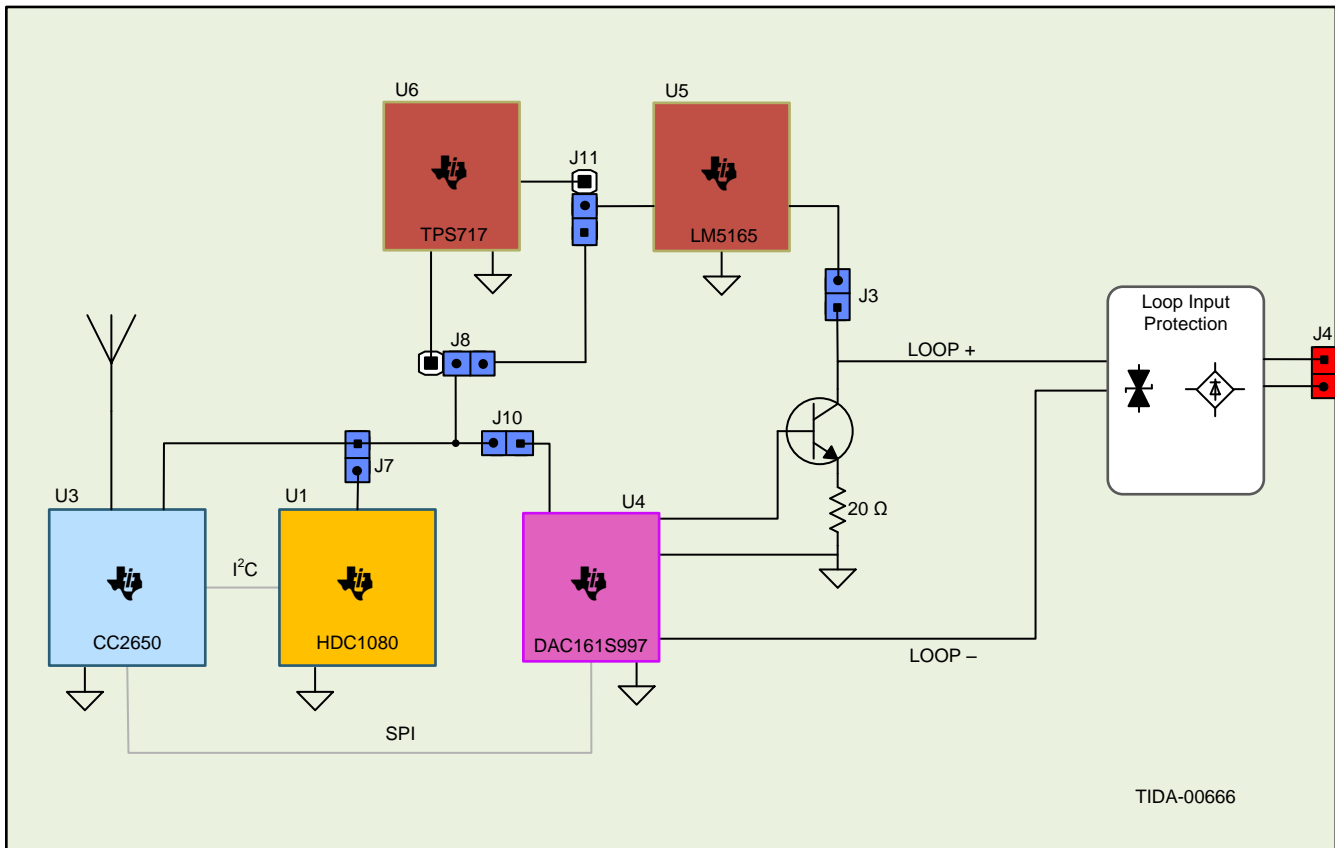
図 1. Block Diagram

1.4 Highlighted Products

The TIDA-00666 Field Transmitter With BLE Connectivity Powered From 4- to 20-mA Current Loop Reference Design features the following devices:

- CC2650: SimpleLink Multistandard 2.4 GHz Ultra-Low-Power Wireless MCU
- DAC161S997: 16-Bit SPI-Programmable DAC for 4- to 20-mA Loops
- LM5165: 3- to 65-V, 150-mA Synchronous Buck Converter With Ultra-Low I_Q
- TPS717xx: Low Noise, High PSRR Low-Dropout 150-mA Linear Regulator

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

1.4.1 CC2650

The CC2650 is a wireless MCU targeting Bluetooth, 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. Its very low-active RF and MCU current and low-power mode current consumption provide excellent battery lifetime and allow for operation on small coin cell batteries and in energy-harvesting applications.

The CC2650 contains a 32-bit ARM® Cortex®-M3 processor that runs at 48 MHz as the main processor and a rich peripheral feature set that includes a unique ultra-low-power sensor controller. This sensor controller is ideal for interfacing external sensors and for collecting analog and digital data autonomously while the rest of the system is in sleep mode. Thus, the CC2650 is 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 and ZigBee stacks are available free of charge from www.TI.com.
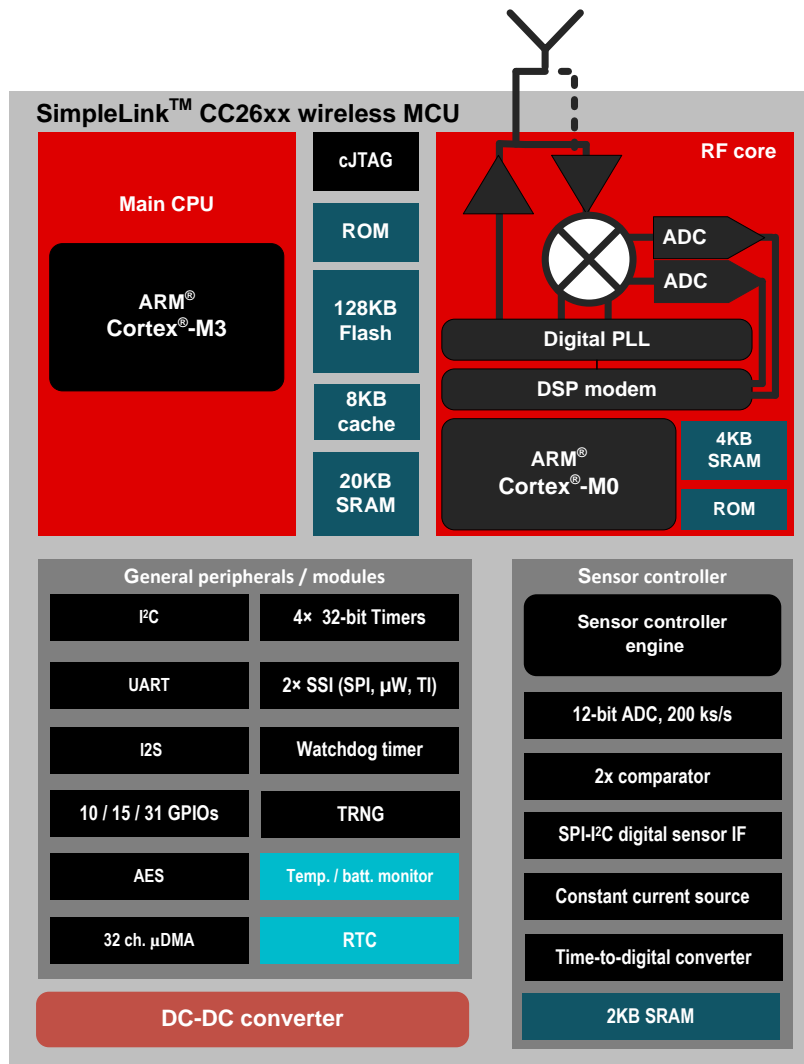
図 2. CC2650 Functional Block Diagram
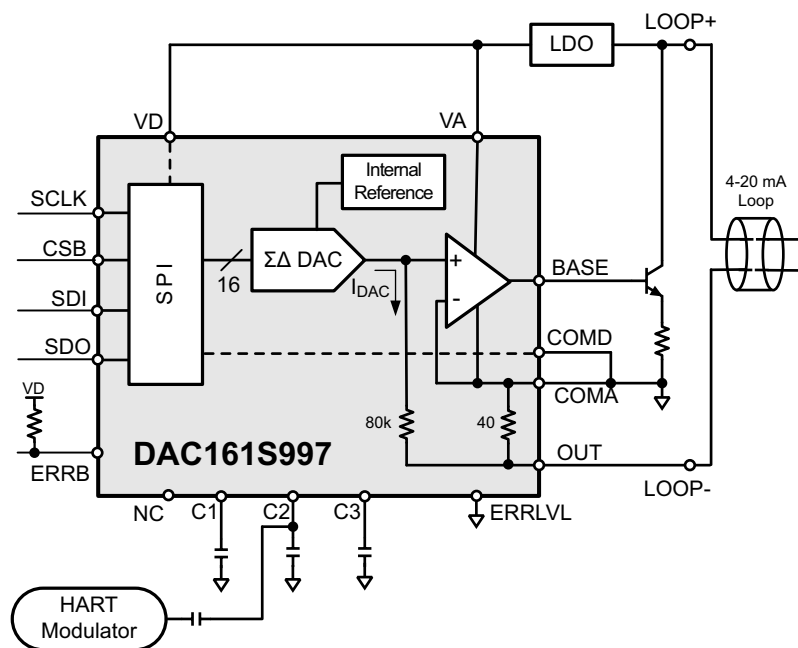
Features:

- Microcontroller
  - Powerful ARM Cortex-M3
  - EEMBC CoreMark® Score: 142
  - Up to 48-MHz clock speed
  - 128KB of in-system programmable flash
  - 8KB of SRAM for cache
  - 20KB of 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
  - 2KB of 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-mm×4-mm RSM VQFN32 (10 GPIOs)
  - 5-mm×5-mm RHB VQFN32 (15 GPIOs)
  - 7-mm×7-mm RGZ VQFN48 (31 GPIOs)
- Peripherals
  - All digital peripheral pins can be routed to any GPIO
  - Four general-purpose timer modules (eight 16-bit or four 32-bit timers, PWM each)
  - 12-bit ADC, 200-ksamples/s, 8-channel analog MUX
  - Continuous time comparator
  - Ultra-low-power analog comparator
  - Programmable current source
  - UART
  - 2× SSI (SPI, Microwire, TI)
  - I^{2}C
  - 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

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- – 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-mm×4-mm and 5-mm×5-mm VQFN 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 (wake up on external events)
- RF section
  - 2.4-GHz RF transceiver compatible with Bluetooth low energy 4.1 Specification and IEEE 802.15.4 PHY and MAC
  - Excellent receiver sensitivity (−97 dBm for Bluetooth low energy and −100 dBm for 802.15.4), selectivity, and blocking performance
  - Link budget of 102 dB/105 dB (Bluetooth low energy/802.15.4)
  - 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™ (CCS)

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1.4.2   DAC161S997

The DAC161S997 is a very low-power 16-bit ΣΔ digital-to-analog converter (DAC) for transmitting an analog output current over an industry standard 4- to 20-mA current loop. The DAC161S997 has a simple 4-wire SPI for data transfer and configuration of the DAC functions. To reduce power and component count in compact loop-powered applications, the DAC161S997 contains an internal ultra-low-power voltage reference and an internal oscillator. The low power consumption of the DAC161S997 results in additional current being available for the remaining portion of the system. The loop drive of the DAC161S997 interfaces to a Highway Addressable Remote Transducer (HART) modulator, allowing injection of FSK modulated digital data into the 4- to 20-mA current loop. This combination of specifications and features makes the DAC161S997 ideal for 2- and 4-wire industrial transmitters. The DAC161S997 is available in a 16-pin 4-mm×4-mm WQFN package and is specified over the extended industrial temperature range of –40°C to 105°C.

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図 3. DAC161S997 Block Diagram

Features:

- 16-bit resolution
- Very-low supply current of 100 μA
- 5 ppm FS/°C gain error
- Pin-programmable power-up condition
- Simple HART Modulator Interfacing
- Highly integrated feature set in small footprint WQFN-16 (4-mm×4-mm, 0.5-mm Pitch)

1.4.3 LM5165

The LM5165 is a compact, easy-to-use, 3- to 65-V, ultra-low I_Q synchronous buck converter with high efficiency over wide input voltage and load current ranges. With integrated high-side and low-side power MOSFETs, up to 150-mA of output current can be delivered at fixed output voltages of 3.3 V or 5 V, or an adjustable output. The converter is designed to simplify implementation while providing options to optimize the performance the target application. Pulse Frequency Modulation (PFM) mode is selected for optimal light-load efficiency or constant on-time (COT) control for nearly constant operating frequency. Both control schemes do not require loop compensation while providing excellent line and load transient response and short PWM on-time for large step-down conversion ratios.

The high-side p-channel MOSFET can operate at 100% duty cycle for lowest dropout voltage and does not require a bootstrap capacitor for gate drive. Also, the current limit set point is adjustable to optimize inductor selection for a particular output current requirement. Selectable or adjustable startup timing options include minimum delay (no soft start), internally fixed (900 µs), and externally programmable soft start through an external capacitor. An open-drain PGOOD indicator can be used for sequencing and output voltage monitoring. The LM5165 is qualified to automotive AEC-Q100 grade 1 and is available in a VSON-10 package with a 0.5-mm pin pitch.
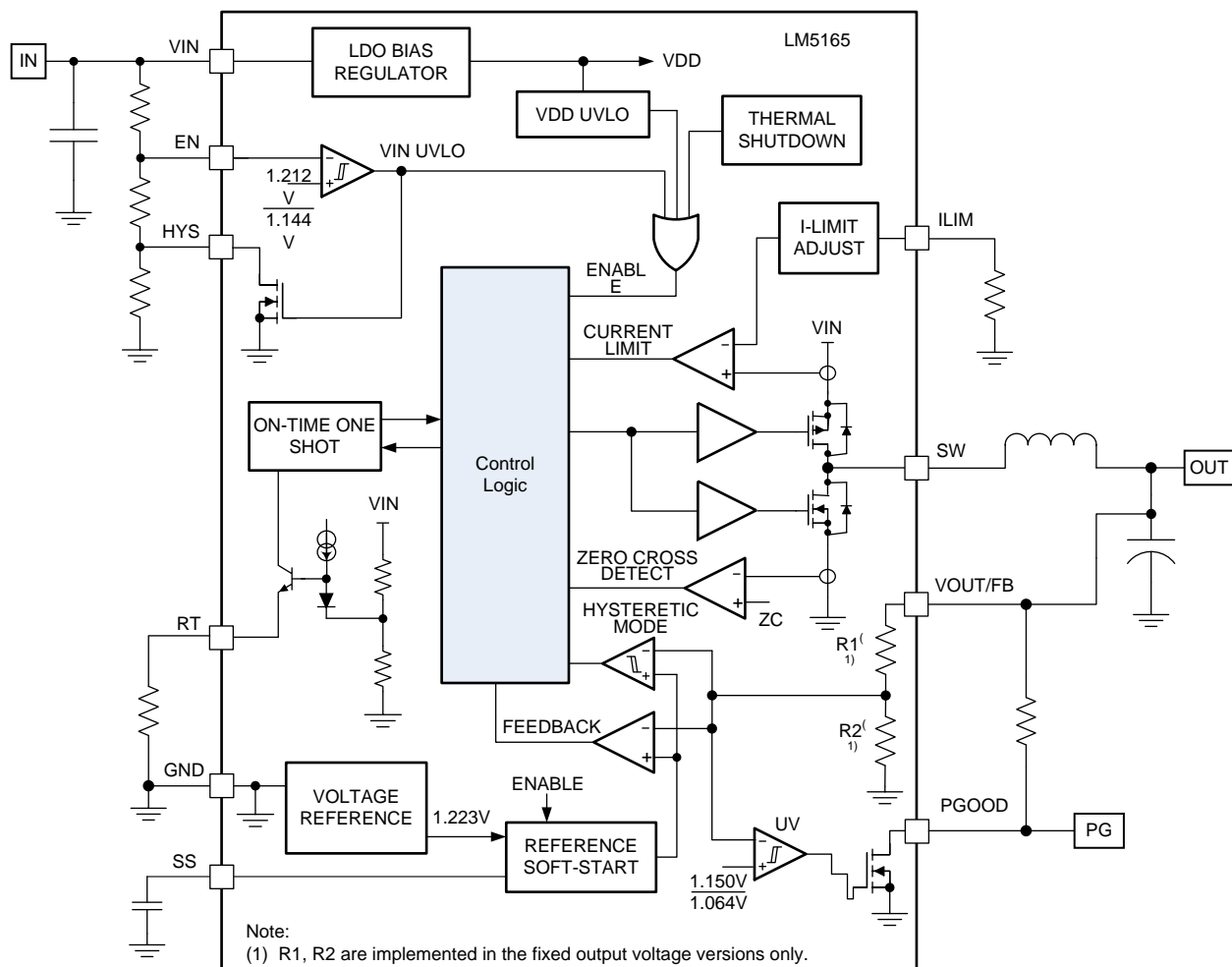
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図 4. LM5165 Functional Block Diagram

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Features:

- Wide input voltage range of 3 to 65 V

- Fixed (3.3 V, 5 V) or adjustable output voltages

- Maximum output current as high as 150 mA

- 10.5-µA no-load quiescent current

- –40°C to 150°C junction temperature range

- Selectable PFM or COT mode operation

- Switching frequency as high as 600 kHz

- Diode emulation mode and pulse skipping for ultra-high light-load efficiency performance

- Integrated 2-Ω PMOS buck switch

    – Supports 100% duty cycle for low dropout

- Integrated 1-Ω NMOS synchronous rectifier

    – Eliminates external rectifier diode

- Programmable current limit set point (4 levels)

- 1.223-V internal voltage reference

- 900-µs Internal or programmable soft start

- Monotonic startup into pre-biased output

- No loop compensation or bootstrap components

- Precision enable and input UVLO with hysteresis

- Open-drain power good indicator

- Active slew rate control for low EMI

- Thermal shutdown protection with hysteresis

- 10-lead, 3-mm×3-mm VSON package

1.4.4 TPS717xx

The TPS717xx family of low-dropout (LDO), low-power linear regulators offers very high power-supply rejection (PSRR) while maintaining very low 45-μA ground current in an ultra-small, five-pin SOT package. The family uses an advanced BiCMOS process and a PMOS pass device to achieve fast start-up, very low noise, excellent transient response, and excellent PSRR performance. The TPS717xx is stable with a 1-μF ceramic output capacitor and uses a precision voltage reference and feedback loop to achieve a worst-case accuracy of 3% over all load, line, process, and temperature variations. The device family is fully specified from T_J = –40°C to 125°C and is offered in a small SOT (SC70-5) package, a 2-mm×2-mm WSON-6 package with a thermal pad, and a 1.5-mm×1.5-mm WSON-6 package, which are ideal for small form factor equipment.

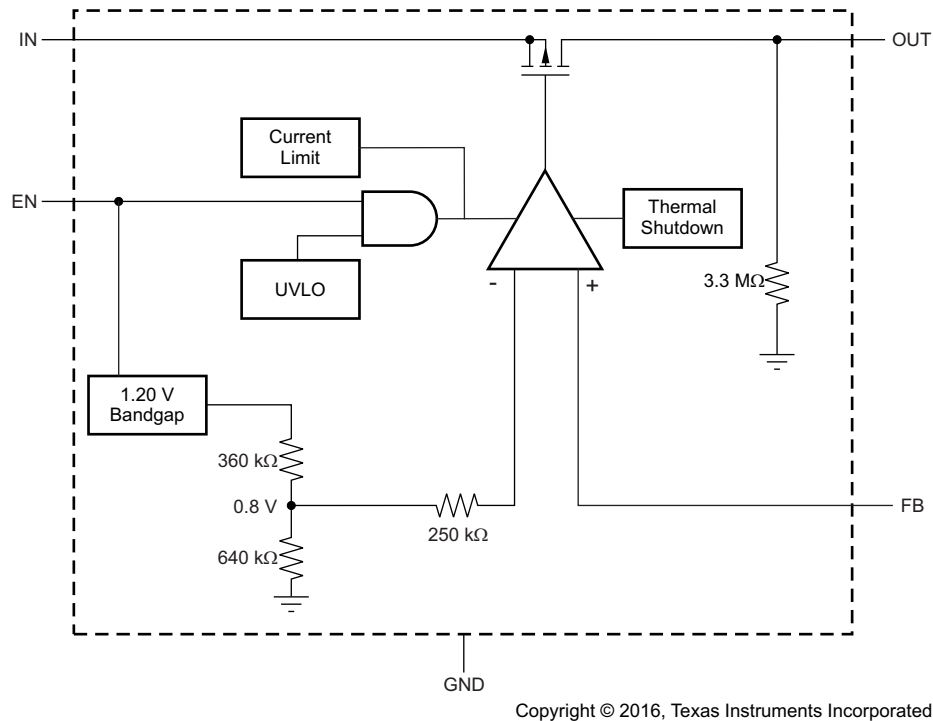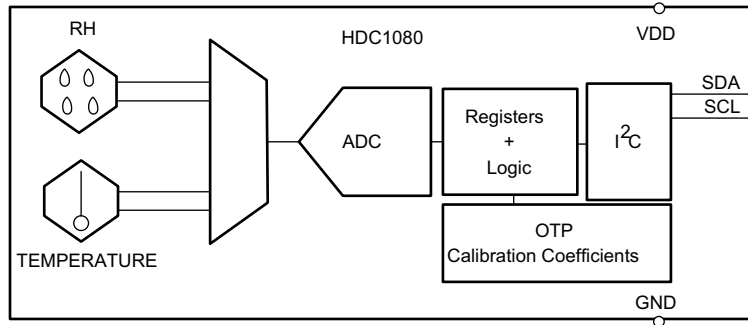Copyright © 2016, Texas Instruments Incorporated

図 5. TPS717xx Block Diagram

Features:

- Input voltage: 2.5 to 6.5 V
- Available in multiple output versions:
  - Fixed output with voltages from 0.9 to 5 V
  - Adjustable output voltage from 0.9 to 6.2 V
- Ultra-high PSRR: 70 dB at 1 kHz, 67 dB at 100 kHz, and 45 dB at 1 MHz
- Excellent load and line transient response
- Very LDO: 170 mV typical at 150 mA
- Low noise: 30 μV_{RMS} typical (100 Hz to 100 kHz)
- Small 5-pin SC-70, 2-mm×2-mm WSON-6, and 1.5-mm×1.5-mm WSON-6 packages

1.4.5   HDC1080

The HDC1080 is a digital humidity sensor with integrated temperature sensor that provides excellent measurement accuracy at very low power. The HDC1080 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 humidity and temperature sensors are factory calibrated.

図 6. HDC1080 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
- Small 3-mm×3-mm device footprint
- I^{2}C interface

2   System Design Theory

A typical current-loop system basically consists of four components as 図 7 shows (typical current-loop system):

- Sensor (temperature, pressure, and so forth)
- 4- to 20-mA current loop transmitter
- Loop power supply
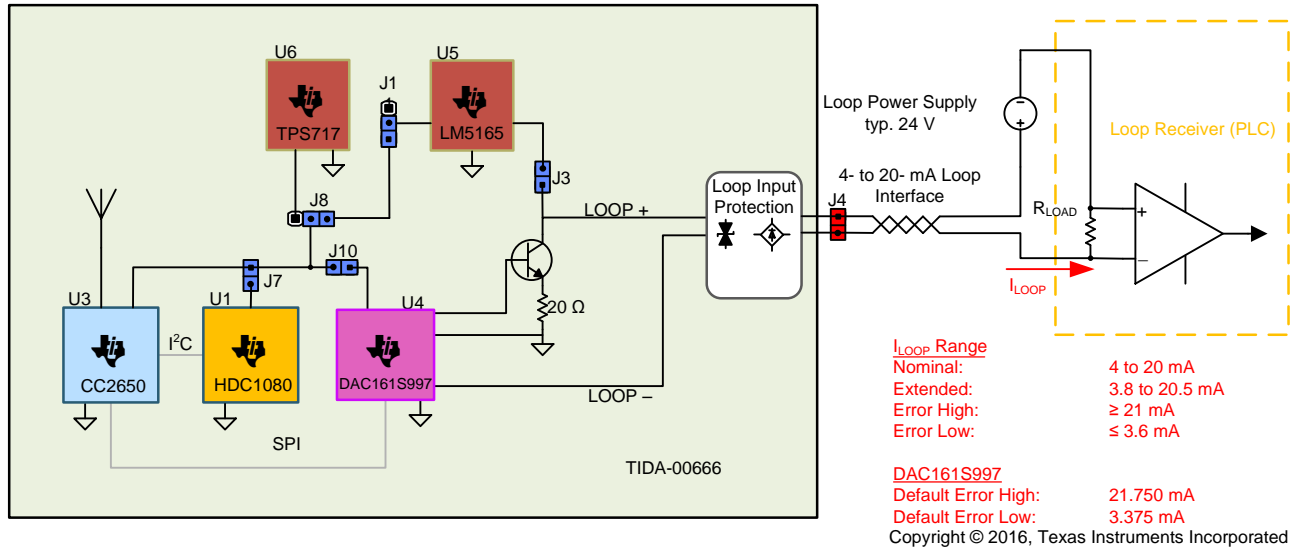- Loop receiver (programmable logic controller (PLC))

図 7. Typical Current-Loop System

The sensor converts a physical parameter (for example, humidity) to an equivalent voltage output. By regulating the current supplied by the loop power supply, the transmitter converts the output of the sensor to a proportional 4- to 20-mA DC current. The zero-value process variable is represented by 4 mA. The full scale process variable is represented by 20 mA. Therefore, a 16-mA span is available to represent the entire measurement information range. The current returns back to the power supply after flowing through a precision load resistor of the loop receiver. Because no system can directly measure the current, the receiver first converts the 4- to 20-mA loop current into a voltage that is easily measured by the analog input module of the PLC system and processed further.

Additional values or value ranges for I_{LOOP} are, for example, specified in the NAMUR recommendation[7], extending the working range from 3.8 to 20.5 mA to support activities like adjustment, calibration, and the detection of range overflow. Furthermore, loop currents below 3.6 mA or above 21 mA are recommended for use for the purpose of failure detection.

Choosing current overvoltage as an information carrier is generally preferential for the following reasons:

- Current loops have inherent immunity against noise.
- Transmitting current signal over long distances does produce the voltage drop (also known as voltage loss or loop drop) across the loop because of wiring resistance. However, the magnitude of signaling is not affected when the loop power supply is high enough to compensate for these losses and still meets the compliance voltage requirement at the transmitter for the transmitter's proper operation.

Basic circuit theory shows that current is the same along the signal line, which means the same amount of current supplied by loop power supply always returns back to the source.

- The residual 4-mA current at zero-point allows easy detection of a wire-break condition. The residual 4-mA current at zero point also allows the transmitter to be powered up if the current requirement is within 4 mA. The current exceeds 20 mA for a short-circuit condition; therefore, current loops are self-monitoring.

- Choosing current over voltage minimizes the cost and simplifies the installation because signal current and transmitter power-supply current share the same pair of conductors.

The complete system is powered by the loop power supply, typically at a 24-V level. This power source forms together with the loop receiver (often a PLC) and with the 2-wire loop powered transmitter, the current loop. A 2-wire cable is sufficient for the electrical connection.
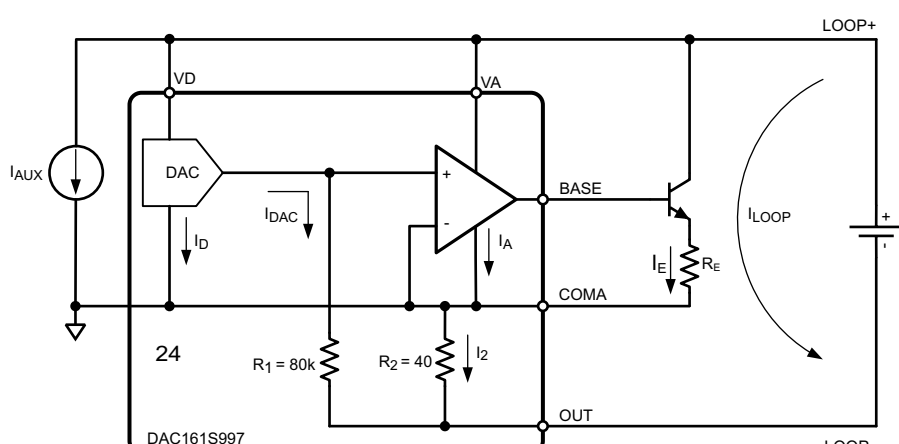
Those two wires are used for powering the transmitter as well as transmitting the signal by controlling the loop current I_{LOOP}, which equals the total current consumption of the transmitter.

On the loop receiver side of the system, the loop current causes a voltage drop across the load resistance R_{LOAD} inside the receiver. This voltage drop is usually amplified and then converted into a digital signal for further processing inside the receiver. Typical receivers are, for example, PLCs. Typical load resistance levels range from some tens of Ω to some hundreds of Ω. With an assumed R_{LOAD} of 250 Ω, which is exemplary, the voltage drop across this resistor changes from 1 to 5 V for loop currents of 4 to 20 mA.

> **注:** This voltage drop reduces the voltage at the loop-input terminals J4. The higher the loop current, the less voltage is available to power the transmitter.

The minimal voltage level required to ensure that the operation of the transmitter is within its performance specification (at the loop-input terminal J4) is called the compliance voltage.

2.1 DAC Theory of Operation

The DAC converts the 16-bit input code in the DACCODE registers to an equivalent current output. The $\Sigma\Delta$ DAC output is a current pulse, which is then filtered by a third-order, resistor-capacitor circuit (RC), low-pass filter, and boosted to produce the loop current (I_{LOOP}) at the device OUT pin. 図 8 shows the principle of operation of the DAC161S997 in the loop-powered transmitter (circuit details are omitted for clarity).
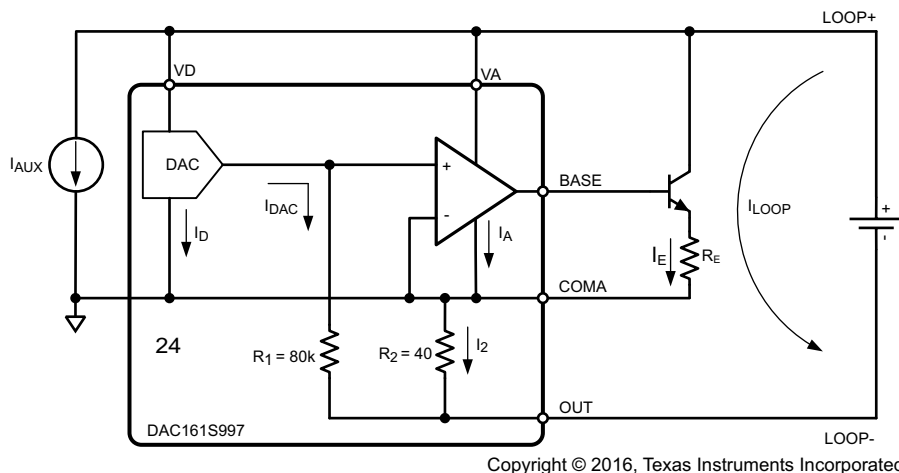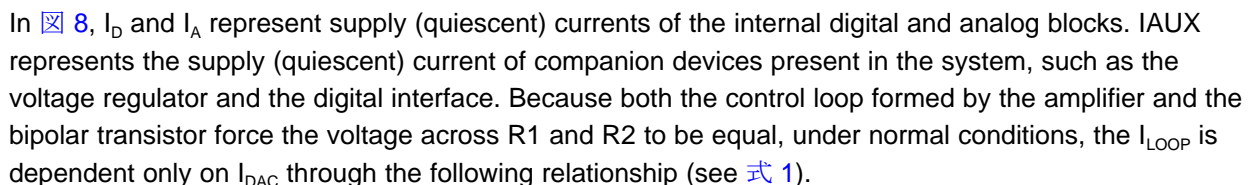

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図 8. Loop-Powered Transmitter

In 図 8, I_D and I_A represent supply (quiescent) currents of the internal digital and analog blocks. IAUX represents the supply (quiescent) current of companion devices present in the system, such as the voltage regulator and the digital interface. Because both the control loop formed by the amplifier and the bipolar transistor force the voltage across R1 and R2 to be equal, under normal conditions, the I_{LOOP} is dependent only on I_{DAC} through the following relationship (see 式 1).

$$I_{LOOP} = (1 + R1 / R2) \times I_{DAC} \tag{1}$$

where:

- $I_{DAC} = f \times DACCODE$

Although I_{LOOP} has a number of component currents, $I_{LOOP} = I_{DAC} + I_D + I_A + I_{AUX} + I_E$, only I_E is regulated by the loop to maintain the relationship shown in 式 1. Because only the magnitude of I_E is controlled, not the direction, there is a lower limit to I_{LOOP}. This limit is dependent on the fixed components (I_A and I_D) and on system implementation through I_{AUX}.

式 2 expresses the output current that is sourced by the OUT pin of the device.

$$I_{LOOP} = 24 \text{ mA (DACCODE} / 2^{16})$$ (2)

The valid DACCODE range is the full 16-bit code space (0x0000 to 0xFFFF), resulting in the I_{DAC} range of 0 to approximately 12 μA. However, this range does not result in the I_{LOOP} range of 0 to 24 mA. The maximum output current sourced out of the OUT pin (I_{LOOP}) is 24 mA. The minimum output current is dependent on the system implementation. The minimum output current is the sum of the supply currents of the DAC161S997 internal blocks (I_A and I_D) and companion devices present in the system, I_{AUX}. The last component current, I_E, is theoretically controlled down to 0; however, because of the stability considerations of the control loop, TI advises not allowing the I_E to drop below 200 μA. 図 9 shows the DC transfer characteristic of the 4- to 20-mA transmitter, including the minimum current limits. The minimum current limit for the loop-powered transmitter is typically around 400 μA ($I_D + I_A + I_{AUX} + I_E$). The typical value for I_D is 57 μA and for the typical value for I_A is 43 μA. The value for I_E depends on the bipolar junction transistor (BJT) device used.
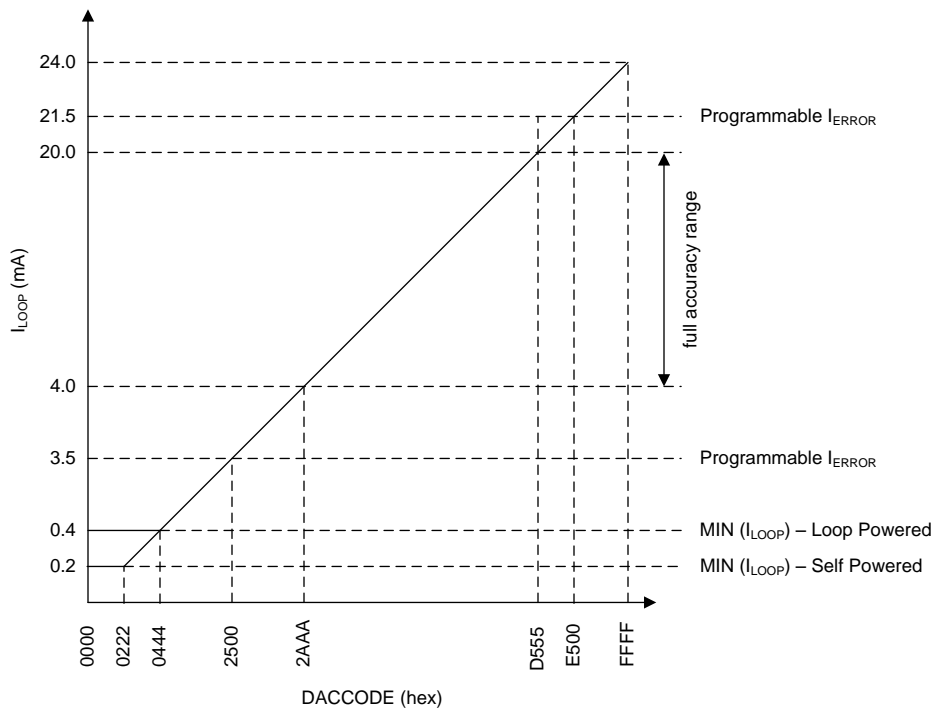

図 9. DAC-DC Transfer Function

The DAC161S997 cannot directly interface to the typical 4- to 20-mA loop because of the excessive loop supply voltage. The loop interface has to provide the means of stepping down the loop supply to 3.3 V.

The LM5165 in this TI Design is used to step down the loop voltage supply to 3.3 V and power the DAC161S997, CC2650, and HDC1080. Optionally, the TPS717xx can be used on this design after the LM5165 to reduce the ripple of the DC/DC regulator.

The second component of the loop interface is the external NPN transistor (BJT). This device is part of the control circuit that regulates the output current of the transmitter (I_{LOOP}). Because the BJT operates over the wide current range, spanning at least 4 to 20 mA, degenerating the emitter is necessary to stabilize the transconductance of the transistor (gm). The degeneration resistor of 20 Ω is suggested in typical applications. See 図 8 for circuit details.

The NPN BJT must not be replaced with an N-channel field-effect transistor (FET) for the following reasons: discrete FETs typically have high threshold voltages (VT), in the order of 1.5 to 2 V, which is beyond the BASE output maximum range; discrete FETs present higher load capacitance, which may degrade system stability margins; and the BASE output relies on the base current of the BJT for biasing.

2.2 Humidity and Temperature Sensing

In this TI Design, a digital humidity sensor with an integrated temperature sensor was chosen to demonstrate a complete wireless field transmitter powered from a 4- to 20-mA loop. Humidity and temperature are both common measurements required in many industrial systems. With a relative humidity accuracy of ±2% and a temperature accuracy of ±0.2°C, the HDC1080 from Texas Instruments is ideally suited to accurately sense environmental information. The innovative placement of the HDC1080 sensing element on the bottom of the device provides resistance to dust, dirt, and other environmental contaminants, which improves system reliability for industrial applications. Furthermore, the power consumption of the HDC1080 is extremely low, averaging 1.3 μA at one sample per second measurement rate and interfacing to the device is straightforward with any microcontroller platform using the I^{2}C communication protocol.

2.3 Wireless Communication

The CC2650 platform comes ready to use, royalty free, and with certified wireless protocol stacks, TI RTOS, CCS integrated development environment (IDE), development tools, online training, and E2E community support.

The TIDA-00666 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 HDC1080 outputs it; no post-processing or correction is implemented on the CC2650 itself.

The advertising is done periodically every 100 ms. An advertising event is where the (Bluetooth) peripheral device broadcasts information in order to either share information or become connected to a (Bluetooth ready) central device, such as a smart phone. The device wakes up and broadcasts packets on three separate channels. For a non-connectable beacon, there are no RX states during the advertising event, which reduces the power consumption further.
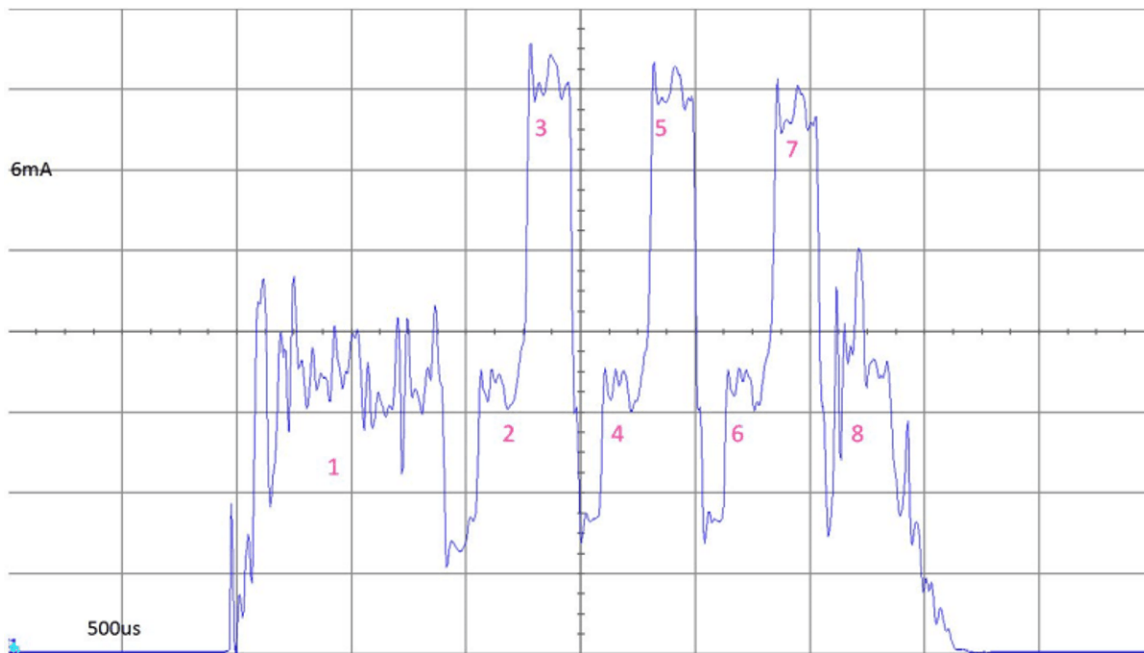
図 10. Beacon Event

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表 2. Beacon Event, State Analysis

PLACEHOLDER	STATE	TIME (μs)	CURRENT (mA)	COMMENTS
1	Pre-processing	1160	3.26	RTOS wake-up, radio setup, XTAL guard time
2	Radio preparation	101	4.3	The radio is turned on and in transition to TX
3	TX	144	7.47	The radio transmits an advertisement packet on Channel 37. Time is dependent on amount of transmitted data
4	TX-to-TX transition	372	3.56	TX to TX transition
5	TX	144	7.47	The radio transmits an advertisement packet on Channel 38. Time is dependent on amount of transmitted data
6	TX-to-TX transition	372	3.56	TX to TX transition
7	TX	144	7.47	The radio transmits an advertisement packet on Channel 39. Time is dependent on amount of transmitted data
8	Post-processing and going to standby	685	2.45	Bluetooth low energy protocol stack sets up the sleep timer in preparation for the next event and then going to standby afterwards

2.4 Power Design

While a basic sensor transmitter circuit's MCU and data converters are usually optimized for low operating current, the added functionality in high-performance smart sensor applications leads to increased current demand. For example, current consumption is greater when the circuit includes features such as isolation, calibration and diagnostics, a liquid crystal display (LCD) interface, or wireless connectivity options such as Bluetooth low energy or wireless HART®.

Such intelligent sensor systems may not be able to meet typical underscale current thresholds or the 4-mA zero-scale level of the 4- to 20-mA current loop. For example, the default loop currents that demarcate low- and high-error currents for TI's DAC161S997 are 3.375 mA and 21.75 mA, respectively.

The NAMUR NE43 specification has similar current thresholds. Fortunately, a high-efficiency synchronous buck converter provides higher output current than a low-dropout regulator (LDO) to power sensor electronics, while harvesting less than 3.375mA from the loop.

For powering sensors, the LM5165 synchronous buck solution from TI has high-efficiency and ultra low quiescent current (I_Q = 10.5 μA). Operating from a wide input voltage (V_{IN}) range and capable of sustaining repetitive 65-V surges, its output voltage is immune to large and noisy voltage swings at the input. Such transient immunity performance is critical in sensor applications that require high reliability.

図 11 shows the converter schematic configured for an output of 3.3 V. Adding an input filter with reverse polarity and transient or surge voltage protection helps achieve electromagnetic compatibility (EMC).
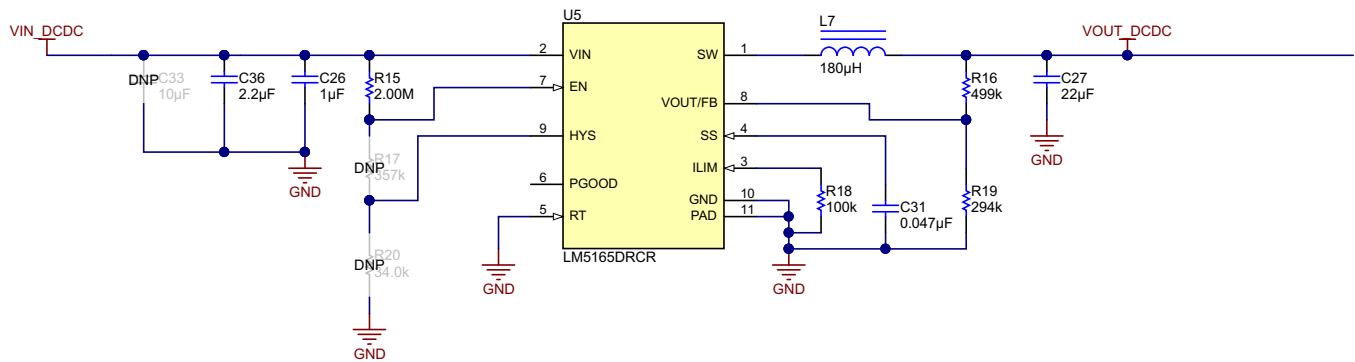
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図 11. Synchronous Buck Converter Schematic

図 12 shows the LM5165 converter efficiency and power dissipation for a load current from 0.1 to 30 mA at V_{IN} = 8 V.
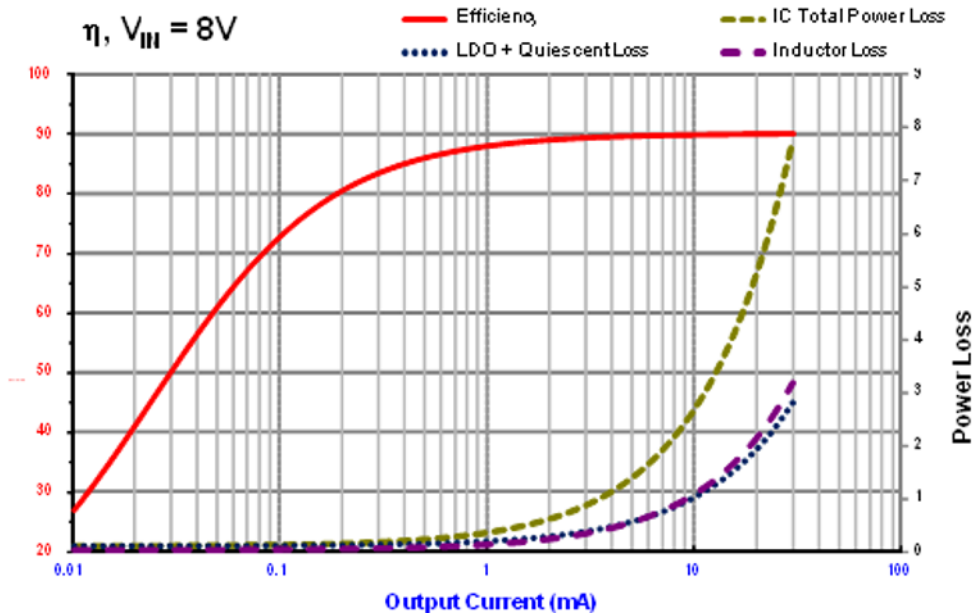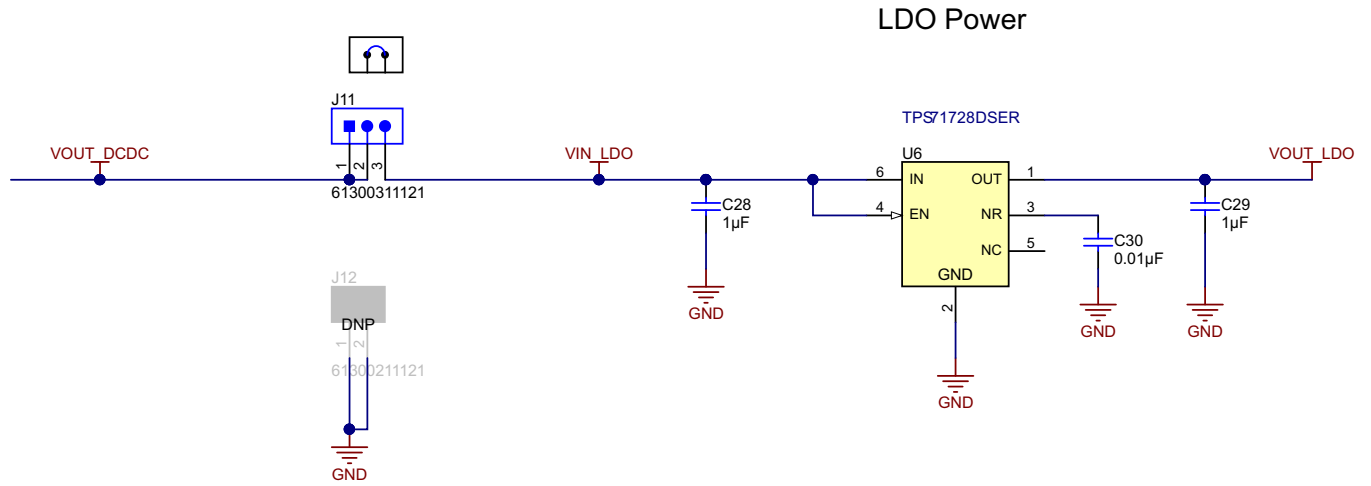

図 12. Typical Efficiency of LM5165 Buck Converter (Output Rated for V_{IN} = 8 V)

To reduce the noise of the LM5165 output, the TPS71728 can be optionally connected to the output of the LM5165. The TPS717xx family of LDO, low-power linear regulators offers very high power supply rejection ratio (PSRR) while maintaining very low 45-μA ground current in an ultra-small, five-pin SOT package. The output voltage of the TPS71728, which is used in this TI Design, is 2.8 V and can be used to power the TIDA-00666.

LDO Power

図 **13. TPS71728 Schematic**

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2.5 Protection

2.5.1 Protection for IEC61000-4

The input overvoltage protection of this design protects all blocks and components of the transmitter that can be considered to have a more-or-less direct connection to the loop.

The nominal maximum input voltage expected is provided either by dedicated modules of the PLC or by a separate (DIN rail) power supply. Possible overvoltage events are mainly transients and overvoltage pulses, which can be caused by the following events:

- Supply voltage overshoot during the power up of the power supply
- The presence of coupling and crosstalk between the loop cable and adjacent cables with large voltage or current transients on these adjacent cables
- Surge, burst, or ESD pulses leading to differential mode voltages (such pulses are used, for example, in EMC compliance testing during the approval procedure of the complete transmitter)

Out of these transients, the most critical pulse (according to the EN 61000-4-5 standard) is the 8/20-μs surge pulse coupled through a total resistance of 42 Ω and through a coupling capacitor of 0.5 μF differentially into the loop input. This design was created with the intention of handling this critical surge pulse.

A bidirectional TVS diode (D4) and a ceramic capacitor (C15) are used to clamp any overvoltage transient on the loop input terminal J4 to a safe voltage level that is independent of the transient voltages polarity. This overvoltage clamping provides a safe voltage level to the BJT controlled by the 4- to 20-mA DAC inside the transmitter electronics.
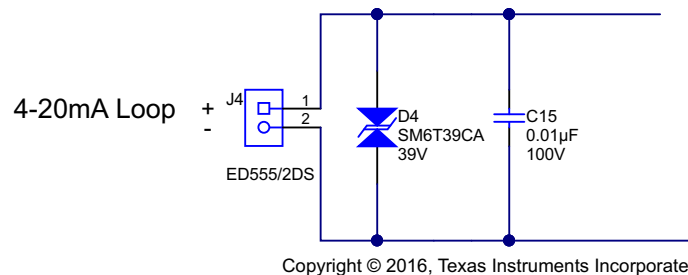

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図 14. Input Overvoltage Protection

2.5.1.1   TVS Diode Selection D4

To choose the TVS appropriately for this TI Design, the following requirements must be satisfied:

1. The TVS stand-off voltage V_{RM}—the voltage where the TVS does not conduct—must be higher than the maximum nominal loop-input voltage to prevent the TVS from conducting during normal operation. For most projects and applications, the condition not conduct can be considered to be fulfilled if the leakage current I_{RM} of the TVS at the given V_{RM} is less than 100 µA. However, the leakage current inside the protection block is not seen by the DAC at all, but adds to the loop current seen by the loop receiver, which causes an error. Therefore, for this design, a leakage current much less than 3 µA was targeted. Because the leakage currents usually grow with increased temperature, the I_{RM} specification of the TVS should be given not only at the maximum nominal loop-input voltage, but also at the maximum operating temperature (85°C) of the design.

2. The TVS peak current and peak pulse power specifications must be higher than the surge current and pulse power under the design-specific conditions. Most of the TVS diode manufacturers specify the device with respect to a 10/1000 µs double-exponential test pulse. However, the pulse used for surge test according to EN 61000-4-5 is an 8/20-µs pulse. Ideally, TVS manufacturers provide the specification for this shorter pulse also. If not, the *Peak-Pulse Power Versus Pulse Time Graph*, which shows how the peak-pulse power of the TVS is affected by shorter or longer pulse duration needs to be used. For shorter pulse widths, the TVS can withstand a higher-peak pulse power.

3. When the TVS conducts and becomes low-impedance to clamp the voltage at a safe level, the TVS clamping voltage V_{CL} at the specific peak pulse current I_{PP}, and at the maximum operating temperature of the design must be lower than the maximum recommended operating voltage of the circuits connected to that voltage.

The affected parts in this design are:

- LM5165 – U5

- BJT controlled by the 4- to 20-mA DAC

- Diodes in the reverse-polarity protection

- Input capacitor C15

The selected TVS is an SM6T39CA, fulfilling these three requirements:

1. I_{RM} (max): 1 µA at V_{RM} = 33.3 V and at 85°C — this is much less than the required 3-µA I_{RM} (max): 0.2 µA at V_{RM} = 33.3 V and at 25°C

2. The datasheet specifications for the 8/20-µs pulse are as follows:
   - I_{PP} (max): 57 A
   - P_{PP} (max): 4 kW

   Both parameters are much higher than the application specific values:
   - I_{PP}: approximately 22.6 A
   - P_{PP}: approximately 1.2 kW

3. V_{CL} (max at 100°C) is approximately 55 V

2.5.1.2 *Selection of Input Capacitor C15*

To bypass the higher-frequency transient voltages caused by burst or ESD, a 10-nF ceramic X7R capacitor was selected. With the 100-V DC voltage rating of the capacitor, the device matches the clamping voltage of the TVS with plenty of margin.

2.5.1.3 *Reverse Input Protection*

The reverse input voltage protection enables a transmitter to withstand operation at reverse input voltage conditions on the loop input (J4). Examples of such conditions are as follows:
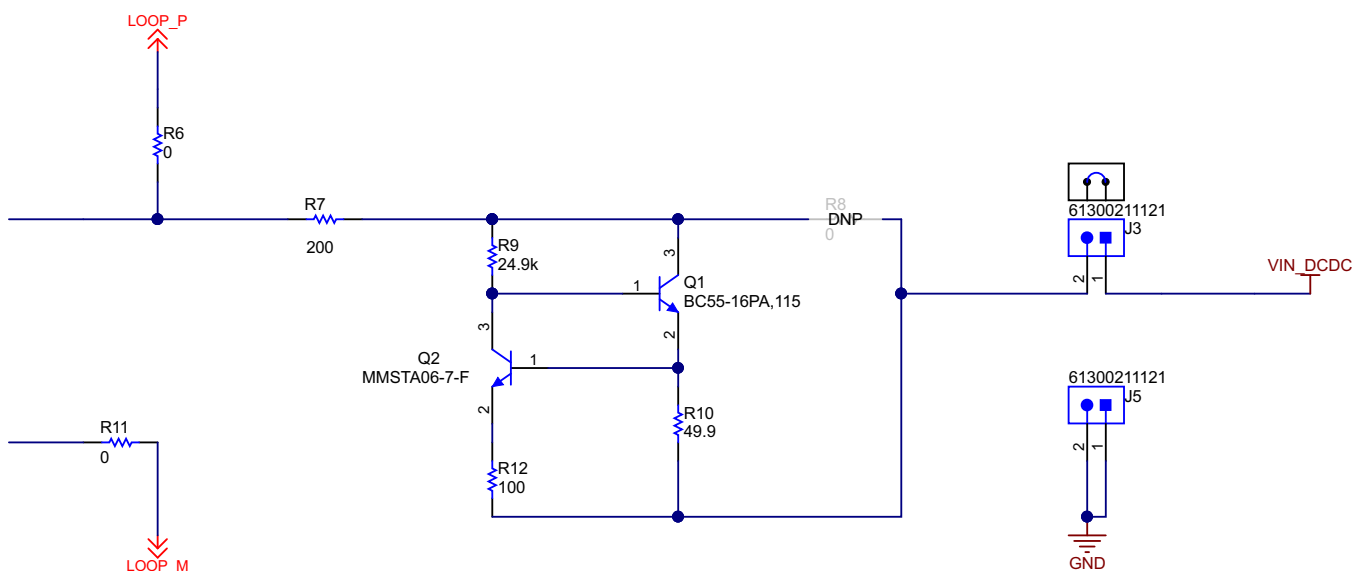
- Interchange of the two wires at the loop input terminals due to miswiring (interchange can last continuously).

- Negative differential-mode surge pulses (can occur due to lightning events or during testing by applying the negative 1-kV surge pulse, according to the EN 61000-4-5 standard).
  The positive and negative input terminals are protected separately by protection diodes. Schottky diodes are preferred, due to their low forward voltage (VF). The huge, high-temperature reverse currents (IRs) of the Schottky diodes (hundreds of μA at > 85°C) do not matter if the diodes are forward-biased. The two forward-biased Schottky diodes D3 and D6 cause a total worst-case VF drop of only 880 mV at 3.3 mA and −40°C.
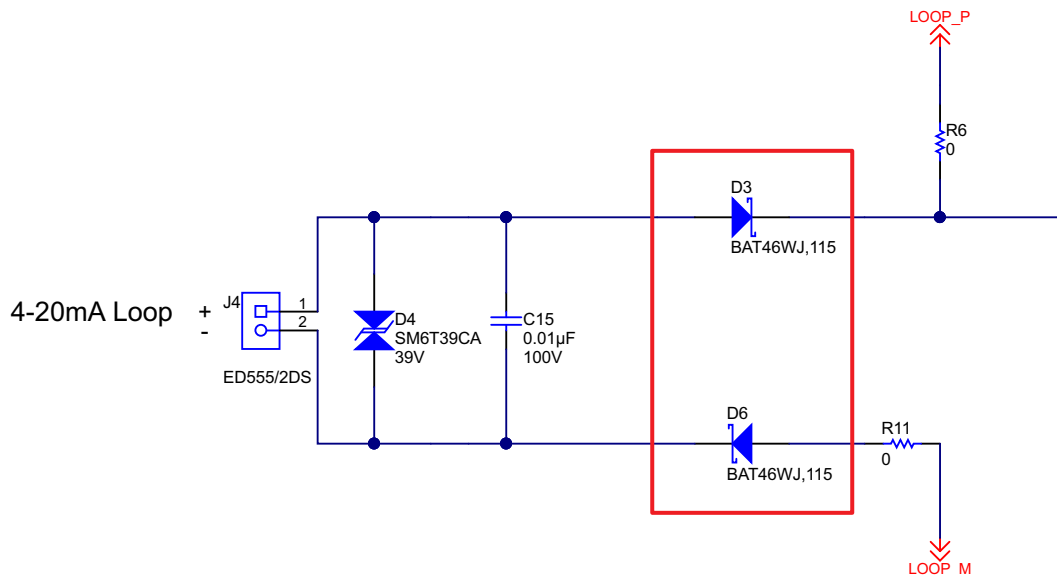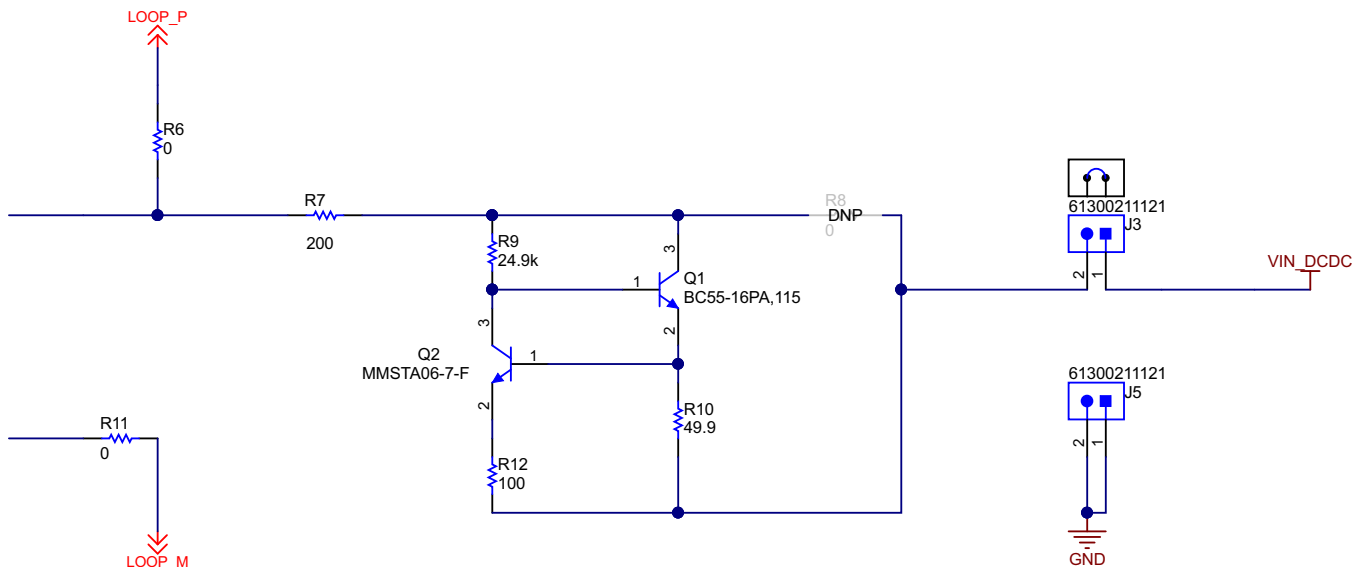

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図 15. Input Reverse Protection

2.5.1.4 Current Limiter and Circuitry to Protect Current-Sensing Circuitry

As 図 16 shows, a dedicated circuit block is responsible for reducing any inrush or surge current. The main concern here is to protect the 40-Ω current sense resistor inside the DAC161S997. Inrush and surge currents are caused by sudden increase in the voltage applied to the loop input terminals. The inrush or surge current charges C36 and C26 from the voltage that C36 and C26 previously hold to the same voltage level as the input terminals. This charge can happen during the following events:

- During initial power-up: This occurrence is especially true when the loop power supply does not have a set, dedicated low-current limit.

- During sudden voltage step of a maximum 33 V (maximum input voltage)

- During 1-kV differential surge: This event is clamped by TVS diode D4 to approximately 60 V, which results in a voltage step of 52 V. These events occur under the assumption that the voltage on the loop input terminals is at the minimum V_{IN} of 8 V before the 1-kV surge.

The 200-Ω resistor (R2) serves as the passive type of current limiter. The active current limiter (which consists of Q2, Q3, and R20 to R22), provides an easy way to limit the current to a value programmable by R10. The active current limiter can be disabled (shorted) by populating R8.
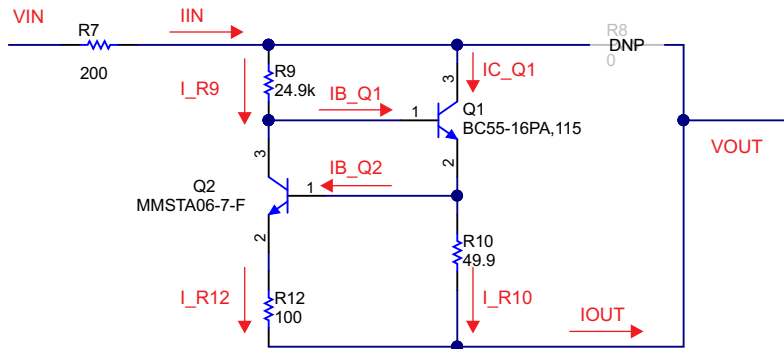

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図 16. Current Limiter and Sense Resistor Protection

The main path for the current flow is controlled by Q1 in 図 17. provides the relation between the main currents:

$$I_{OUT} = I_{IN} + I_{R10} + I_{R12} \tag{3}$$

- The influence of Q2 and R12 on the current flow is negligible if the difference in voltage between V_{IN} and V_{OUT} (designated as $V_{IN} - V_{OUT}$) is less than 2.5 V.

- In this range of differences less than 2.5 V, the output current is completely provided by Q1 through R10. R9, R10, and the DC current gain of Q3 determine the value of I_{OUT}. R9 is biasing Q1 with the base current IB_{Q1}. For a $V_{IN} - V_{OUT}$ of 2.5 V, the I_{OUT} is in the range of 9 mA.

- For voltage differences larger than 2.5 V, Q2 activates and finally tries to keep the voltage across R10 at the sum of its base-emitter voltage V_{BE} and the voltage drop across R12.

- For a $V_{IN} - V_{OUT}$ from 3 to 40 V, the I_{OUT} rises from 10 mA to slightly more than 15 mA (see 図 17).

- R12 stabilizes the circuitry against temperature changes.

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図 **17. Active Current Limiter Schematics and Operation**
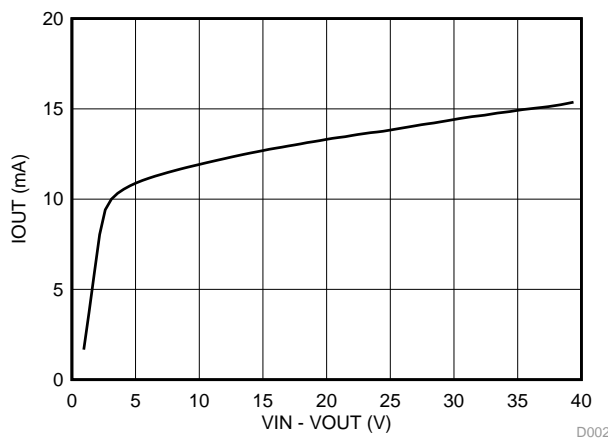
図 **18. Active Current Limiter Characteristic (I_{OUT} versus $V_{IN} - V_{OUT}$)**

3   Getting Started Hardware and Firmware

3.1   Hardware Overview

The Wireless Field Transmitter TI Design hardware is shown in 図 19. All of the integrated circuits (CC2650, DAC161S997, HDC1080, LM5165, and TPS717) are located on the top side of the PCB. The 2.4-GHz chip antenna is also located on the top side of the PCB. There are four unused GPIOs that have been brought out from the CC2650 to the header J9 to facilitate future prototyping and debugging.
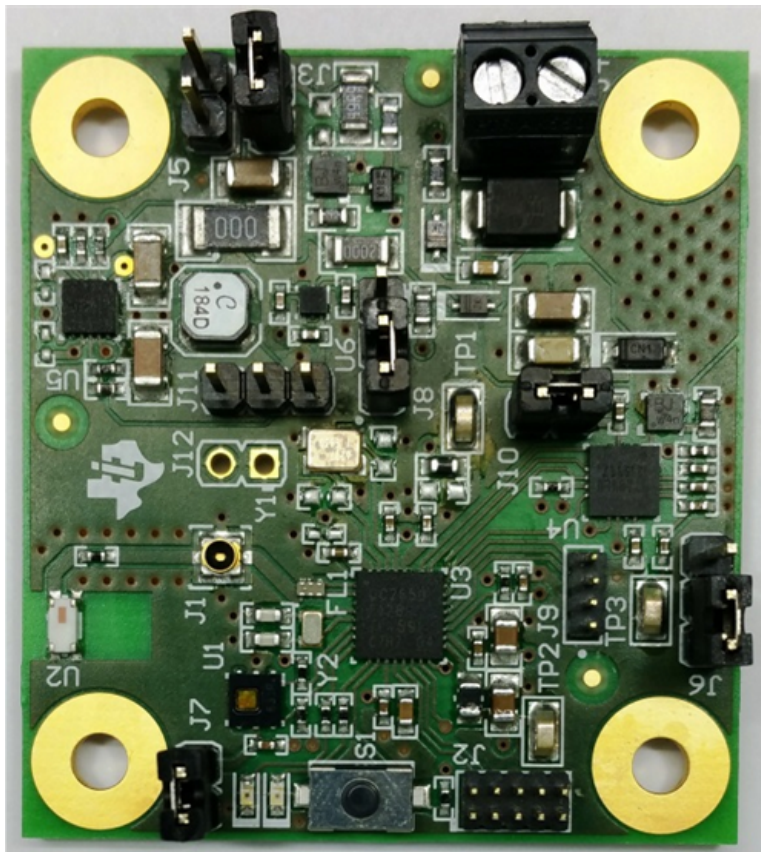

図 19. TIDA-00666 Wireless Field Transmitter Reference Design

3.1.1 Jumper Settings

図 20 shows the default jumper settings on the TIDA-00666 board. In this configuration, the board is powered from the LM5165 and the TPS71728 is not used. Header J11 needs to be open and pin 2 and pin 3 on header J8 needs to be connected. To set the output current error level for the DAC161S997 to 3.375 mA, pin 2 and pin 3 on header J6 need to be connected. To enable the TPS71728 and use it to power the board, pin 2 and 3 on header J11 need to be connected and pin 1 and 2 on header J8 need to be connected.
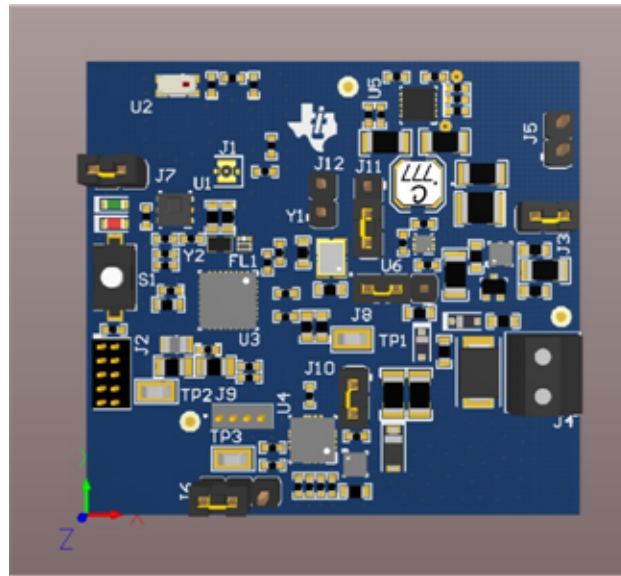
図 20. TIDA-00666 Board

表 3 shows the different functions of the headers.

表 3. Header Functions

HEADERS	DESCRIPTION
J1	RF connector
J2	cJTAG programming interface
J3	VCC input connection for LM5165
J4	J4 is the connection for the 4- to 20-mA current loop
J5	GND
J6	J6 sets the output current level at power up and under error conditions.
J7	VCC connection for HDC1080
J8	If the board is powered from the LM5165, connect pin 2 and 3 on J8. If the board is powered from TPS71728, connect pin 1 and 2 on J8.
J9	On J9 there are four unused GPIOs that have been brought out from the CC2650 to facilitate future prototyping and debugging
J10	VCC connection for DAC161S997
J11	If the board is powered from the TPS71728, connect pin 2 and 3 on J11. If the board is powered from the LM5165, leave the pins on J11 open.
J12	GND

3.1.2   4- to 20-mA Loop Connection and Power Options

The LM5165 supplies 3.3 V on the output if a voltage in the range of 8 to 33 V is supplied to the 4- to 20-mA loop on Terminal J4. In the default configuration, the CC2650, the HDC1080, and the DAC161S997 are powered from this 3.3 V. Depending on the TX power setting of the CC2650, the 8 V on the 4- to 20-mA loop input might not be sufficient to power the board and have the loop current below 3.375 mA. One option for higher TX power settings is to increase the loop voltage. Another option is to add an additional capacitor on the input of the LM5165. On the TIDA-00666 board, there is an optional capacitor C33 that can be added for this reason.

3.2   Firmware Overview

The firmware used on this TI Design was developed using TI's CCS software (version 6.1.2). 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 power the TIDA-00666 board on terminal J4 with 8 to 33 V.

The TI Design hardware is programmed by connecting a 10-pin mini ribbon cable from J6 to the XDS200 Debugger. See 図 21 for a photo of the correct setup for connecting the TI Designs hardware to the XDS200 Debugger.
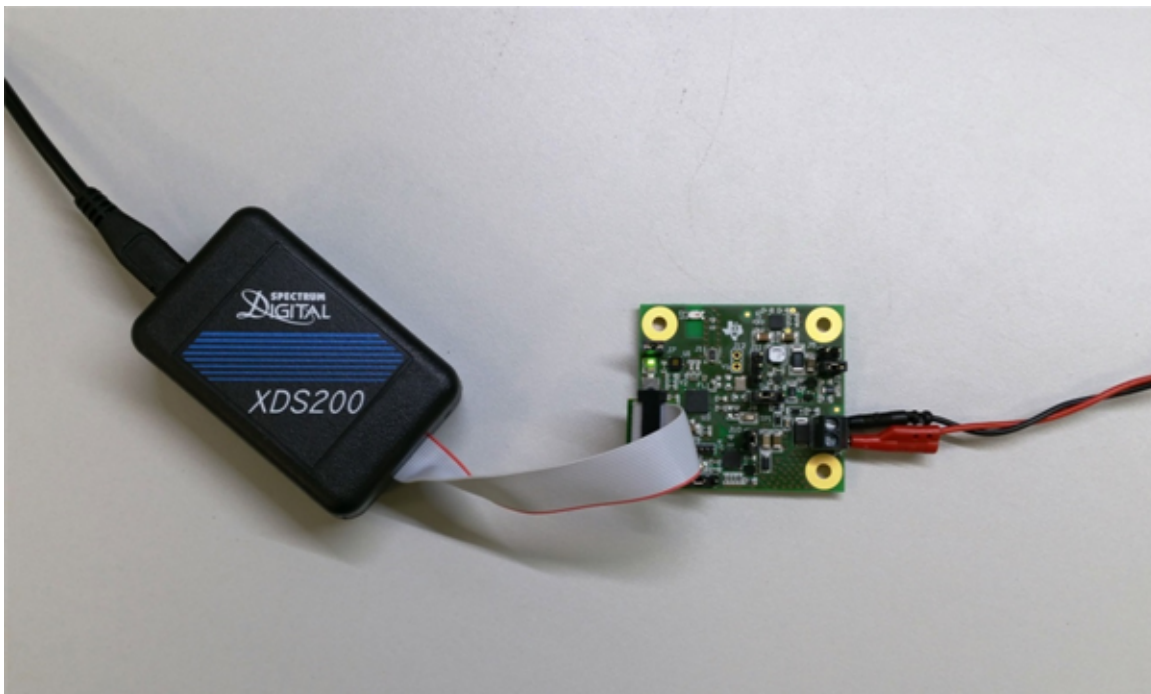
図 21. TIDA-00666 Test Setup

The BLE stack is the software development kit (SDK) for the CC26xx Bluetooth devices provided by Texas Instruments (http://www.ti.com/tool/ble-stack) . The software package includes full Bluetooth low energy (BT4.1) protocol stack along with sample applications. The protocol stack is provided as a pre-qualified library component and the complete system is operated by a RTOS that introduces a threaded environment with full power management. The power management is maintained by the RTOS automatically, and the application can constrain tasks or disallow certain power modes if required. The power modes are presented in 表 4.

表 4. CC2650 Power Modes

POWER MODE	DESCRIPTION	CURRENT
Active	System CPU is running	61 μA / MHz
Idle	The power domain in which CPU resides is off	550 µA
Standby	The voltage domain in which CPU resides is off	1 µA
Shutdown	Only IOs maintain their operation. All voltage regulators, voltage and power domains are off	0.1 µA

3.2.1 Emulator, IDE Support, and Tools

For a complete overview of the emulators, integrated development environments (IDEs) and tools that support the CC26xx product family, see processors.wiki.ti.com/index.php/CC13xx_CC26xx_Tools_Overview.

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

As described earlier, this TI Design is programmed to read the relative humidity and temperature data from the HDC1080 device, and then broadcast that data as a Bluetooth non-connectable advertisement packet. The data payload consists of 2 bytes of temperature data, followed by 2 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.
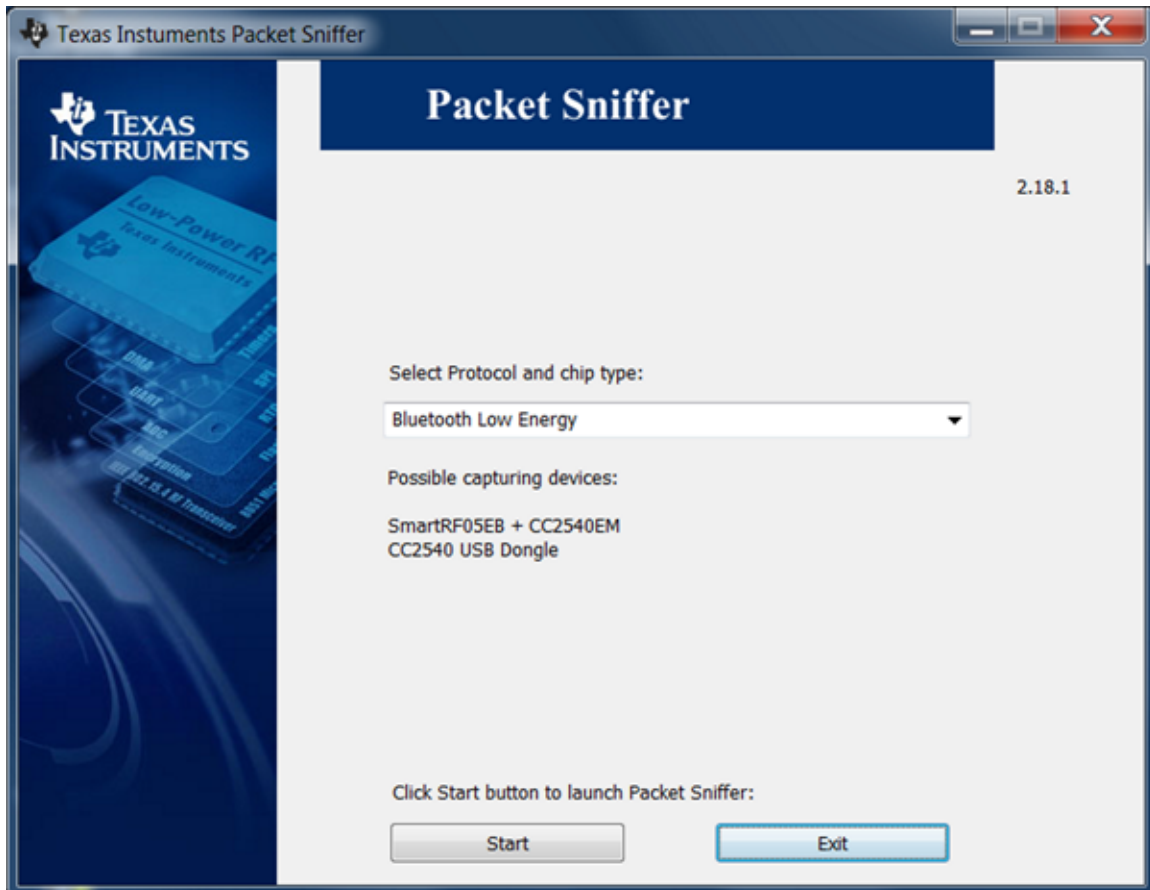2. Open the Packet Sniffer software; choose BLE as the protocol and hit Start.

図 22. Packet Sniffer Start-up Dialog

3. Click the Radio Configuration tab on the bottom toolbar and select 37 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 protocol. To view only the packets sent from the TI Design hardware, apply a display filter. 図 23 shows a sample display of what will be recorded. The field AdvData has the first 2 bytes for the temperature value and the second 2 bytes for the humidity value.
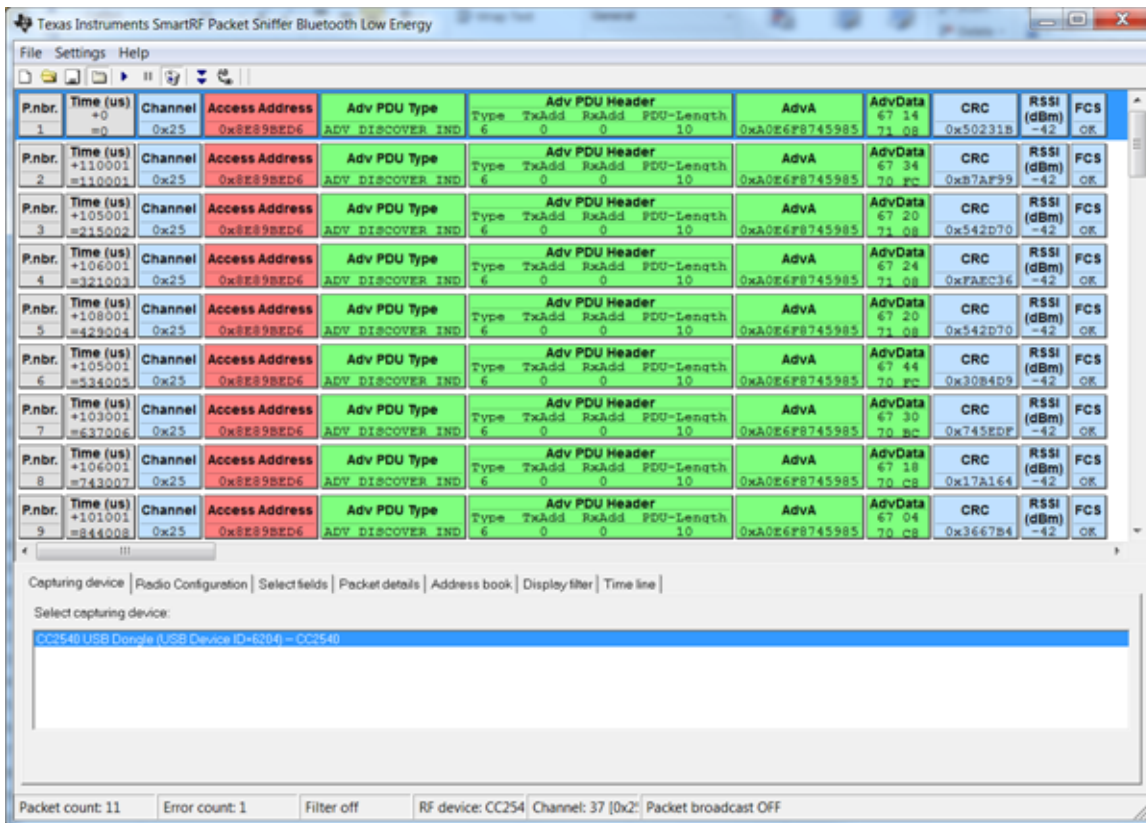
図 **23. Packet Sniffer**

The TIDA-00666 sends out non-connectable advertisement packets that contain 4 bytes of data: 2 bytes of temperature data and 2 bytes of relative humidity data. This data is transmitted directly as the HDC1080 outputs it; no post-processing or correction is implemented on the CC2650 device itself.

Advertising byte 0 and byte 1 is the 16-bit temperature value in binary format. Byte 0 is the MSB and byte 1 is the LSB. The temperature can be calculated from the output data with:

$$\text{Temperature} \left(°\text{C}\right) = \left(\frac{\text{Temperature}\left[15:00\right]}{2^{16}} \right) \times 165°\text{C} - 40°\text{C}$$

(4)

Advertising byte 2 and byte 3 is the 16-bit humidity value in binary format. Byte 2 is the MSB and byte 3 is the LSB. The humidity can be calculated from the output data with:

$$\text{Relative Humidity} \left(\%\text{RH}\right) = \left(\frac{\text{Humidity}\left[15:00\right]}{2^{16}} \right) \times 100\%\text{RH}$$

(5)

The advertising is done periodically every 100 ms.

4   Testing and Results

One goal of this TI Design was to avoid that the protection circuitry and the LM5165 negatively impact the total system performance. The term system performance is especially related to the accuracy of the loop current. The basis for this accuracy is actually an accurate sensing of the loop current. For the test setup, a 100-Ω shunt resistor was used in series to the loop input on terminal J4. The 16-bit DAC output code of the DAC161S997 was set to 0x2335, which represents a loop current of 3.3 mA. The loop voltage was set to 24 V. The application software that was running during the test was based on the BLE Stack version ble_cc26xx_2_01_00_44423. The TIDA-00666 sent out non-connectable advertisement packets that contained 4 bytes of data: 2 bytes of temperature data and 2 bytes of relative humidity data. This data was transmitted directly as the HDC1080 output it; no post-processing or correction was implemented on the CC2650 device itself. The advertising was done periodically every 100 ms.

4.1   Test Data

The voltage drop over the 100-Ω shunt resistor was measured with an oscilloscope Tektronix MSO4043. 図 24 and 図 25 show the results for voltage drop over the 100-Ω shunt resistor. The voltage ripple is below 1mV. As a 100-Ω shunt resistor has been used this results in a current ripple of less than 10 µA on the loop. In 図 25, a slightly higher pulse occurs every 100 ms, but is still below 1 mV. This glitch occurs when the CC2650 goes into TX mode every 100 ms. Adding an additional capacitor C33, which is not populated at the moment on the board, can reduce these small glitches.
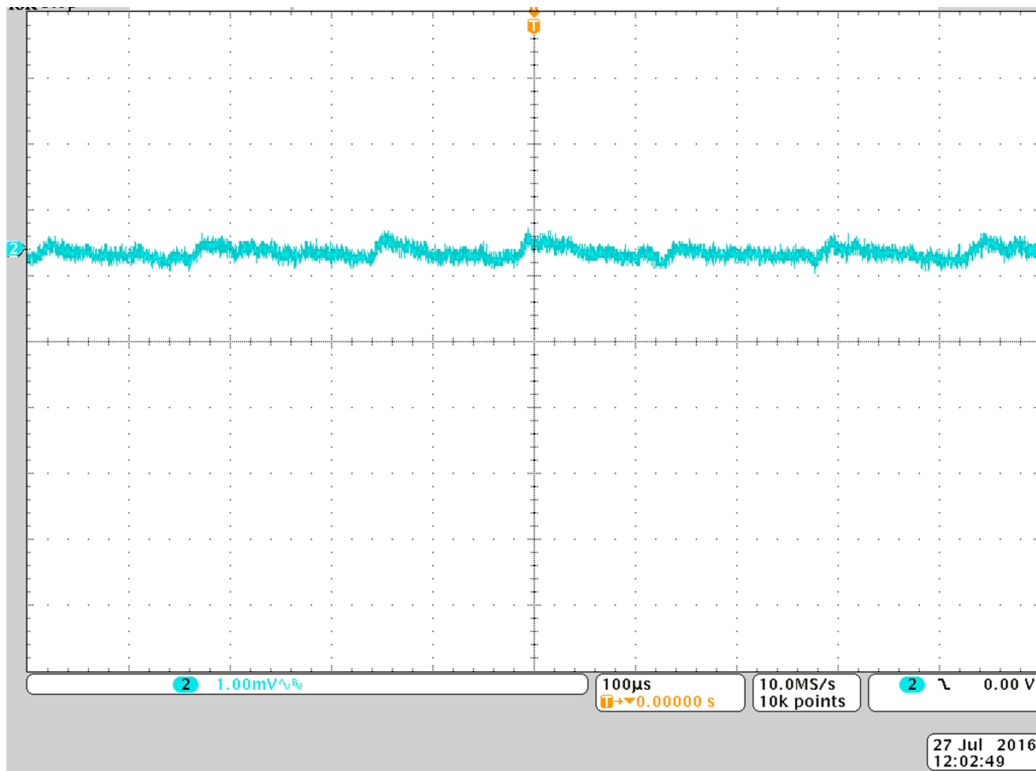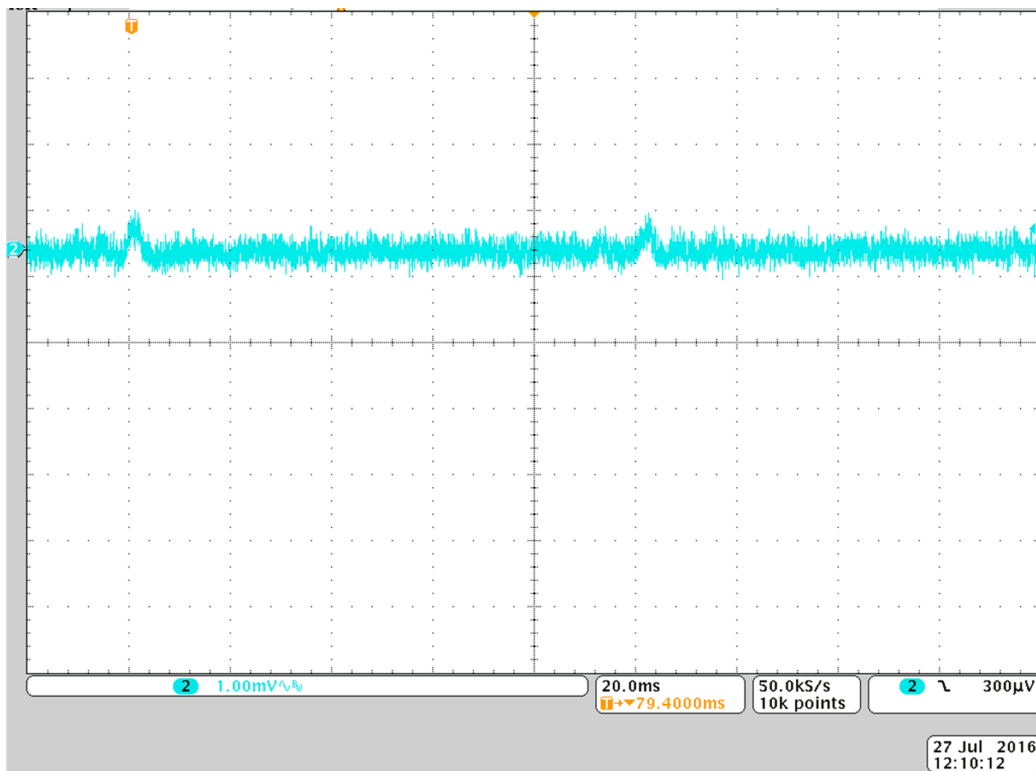
図 24. Loop Voltage Ripple on 100-Ω Shunt Resistor(1)

図 25. Loop Voltage Ripple on 100-Ω Shunt Resistor(2)

5   Design Files

5.1   Schematics

To download the schematics, see the design files at TIDA-00666.

5.2   Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00666.

5.3   PCB Layout Recommendations

5.3.1   Layout Prints

To download the layer plots, see the design files at TIDA-00666.

5.4   Altium Project

To download the Altium project files, see the design files at TIDA-00666.

5.5   Gerber Files

To download the Gerber files, see the design files at TIDA-00666.

5.6   Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00666.

6   Software Files

To download the software files, see the design files at TIDA-00666.

7   Related Documentation

1. Texas Instruments, *CC2650 SimpleLink™ Multistandard Wireless MCU*, CC2650 Datasheet (SWRS158)
2. Texas Instruments, *DAC161S997, SPI 16-bit Precision DAC for 4-20mA Loops*, DAC161S997 Datasheet (SNAS621)
3. Texas Instruments, *LM5165 3-V to 65-V Input, 150-mA Synchronous Buck Converter with Ultra-Low IQ*, LM5165 Datasheet (SNVSA47)
4. Texas Instruments, *TPS717 Low-Noise, High-Bandwidth PSRR, Low-Dropout, 150-mA Linear Regulator*, TPS717 Datasheet (SBVS068)
5. Texas Instruments, *HDC1080 Low Power, High Accuracy Digital Humidity Sensor with Temperature Sensor* (SNAS672)
6. Johanson Technology, 2.45 GHz SMD Antenna 2450AT18D0100, Datasheet (PDF)
7. NAMUR, *NAMUR Recommendation NE 043: Standardization of the Signal Level for the Failure Information of Digital Transmitters*; 2003, February 03 (Worksheets).
8. Texas Instruments, BLE-STACK (www.ti.com/ble-stack)
9. Texas Instruments, Code Composer Studio (CCS) Integrated Development Environment (IDE) (www.ti.com/tool/CCSTUDIO)

7.1 商標

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8 About the Author

THOMAS SCHNEIDER is a systems engineer at Texas Instruments, where he is responsible for developing reference design solutions for the industrial segment. Thomas earned his Dipl.-Ing. (Univ.) degree in electrical engineering from the Technical University Munich (TUM) in Munich, Germany.

リビジョンBの改訂履歴

資料番号末尾の英字は改訂を表しています。その改訂履歴は英語版に準じています。

Revision A (November 2016) から **Revision B** に変更   **Page**

- 現行のBluetoothブランディング・ガイドラインを反映し、BLEのすべての使用箇所を 削除 1
- 現行のBluetoothブランディング・ガイドラインを反映し、Bluetooth Smartのすべての使用箇所を 削除............................ 1

リビジョンAの改訂履歴

2016年8月発行のものから更新   **Page**

- プレビュー・ドラフトから 変更 1

TIの設計情報およびリソースに関する重要な注意事項

Texas Instruments Incorporated ("TI")の技術、アプリケーションその他設計に関する助言、サービスまたは情報は、TI製品を組み込んだアプリケーションを開発する設計者に役立つことを目的として提供するものです。これにはリファレンス設計や、評価モジュールに関係する資料が含まれますが、これらに限られません。以下、これらを総称して「TIリソース」と呼びます。いかなる方法であっても、TIリソースのいずれかをダウンロード、アクセス、または使用した場合、お客様(個人、または会社を代表している場合にはお客様の会社)は、これらのリソースをここに記載された目的にのみ使用し、この注意事項の条項に従うことに合意したものとします。

TIによるTIリソースの提供は、TI製品に対する該当の発行済み保証事項または免責事項を拡張またはいかなる形でも変更するものではなく、これらのTIリソースを提供することによって、TIにはいかなる追加義務も責任も発生しないものとします。TIは、自社のTIリソースに訂正、拡張、改良、およびその他の変更を加える権利を留保します。

お客様は、自らのアプリケーションの設計において、ご自身が独自に分析、評価、判断を行う責任がお客様にあり、お客様のアプリケーション(および、お客様のアプリケーションに使用されるすべてのTI製品)の安全性、および該当するすべての規制、法、その他適用される要件への遵守を保証するすべての責任をお客様のみが負うことを理解し、合意するものとします。お客様は、自身のアプリケーションに関して、(1) 故障による危険な結果を予測し、(2) 障害とその結果を監視し、および、(3) 損害を引き起こす障害の可能性を減らし、適切な対策を行う目的での、安全策を開発し実装するために必要な、すべての技術を保持していることを表明するものとします。お客様は、TI製品を含むアプリケーションを使用または配布する前に、それらのアプリケーション、およびアプリケーションに使用されているTI製品の機能性を完全にテストすることに合意するものとします。TIは、特定のTIリソース用に発行されたドキュメントで明示的に記載されているもの以外のテストを実行していません。

お客様は、個別のTIリソースにつき、当該TIリソースに記載されているTI製品を含むアプリケーションの開発に関連する目的でのみ、使用、コピー、変更することが許可されています。明示的または黙示的を問わず、禁反言の法理その他どのような理由でも、他のTIの知的所有権に対するその他のライセンスは付与されません。また、TIまたは他のいかなる第三者のテクノロジまたは知的所有権についても、いかなるライセンスも付与されるものではありません。付与されないものには、TI製品またはサービスが使用される組み合わせ、機械、プロセスに関連する特許権、著作権、回路配置利用権、その他の知的所有権が含まれますが、これらに限られません。第三者の製品やサービスに関する、またはそれらを参照する情報は、そのような製品またはサービスを利用するライセンスを構成するものではなく、それらに対する保証または推奨を意味するものでもありません。TIリソースを使用するため、第三者の特許または他の知的所有権に基づく第三者からのライセンス、あるいはTIの特許または他の知的所有権に基づくTIからのライセンスが必要な場合があります。

TIのリソースは、それに含まれるあらゆる欠陥も含めて、「現状のまま」提供されます。TIは、TIリソースまたはその仕様に関して、明示的か暗黙的かにかかわらず、他のいかなる保証または表明も行いません。これには、正確性または完全性、権原、続発性の障害に関する保証、および商品性、特定目的への適合性、第三者の知的所有権の非侵害に対する黙示の保証が含まれますが、これらに限られません。

TIは、いかなる苦情に対しても、お客様への弁護または補償を行う義務はなく、行わないものとします。これには、任意の製品の組み合わせに関連する、またはそれらに基づく侵害の請求も含まれますが、これらに限られず、またその事実についてTIリソースまたは他の場所に記載されているか否かを問わないものとします。いかなる場合も、TIリソースまたはその使用に関連して、またはそれらにより発生した、実際的、直接的、特別、付随的、間接的、懲罰的、偶発的、または、結果的な損害について、そのような損害の可能性についてTIが知らされていたかどうかにかかわらず、TIは責任を負わないものとします。

お客様は、この注意事項の条件および条項に従わなかったために発生した、いかなる損害、コスト、損失、責任からも、TIおよびその代表者を完全に免責するものとします。

この注意事項はTIリソースに適用されます。特定の種類の資料、TI製品、およびサービスの使用および購入については、追加条項が適用されます。これには、半導体製品(http://www.ti.com/sc/docs/stdterms.htm)、評価モジュール、およびサンプル(http://www.ti.com/sc/docs/sampterms.htm)についてのTIの標準条項が含まれますが、これらに限られません。