TI Designs: TIDA-01439
Wireless Mesh Network for Predictive Maintenance Reference Design

TEXAS INSTRUMENTS

Description

Predictive maintenance uses data collected on a machine's function to determine whether or not repairs are necessary. The sensors, which are used for data collection, are often housed in hard-to-access locations, and the sensors may not be accessible through ordinary wired connections. As the sensors usually must communicate with upstream data-gathering nodes, wireless communication is required. This reference design has several inputs, like RS232, RS485, or resistance temperature detectors (RTDs), to connect different sensors and machines to collect data for predictive maintenance. For data processing a high-performance Arm ® Cortex®-M4F microcontroller (MCU) with floating-point unit and DSP acceleration is on the board.

Features

- Industrial-Grade Wireless Connectivity
- Powerful Arm Cortex®-M4 and Cortex®-M3 MCUs
- Three-Wire RTD Sensor (PT100) Input
- RS232 and RS485 or RS422 Interface
- Onboard Display

Applications

- Industrial
- Factory Automation and Process Control
- Industrial Communications
- Industry 4.0
- Internet of Things (IoT)

Resources

TIDA-01439	Design Folder
CC2650	Product Folder
MSP432P401R	Product Folder
LM5165	Product Folder
TPS717	Product Folder
SN65HVD70	Product Folder
MAX3232	Product Folder
ADS1220	Product Folder
TVS3300	Product Folder
CC2650 SensorTag	Tool Folder
BeagleBone Black	Tool Folder

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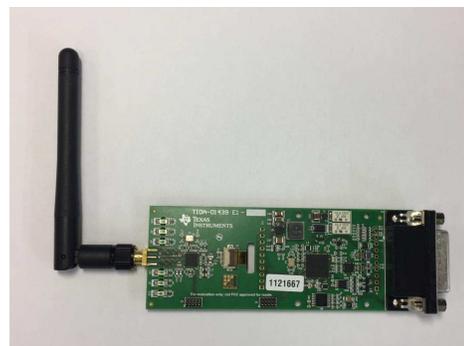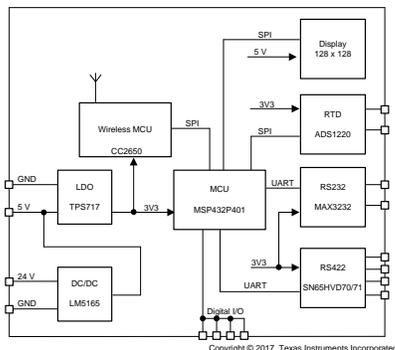
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1 System Description

Predictive maintenance allows for the repair of machines before they break down and enables the permanent monitoring of components inside the machine using sensors that measure vibration, pressure, temperature, or humidity. Specialized maintenance software collects this sensor data, evaluates the data, and recognizes in advance when a component might be in danger of failing. For the predictive maintenance data processing, this reference design has the MSP432P401 on board, which is a high-performance Arm Cortex-M4F MCU with floating-point unit and DSP acceleration. The sensors used for the data collection are often housed in hard-to-access locations, and the sensors may not be accessible through ordinary wired connections. As the sensors usually must communicate with upstream data-gathering nodes, wireless communication is required. This reference design uses the wireless communication 6LoWPAN, which enables IPv6 over the IEEE802.15.4 standard. This standard allows for low-power sensor nodes that work in mesh architectures. With the onboard, multistandard 2.4-GHz wireless CC2650 MCU, this reference design could also support Zigbee®, *Bluetooth* ® low energy, or proprietary solutions.

Permanent machine monitoring traditionally uses wired sensors; however, wireless sensors provide a cost-effective, simple, and reliable way to deploy new points of measurement and control without the wiring costs. With a predictive maintenance program, maintenance activities can be scheduled, and replacement parts can be ordered only as required, which minimizes onsite inventory. The operation of equipment can be optimized, and the factory reliability can be improved.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS AND FEATURES
POWER SUPPLY	
Operating supply voltage	Typically 24 V
MCUs	
MSP432P401R	48-MHz MCU, 256-KB Flash, 64-KB RAM, 14-bit ADC, AES-256
CC2650	48-MHz MCU, 128-KB Flash, 20-KB RAM, AES-128
INTERFACES	
Wireless interface	6LoWPAN, IEEE 802.15.4
RS232	Up to 250 kbit/s
RS485, RS422	Up to 400 kbps (70, 71) Options available for 20 Mbps (73, 74) and 50 Mbps (76, 77)
TEMPERATURE MEASUREMENT	
Sensor type	PT100 (three-wire mode)
Temperature range	−200ºC to 850ºC
Current excitation	Programmable (10, 50, 100, 250, 500, 1000, 1500 μA)
Reference resistor	3.24 kΩ, Tol = 0.1%, TC = 10 ppm/C
Resolution	24-bit ADC

2 System Overview

2.1 Block Diagram
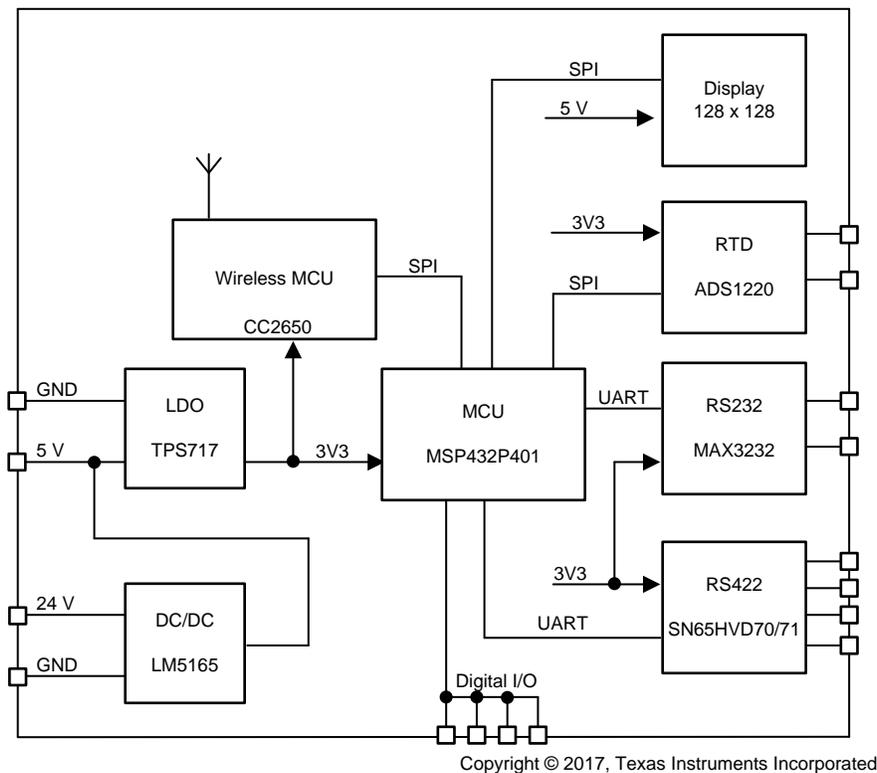
Figure 1. TIDA-01439 Block Diagram

2.2 Highlighted Products

This reference design features the following devices:

- CC2650: multistandard 2.4-GHz ultra-low-power wireless SimpleLink™ MCU
- MSP432P401R: ultra-low-power 32-bit Arm Cortex-M4F SimpleLink MCU with 14-bit analog-to-digital converter (ADC), 256-KB Flash, and 64-KB RAM
- LM5165: 3-V to 65-V, 150-mA synchronous buck converter with ultra-low I_Q
- TPS717xx: low noise, high PSRR low-dropout 150-mA linear regulator
- SN65HVD70: 3.3-V, full-duplex RS-485, 12-kV IEC ESD, 400-kbps data rate with enables
- MAX3232: 3-V to 5.5-V multichannel RS-232 line driver and receiver
- ADS1220: 24-bit, 2-kSPS, 4-channel, low-power delta-sigma ADC with programmable gain amplifier(PGA)and VREF for small signal sensors
- TVS3300: 33-V precision surge protection clamp

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

2.2.1   CC2650

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

The device is a member of the CC26xx family of cost-effective, ultra-low-power, 2.4-GHz RF devices. Very low-active RF and MCU current and low-power mode current consumption 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.

Many of the stacks are available free of charge from www.ti.com.
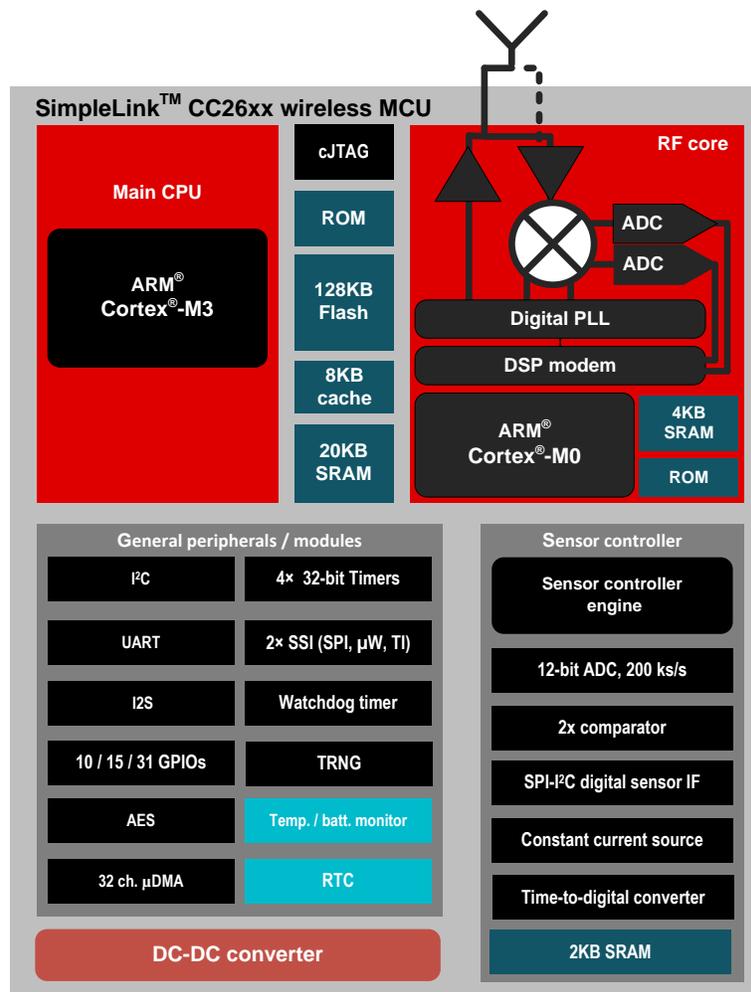
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Figure 2. CC26xx Functional Block Diagram

Features:

- MCU:
  - 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:
  - 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 V to 3.8 V
    - External regulator mode: 1.7 V 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)

2.2.2 MSP432P401R

The MSP432P401x SimpleLink MCUs are optimized wireless host MCUs with an integrated 14-bit ADC capable of up to 16 ENOB delivering ultra-low-power performance including 80 µA/MHz in active power and 660 nA in standby power with FPU and DSP extensions. As an optimized wireless host MCU, the MSP432P401x allows developers to add high-precision analog and memory extension to applications based on SimpleLink wireless connectivity solutions.

The MSP432P401x devices are part of the SimpleLink microcontroller (MCU) platform, which consists of Wi-Fi, Bluetooth low energy, Sub-1 GHz, and host MCUs. All share a common, easy-to-use development environment with a single-core software development kit (SDK) and rich tool set. A one-time integration of the SimpleLink platform allows the addition of any combination of devices from the portfolio into the design. The ultimate goal of the SimpleLink platform is to achieve 100% code reuse when design requirements change. For more information, visit *SimpleLink Solutions* .

MSP432P401x devices are supported by a comprehensive ecosystem of tools, software, documentation, training, and support to get development started quickly. The MSP-EXP432P401R LaunchPad™ development kit or MSP-TS432PZ100 target socket board (with additional MCU sample) along with the free SimpleLink MSP432 SDK to get started.

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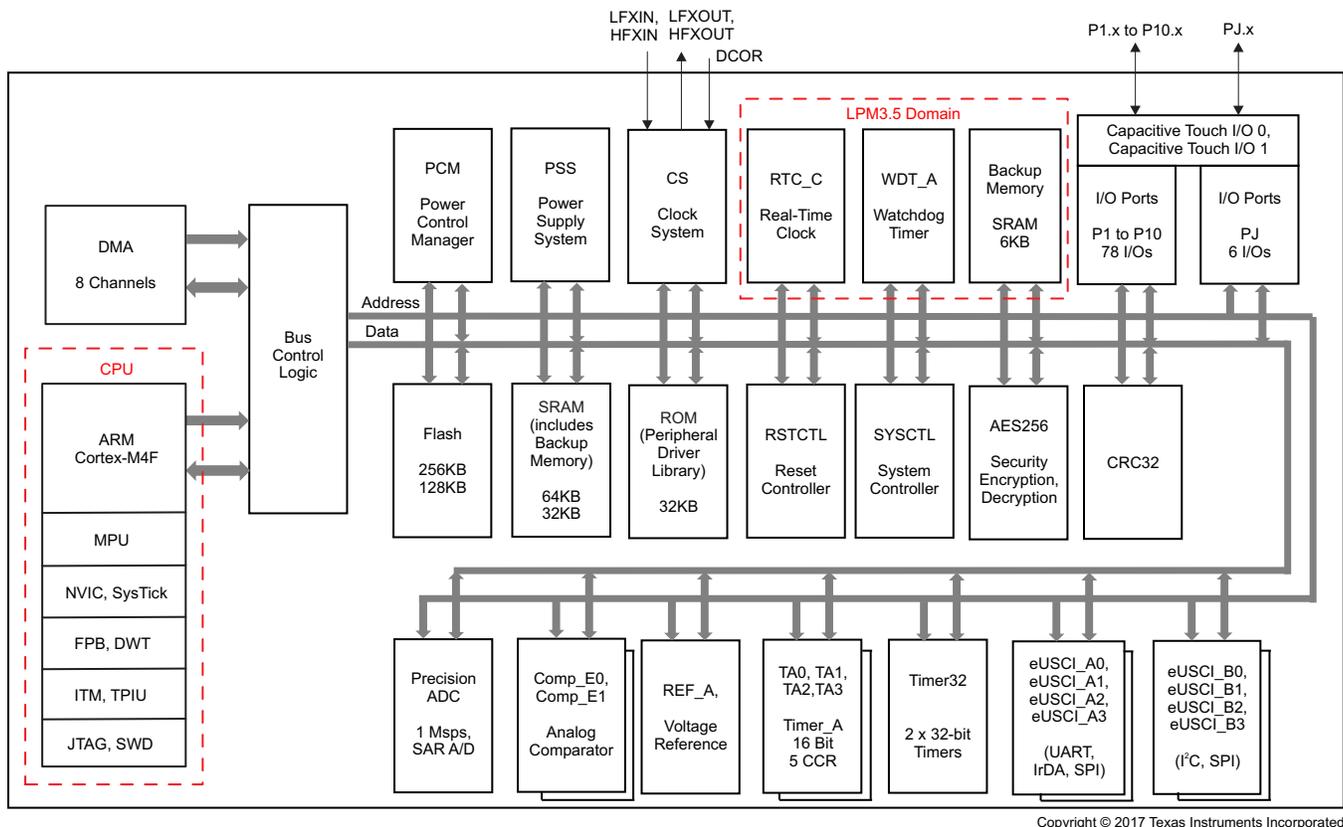
Figure 3. MSP432P401R, MSP432P401M Functional Block Diagram

The CPU and all of the peripherals in the device interact with each other through a common AHB matrix. In some cases, there are bridges between the AHB ports and the peripherals. These bridges are transparent to the application from a memory map perspective and, therefore, are not shown in the block diagram.

Features:

- Core:
  - Arm 32-bit Cortex-M4F CPU with floating-point unit and memory protection unit
  - Frequency up to 48 MHz
  - ULPBench™ Benchmark:
    - 192.3 ULPMark™-CP
  - Performance benchmark:
    - 3.41 CoreMark/MHz
    - 1.22 DMIPS/MHz (Dhrystone 2.1)
- Advanced low-power analog features:
  - 14-bit 1-MSPS SAR ADC with 13.2 ENOB native and capability to reach 16 ENOB with oversampling, differential, and single-ended inputs
  - Internal voltage reference with 10-ppm/°C typical stability
  - Two analog comparators
- Memories:
  - Up to 256KB of Flash main memory (organized into two banks enabling simultaneous read/execute during erase)
  - 16KB of Flash information memory (used for BSL, TLV, and Flash mailbox)

- – Up to 64KB of SRAM (including 6KB of backup memory)
- – 32KB of ROM with MSP432™peripheral driver libraries
- • Ultra-low-power operating modes:
  - – Active: 80 µA/MHz
  - – Low-frequency active: 83 µA at 128 kHz
  - – LPM3 (With RTC): 660 nA
  - – LPM3.5 (With RTC): 630 nA
  - – LPM4: 500 nA
  - – LPM4.5: 25 nA
- • Development kits and software (see tools and software):
  - – MSP-EXP432P401R LaunchPaddevelopment kit
  - – MSP-TS432PZ100 100-pin target board
  - – MSP432 SimpleLinkSDK
- • Operating characteristics:
  - – Wide supply voltage range: 1.62 V to 3.7 V
  - – Temperature range (ambient): –40°C to 85°C
- • Flexible clocking features:
  - – Tunable internal DCO (up to 48 MHz)
  - – 32.768-kHz low-frequency crystal support (LFXT)
  - – High-frequency crystal support (HFXT) up to 48 MHz
  - – Low-frequency internal reference oscillator (REFO)
  - – Very low-power low-frequency internal oscillator (VLO)
  - – Module oscillator (MODOSC)
  - – System oscillator (SYSOSC)
- • Code security features:
  - – JTAG and SWD lock
  - – IP protection (up to four secure flash zones, each with configurable start address and size)
- • Enhanced system features:
  - – Programmable supervision and monitoring of supply voltage
  - – Multiple-class resets for better control of application and debug
  - – 8-channel DMA
  - – RTC with calendar and alarm functions
- • Timing and control:
  - – Up to four 16-bit timers, each with up to five capture, compare, PWM capability
  - – Two 32-bit timers, each with interrupt generation capability
- • Serial communication:
  - – Up to four eUSCI_A modules
    - • UART with automatic baud-rate detection
    - • IrDA encode and decode
    - • SPI (up to 16 Mbps)
  - – Up to four eUSCI_B modules
    - • I²C (with multiple-slave addressing)
    - • SPI (up to 16 Mbps)
- • Flexible I/O features:
  - – Ultra-low-leakage I/Os (±20 nA Maximum)

- – All I/Os with capacitive-touch capability
- – Up to 48 I/Os with interrupt and wake-up capability
- – Up to 24 I/Os with port mapping capability
- – Eight I/Os with glitch filtering capability
- • Encryption and data integrity accelerators
  - – 128-, 192-, or 256-bit AES encryption and decryption accelerator
  - – 32-bit hardware CRC engine
- • JTAG and debug support
  - – 4-pin JTAG and 2-pin swd debug interfaces
  - – Serial wire trace
  - – Power debug and profiling of applications

2.2.3   LM5165

The LM5165 is a compact, easy-to-use, 3-V 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 for optimal light-load efficiency or constant on-time (COT) control for nearly constant operating frequency. Both control schemes do not require loop compensation and 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.
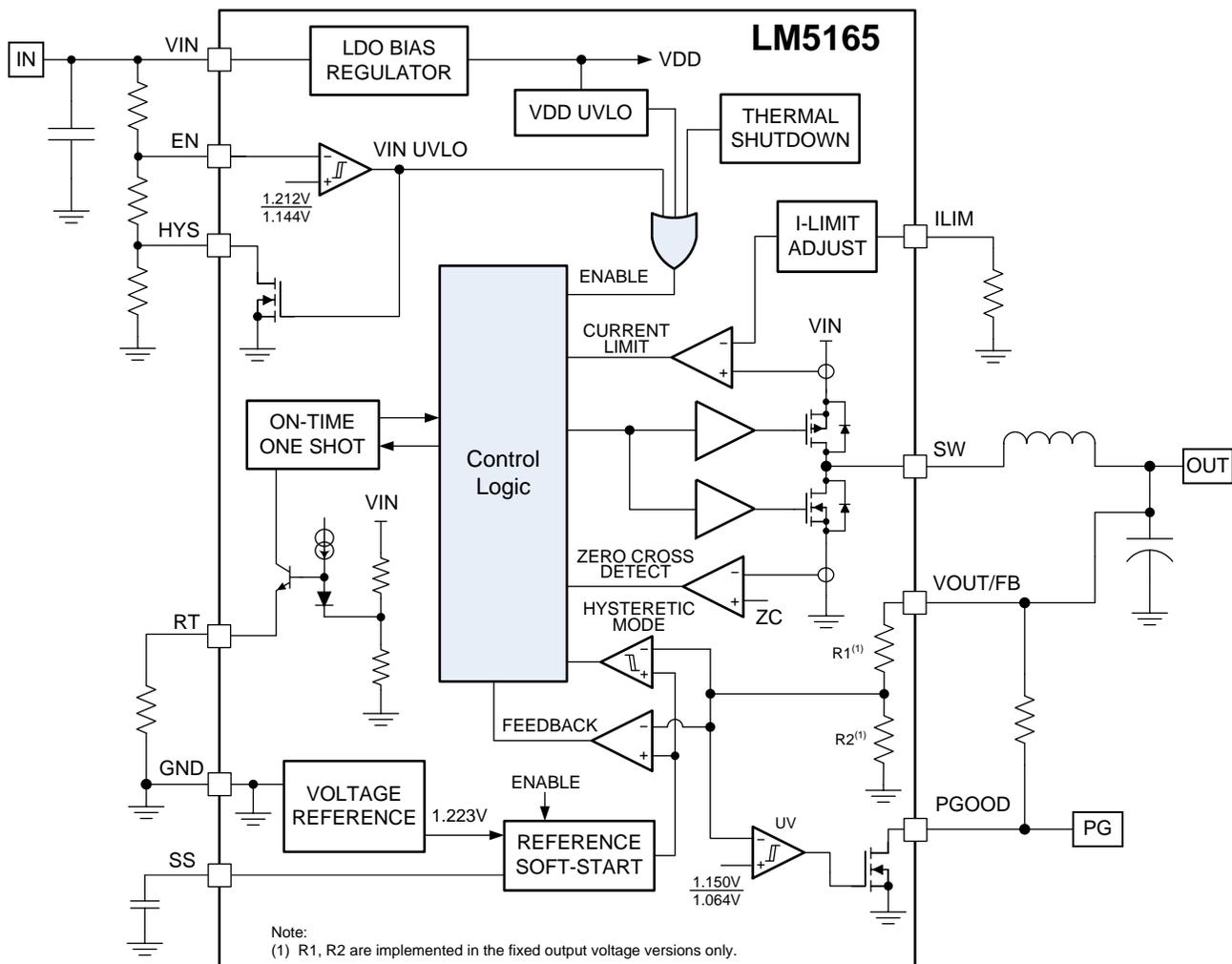
Figure 4. LM5165 Functional Block Diagram

Features:

- Wide input voltage range of 3 V 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 (four 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

2.2.4 TPS717

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.
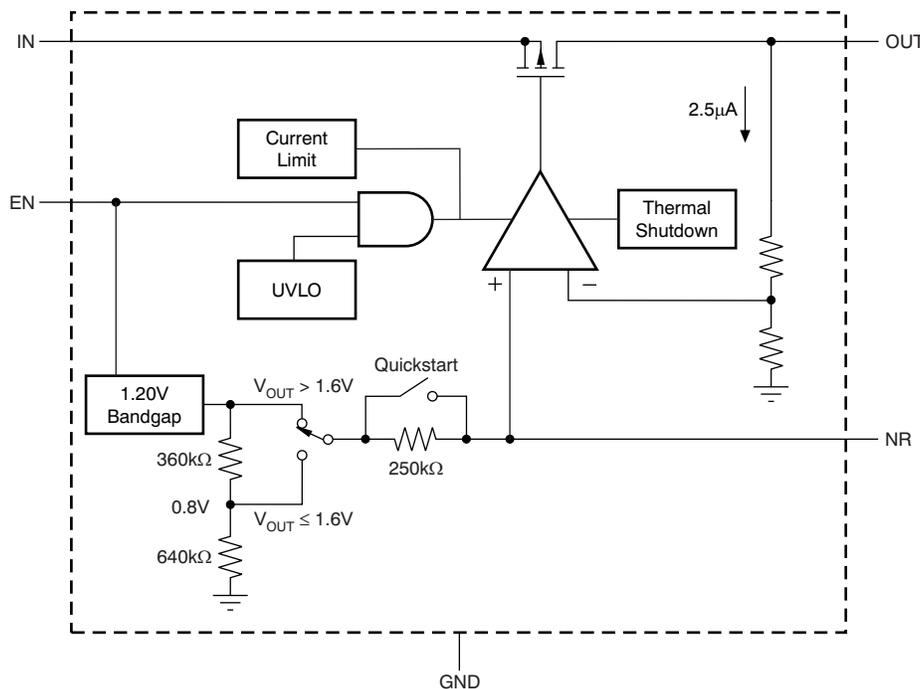
Figure 5. TPS717 Functional Block Diagram

Features:
- Input voltage: 2.5 V to 6.5 V
- Available in multiple output versions:
  - Fixed output with voltages from 0.9 V to 5 V
  - Adjustable output voltage from 0.9 V 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

2.2.5 SN65HVD70

These devices extend the RS-485 portfolio with a family of full-duplex transceivers with robust 3.3-V drivers and receivers and high levels of ESD protection. The ESD protection includes > ±30-kV HBM and > ±12-kV IEC61000-4-2 contact discharge. The large receiver hysteresis of the SN65HVD7x devices provides immunity to conducted differential noise and the wide operating temperature enables reliability in harsh operating environments. The SN65HVD7x devices are offered in a standard SOIC package as well as in a small-footprint MSOP package.

These devices each combine a differential driver and a differential receiver, which operate from a single 3.3-V power supply. Each driver and receiver has separate input and output pins for full-duplex bus communication designs. These devices all feature a wide common-mode voltage range which makes the devices suitable for multi-point applications over long cable runs.

The SN65HVD71, SN65HVD74, and SN65HVD77 devices are fully enabled with no external enabling pins.

The SN65HVD70, SN65HVD73, and SN65HVD76 devices have active-high driver enables and active-low receiver enables. A low, less than 5-µA standby current can be achieved by disabling both the driver and receiver.
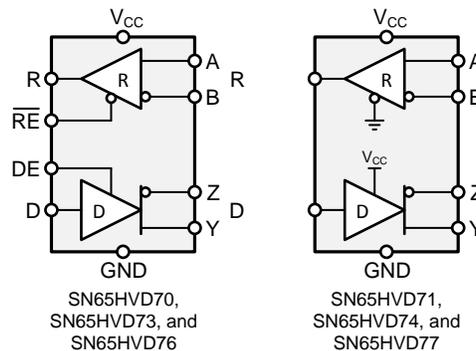
Figure 6. SN65HVD70 Functional Block Diagram

Features:
• 1/8 unit-load options available
  – Up to 256 nodes on the bus
• Bus I/O protection
  – > ±30-kV HBM protection
  – > ±12-kV IEC61000-4-2 contact discharge
  – > ±4-kV IEC61000-4-4 fast transient burst
• Extended industrial temperature range: –40°C to 125°C
• Large receiver hysteresis (70 mV) for noise rejection
• Low power consumption
  – < 1.1-mA quiescent current during operation
  – Low standby supply current: 10 nA typical, < 5 µA (maximum)
• Glitch-free power-up and power-down protection for hot-plugging applications
• 5-V tolerant logic inputs compatible with 3.3-V or 5-V controllers
• Signaling rate options optimized for: 400 kbps (70, 71), 20 Mbps (73, 74), 50 Mbps (76, 77)

2.2.6 MAX3232

The MAX3232 device consists of two line drivers, two line receivers, and a dual charge-pump circuit with ±15-kV ESD protection terminal to terminal (serial-port connection terminals, including GND). The device meets the requirements of TIA/EIA-232-F and provides the electrical interface between an asynchronous communication controller and the serial-port connector. The charge pump and four small external capacitors allow operation from a single 3-V to 5.5-V supply. The devices operate at data signaling rates up to 250 kbit/s and a maximum of 30-V/μs driver output slew rate.
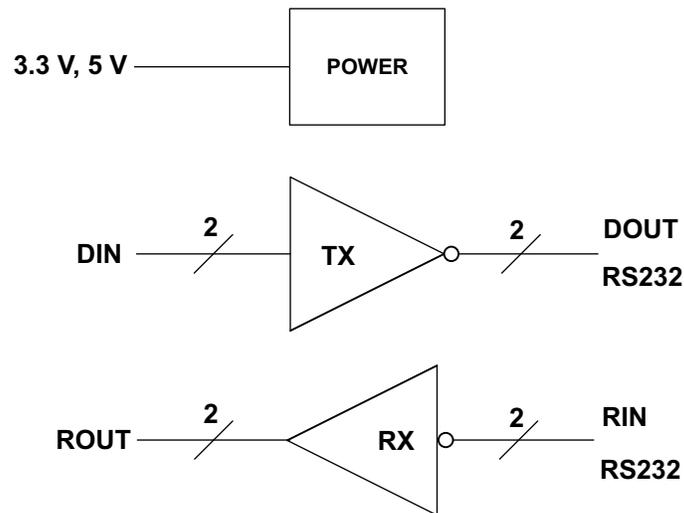
Figure 7. MAX3232 Functional Block Diagram

Features:

* RS-232 bus-terminal ESD protection exceeds ±15 kV using human-body model (HBM)
* Meets or exceeds the requirements of TIA/EIA-232-F and ITU V.28 standards
* Operates with 3-V to 5.5-V VCC supply
* Operates up to 250 kbit/s
* Two drivers and two receivers
* Low supply current: 300 μA typical
* External capacitors: 4 × 0.1 μF
* Accepts 5-V logic input with 3.3-V supply

2.2.7 ADS1220

The ADS1220 is a precision, 24-bit, ADC that offers many integrated features to reduce system cost and component count in applications measuring small sensor signals. The device features two differential or four single-ended inputs through a flexible input multiplexer (MUX), a low-noise, PGA, two programmable excitation current sources, a voltage reference, an oscillator, a low-side switch, and a precision temperature sensor.

The device can perform conversions at data rates up to 2000 samples-per-second (SPS) with single-cycle settling. At 20 SPS, the digital filter offers simultaneous 50-Hz and 60-Hz rejection for noisy industrial applications. The internal PGA offers gains up to 128 V/V. This PGA makes the ADS1220 ideally-suited for applications measuring small sensor signals, such as RTDs, thermocouples, thermistors, and resistive bridge sensors. The device supports measurements of pseudo- or fully-differential signals when using the PGA. Alternatively, the device can be configured to bypass the internal PGA while still providing high input impedance and gains up to 4 V/V, which alllows for single-ended measurements.

Power consumption is as low as 120 μA when operating in duty-cycle mode with the PGA disabled. The ADS1220 is offered in a leadless VQFN-16 or a TSSOP-16 package and is specified over a temperature range of –40°C to 125°C.
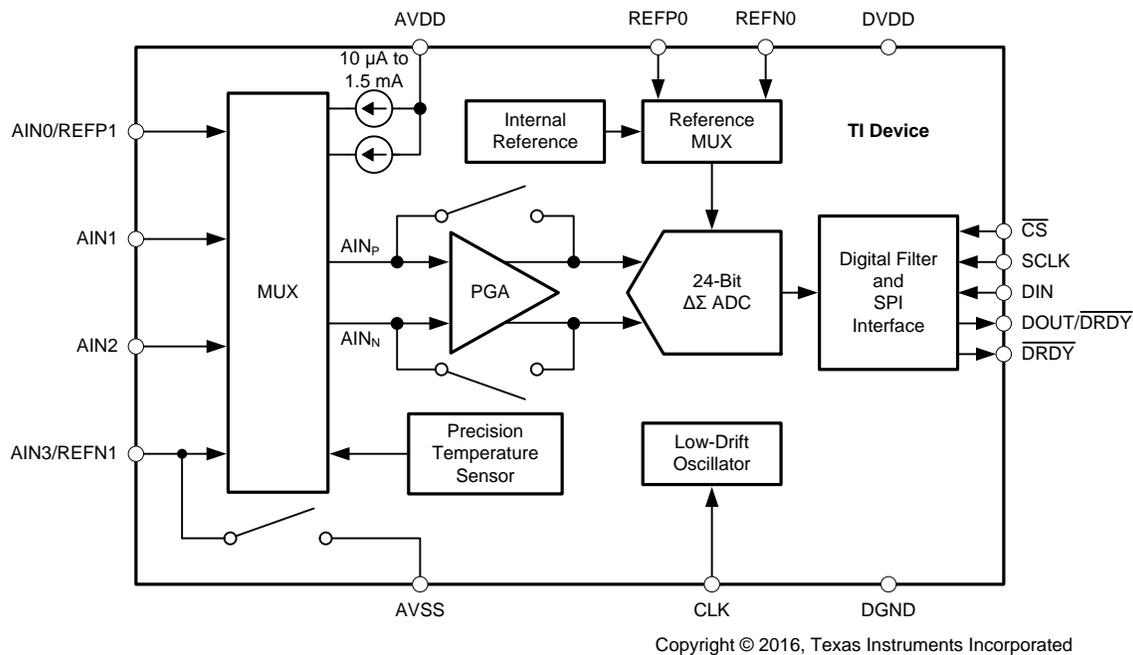
Figure 8. ADS1220 Functional Block Diagram

Features:

- Low current consumption: as low as 120 µA (typ) in duty-cycle mode
- Wide supply range: 2.3 V to 5.5 V
- Programmable gain: 1 V/V to 128 V/V
- Programmable data rates: Up to 2 kSPS
- Up to 20-bits effective resolution
- Simultaneous 50-Hz and 60-Hz rejection at 20 SPS with single-cycle settling digital filter
- Two differential or four single-ended inputs
- Dual matched programmable current sources: 10 µA to 1.5 mA
- Internal 2.048-V reference: 5 ppm/°C (typ) drift
- Internal 2% accurateoscillator
- Internal temperature sensor: 0.5°C (typ) accuracy
- SPI-compatible interface (mode 1)
- Package: 3.5-mm × 3.5-mm × 0.9-mm VQFN

2.2.8 TVS3300

The TVS3300 is a transient voltage suppressor (TVS)that provides robust protection for electronic circuits exposed to high transient voltage events. Unlike a traditional TVS diode, the TVS3300 precision clamp triggers at a lower breakdown voltage and regulates to maintain a flat-clamping voltage throughout a transient overvoltage event. The lower clamping voltage combined with a low dynamic resistance enables a unique TVS protection solution that can lower the voltage a system is exposed during a surge event by up to 30% in unidirectional configuration and up to 20% in bidirectional configuration when compared to traditional TVS diodes. The low-clamping voltage and flat-clamping performance allow designers to confidently select downstream system components with maximum voltage rating than is possible with traditional TVS diodes, which saves system cost and board area and improves overall performance.

The TVS3300 is a unidirectional precision surge protection clamp with a 33-V working voltage designed specifically to protect systems with midvoltage rails in industrial, communication, and factory automation applications. The TVS3300 has a fast response time when surge current is applied, so there is no overshoot voltage during clamping, which makesthe device ideal to replace traditional TVS and zener diodes.

The TVS3300 is available in two small footprint packages that, when used in place of an industry standard SMB package, can reduce footprint by 94% (WCSP package) and 79% (SON package) for space constrained applications. Both package options robustly dissipate the surge power and provide up to 58% lower leakage current compared to traditional TVS diodes in SMA and SMB package, which allows for higher accuracy 4 mA to 20-mA current loop measurements.
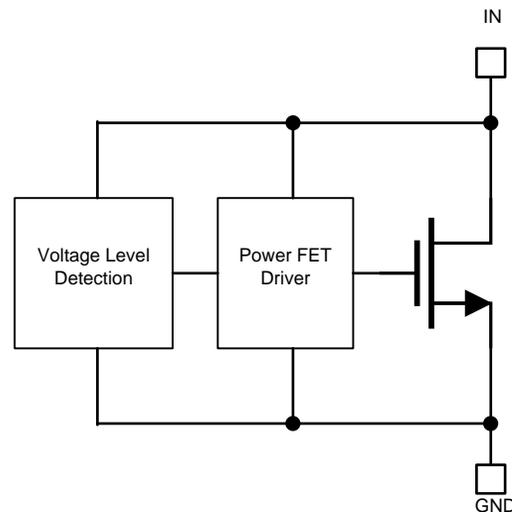
Figure 9. TVS3300 Functional Block Diagram

Features:
* Ultra-low and flat clamping voltage
  – 38 V at 35 A (8/20 μs)
  – R_{DYN}: 40 mΩ
* Standoff voltage: 33 V
* Low leakage current:
  – 19 nA at 27°C
  – 28 nA at 85°C
* Peak pulse power:
  – 1330 W (8/20 μs)
  – 150 W (10/1000 μs)
* IEC 61000-4-2 level 4 ESD protection
  – ±14-kV contact discharge
  – ±11-kV contact discharge (SON)
  – ±30-kV air gap discharge
* IEC 61000-4-4 EFT Protection
  – 80 A (5/50 ns)
* IEC 61000-4-5 surge protection
  – 35 A (8/20 μs)
* Industrial temperature range: –40°C to +125°C

- Compact packages:
  - 4-pin WCSP package (1.062 mm × 1.116 mm)
  - 6-pin SON package (2 mm × 2 mm)

2.3   System Design Theory

This reference design can quickly establish a wireless mesh network that connects various types of sensors for predictive maintenance and more. Mesh networks make radio systems more reliable by allowing radios to forward messages for other radios. For example, if a node cannot send a message directly to another node, the mesh network forwards the message through one or more intermediary nodes. This reference design uses 6LoWPAN. 6LoWPAN is an open standard defined in RFC 6282 by the Internet Engineering Task Force (IETF). The 6LoWPAN layer is a tiny layer in the stack located below IPv6 and above the IEEE802.15.4 MAC. The 6LoWPAN layer fragments and compresses IP frames, so the frames can be sent over the IEEE MAC layer. The main idea is to compress IPv6 headers and to not send data and information that the devices already detects. For example, sending the IPv6 destination and source address in every header is not necessary becausethe node detects this information once the header joins the 6LoWPAN network. The other big feature of 6LoWPAN is the fragmentation, that is the splitting of packets to fit into IEEE802.15.4 MAC frames. 6LoWPAN networks are self-healing mesh networks, which means the devices automatically connect to an edge router (gateway) with the right RF and security settings (Figure 10). If a node fails or drops out of the network, the routing protocol is smart enough to find a new way around the failing device.
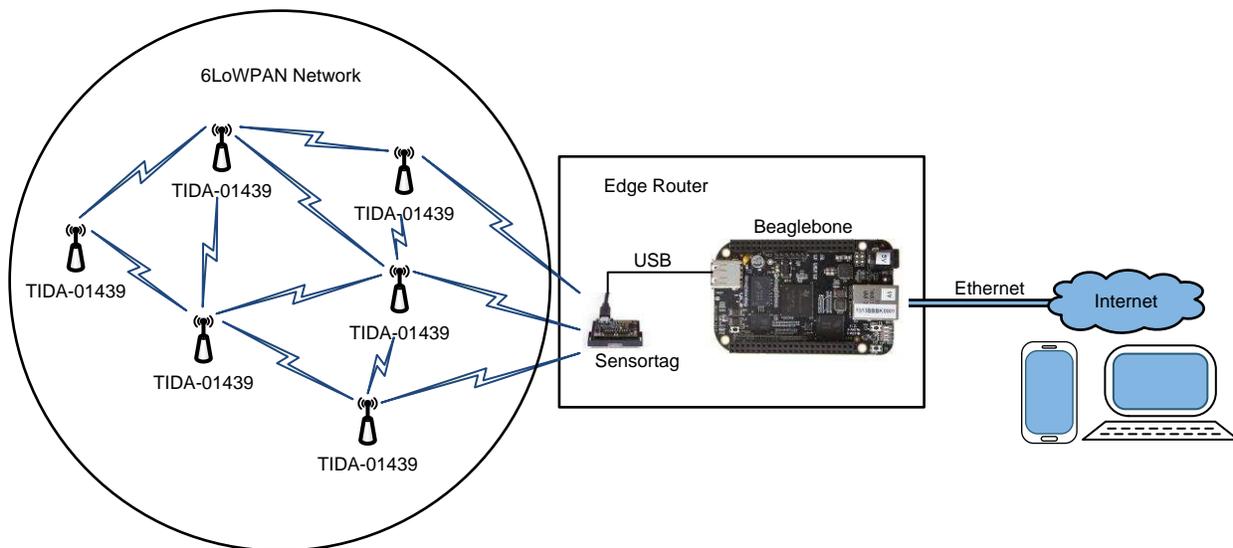
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Figure 10. Network Overview

A BeagleBone Black board connected to a CC2650 SensorTag forms the Edge Router to the Internet. The CC2650 SensorTag acts as the root node. The compressed IPv6 header requires an intermediary device to provide a conversion between 6LoWPAN and standard IP header. An edge router can be seen as this simplified *gateway.*

2.3.1   Sensor Node

This reference design has one Arm Cortex-M4 MCU (MSP432P401) and a Cortex-M3 MCU (CC2650) on the board (Figure 11). The MSP432P401 acts as the application processor, and the CC2650 acts as the connectivity processor. The MCUs are connected through SPI to exchange messages and sensor data.

The reference design has several different inputs, like RTD, RS232, or RS422, to connect different sensors and machines to collect data for predictive maintenance. For the sensor data processing the MSP432P401 Arm Cortex-M4F MCU with floating-point unit and DSP acceleration is a perfect fit. In combination with IEPE Vibration Sensor Interface for PLC Analog Input Reference Design , this reference design can also measure and monitor the vibration of motors and pumps. Vibration sensing is a crucial part in condition monitoring necessary for predictive maintenance. Misalignment, defect bearing, loose machine foot, defective gears, defect pumps, and defect motors are some of the faults that are readily detectable through vibration monitoring.
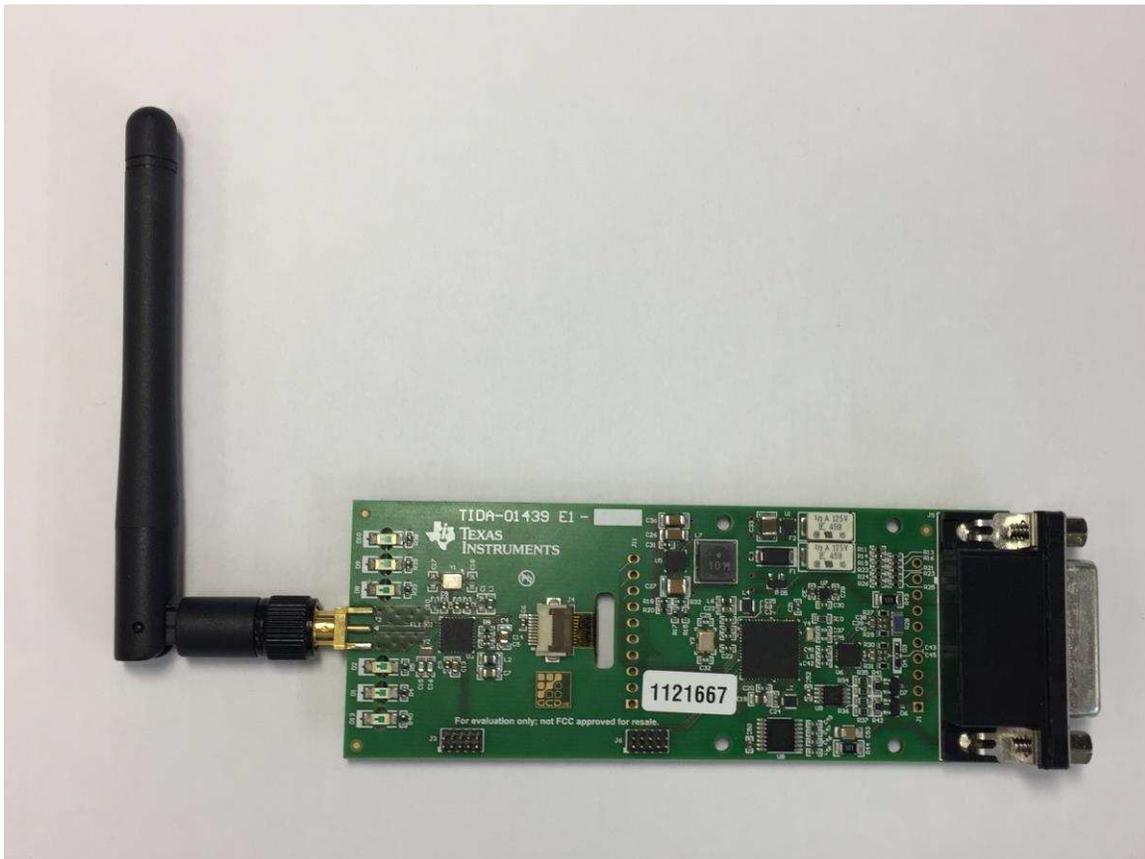
Figure 11. Design Board

Figure 12 shows the design's sensor node software architecture. On the MSP432P401 the application code runs. The CC2650 is the connectivity MCU responsible for the wireless mesh network. Both MCUs communicate using SPI.
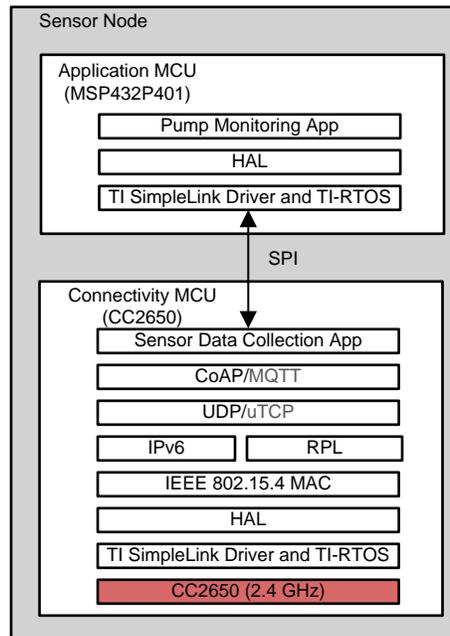
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Figure 12. Sensor Node Software Architecture

2.3.2   Edge Router

The edge router consists of a BeagleBone Black board and a CC2650 SensorTag (see Figure 13). The CC2650 SensorTag acts as the root node.
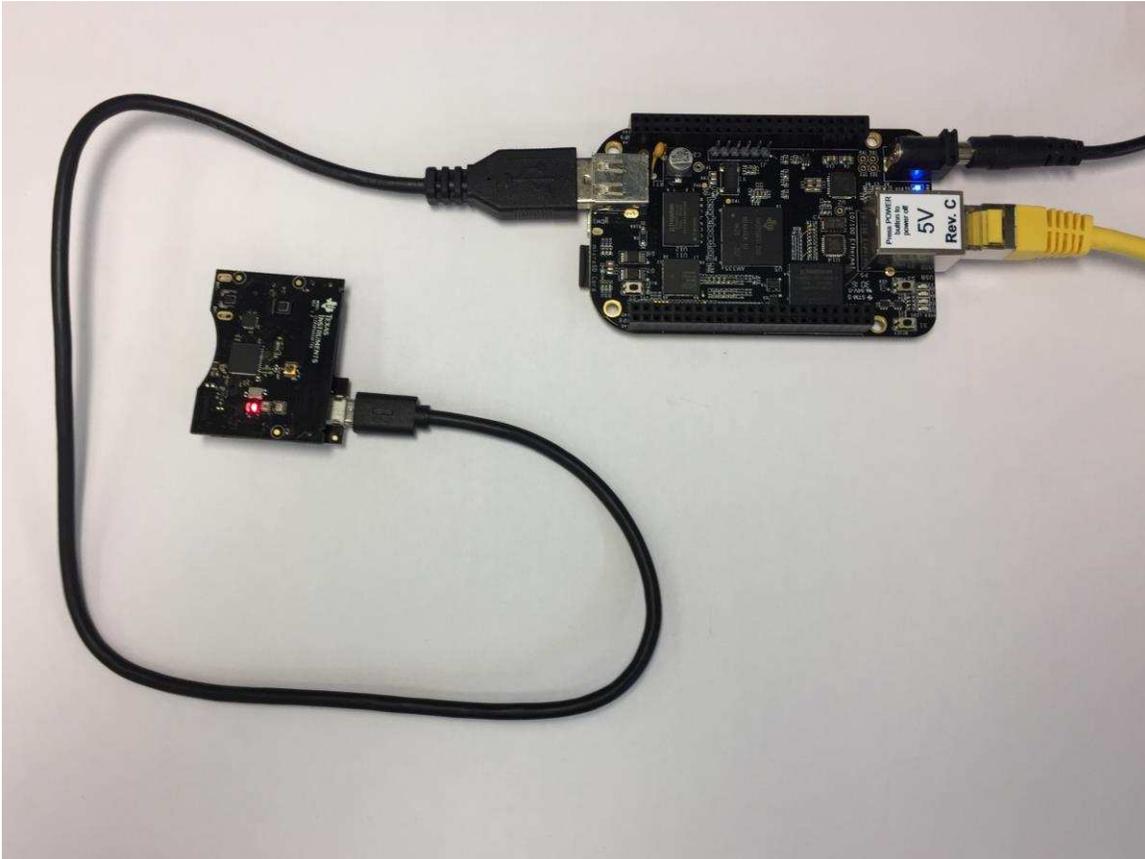
Figure 13. Edge Router

The root node (sensortag) contains the IEEE 802.15.4 MAC and lower layers. This node uses a UART connection to communicate with the Beaglebone Black. For the UART connection a Debugger DevPack board connects to the CC2650 SensorTag board.

Figure 14 shows the Edge Router software architecture.
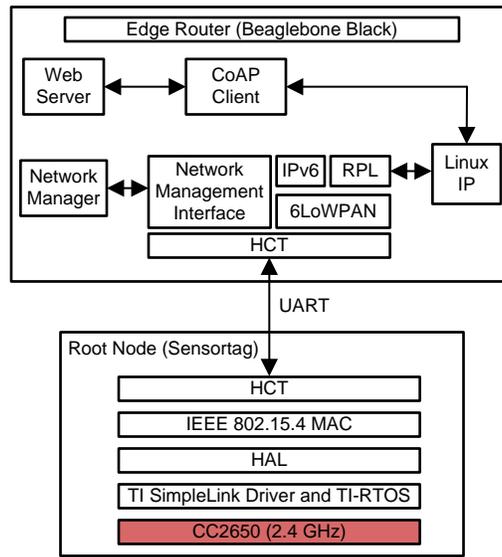
Copyright © 2017, Texas Instruments Incorporated

Figure 14. Edge Router Software Architecture

2.3.3 Web GUI

The BeagleBone Black Gateway is running a web server. A standard web browser (Internet Explorer®, Firefox®, Chrome®) can be used to connect to the BeagleBone Black webserver and view the sensor nodes. Figure 15 shows the web GUI.
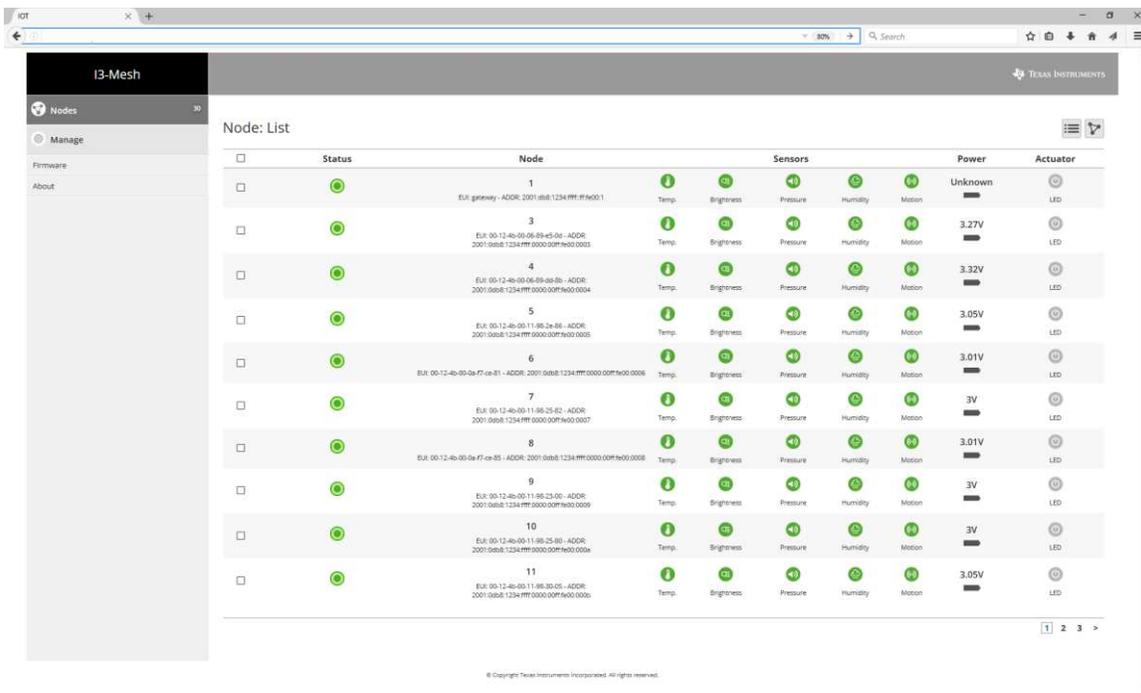
Figure 15. Web GUI

3   Hardware, Software, Testing Requirements and Test Results

3.1   *Required Hardware and Software*

3.1.1   Hardware

Figure 16 shows the different building blocks of this reference design. All components are located on the top layer of the PCB for easy evaluation.
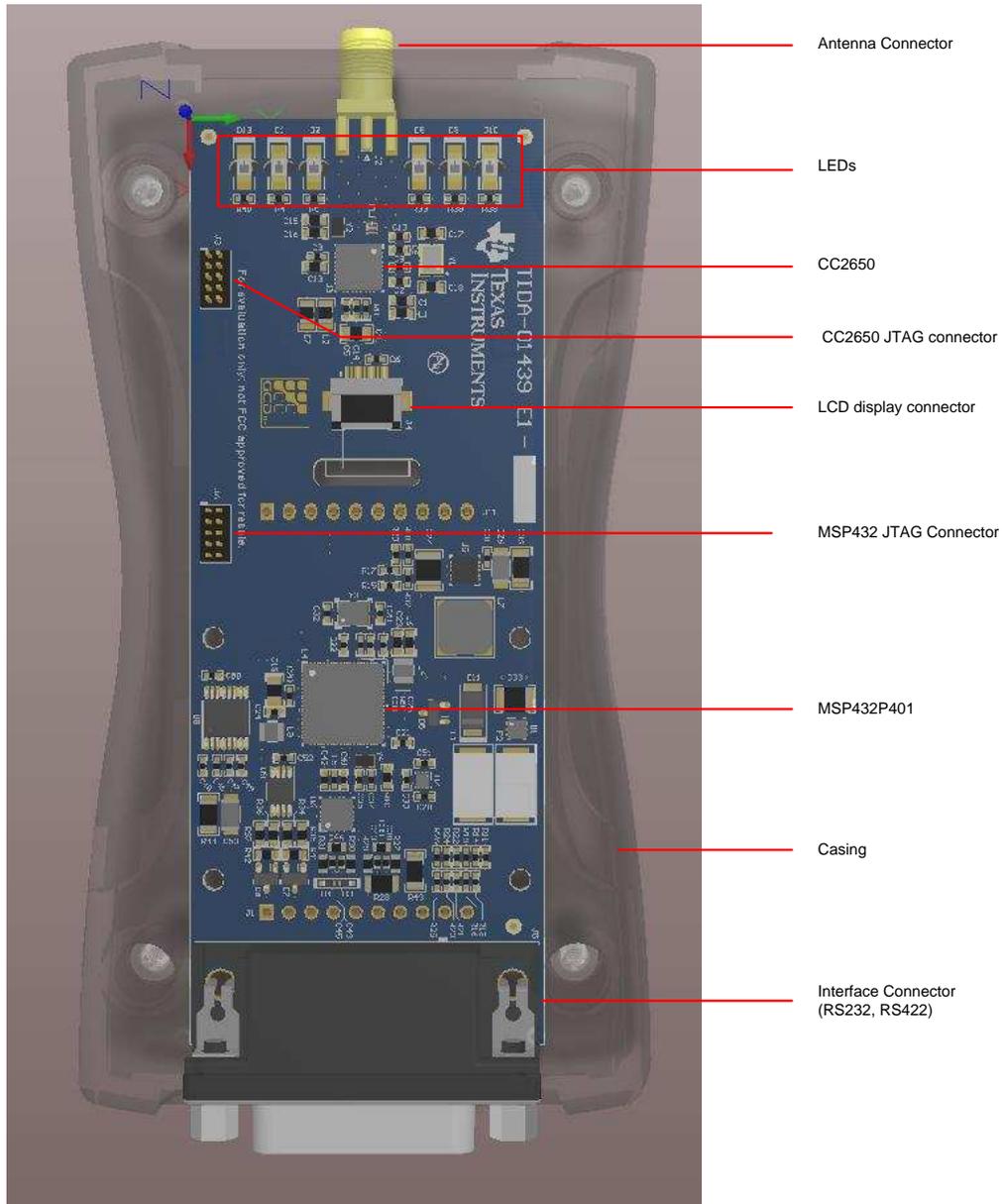
Copyright © 2017, Texas Instruments Incorporated

Figure 16. Reference Design Hardware Component Description

3.1.1.1   Antenna

The design board contains a 50-Ω SMA connector J2 to use with any standard 2.4-GHz external antenna.

3.1.1.2   Display

The design board has the onboard eight-color LCD module LS013B7DH06, which is connected to J4. The MSP432P401 controls the display using SPI interface.

3.1.1.3   RS232 and RS485 Interfaces

On connector J5 there is a RS232 and a RS485 or RS422 interface available. Figure 17 shows the pin configuration of connector J5.
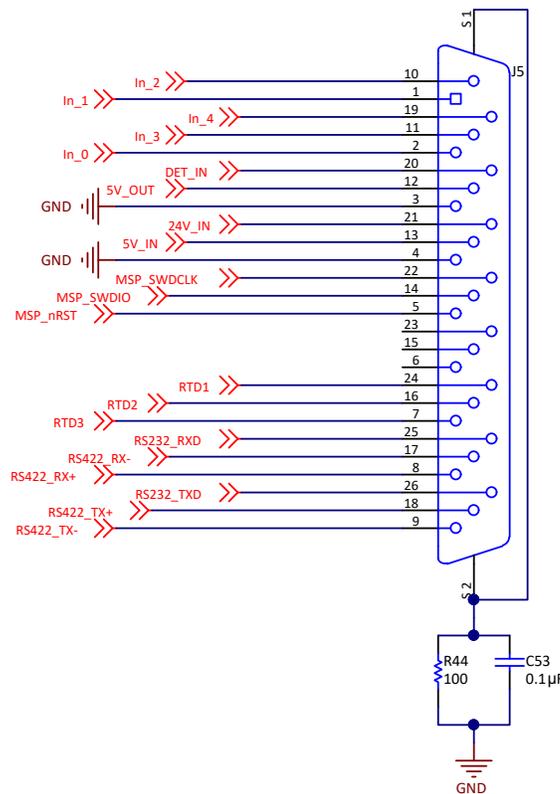
Copyright © 2017, Texas Instruments Incorporated

Figure 17. Connector J5 Pin Configuration

In the example, the design boards have been connected through the RS485 interface on J5 to several vacuum pumps (Busch Cobra® DS) in a semiconductor fabrication plant. The interface on these pumps is RS-485 compatible and uses the GE® Fanuc®series ninety protocol (SNP) protocol. With this interface permanent measurement data of the casing temperature, motor current, nitrogen flow, and water flow can be read out of the vacuum pumps.

3.1.1.4 BoosterPack™ Plug-in Module Interface

The MSP432P401 on the design board can be connected to Boosterpack plug-in modules. J1 and J11 are connectors for the BoosterPackplug-in module interface (Figure 18). Adding sensor functionality to the board is simple using the BoosterPack™ plug-in module approach. A broad range of sensor-specific BoosterPack plug-in modules are available from Texas Instruments as well as third parties. To create a BoosterPack plug-in module for specific requirements, use the resources at *Build your own BoosterPack plug-in module* .
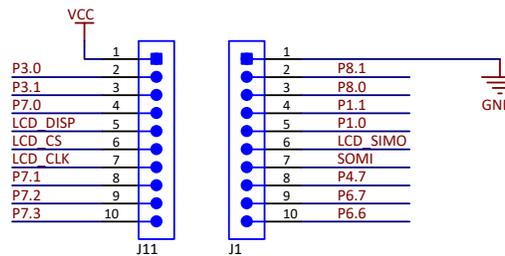
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Figure 18. BoosterPack™ Interface on Design Board

3.2 Testing and Results

3.2.1 Test Setup

3.2.1.1 Power Design

For powering sensors, the LM5165 synchronous buck solution has high-efficiency and ultra low quiescent current (I_Q = 10.5 μA). Operating from a wide input voltage (VIN) 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.

Figure 19 shows the converter schematic configured for a 5.5-V output on the LM5165. The typical input voltage on the design board is 24 V. The LM5165 supports adjustable input undervoltage lockout (UVLO) with hysteresis programmed independently through the HYS pin. The resistor divider R15 and R17 (as shown in Figure 19) can be modified to define different precision UVLO levels. With the actual configuration, the UVLO level is 20V, but the level can be adjusted as necessary by modifying R15 and R17. With resistor R20 the hysteresis of the UVLO can be adjusted. The *LM5165 DC/DC Converter Design Tool* facilitates and assists the power supply engineer with design of a DC/DC buck converter based on the LM5165.

The TVS33000 diode (U1) is used to clamp any overvoltage transient on the 24-V input terminal.
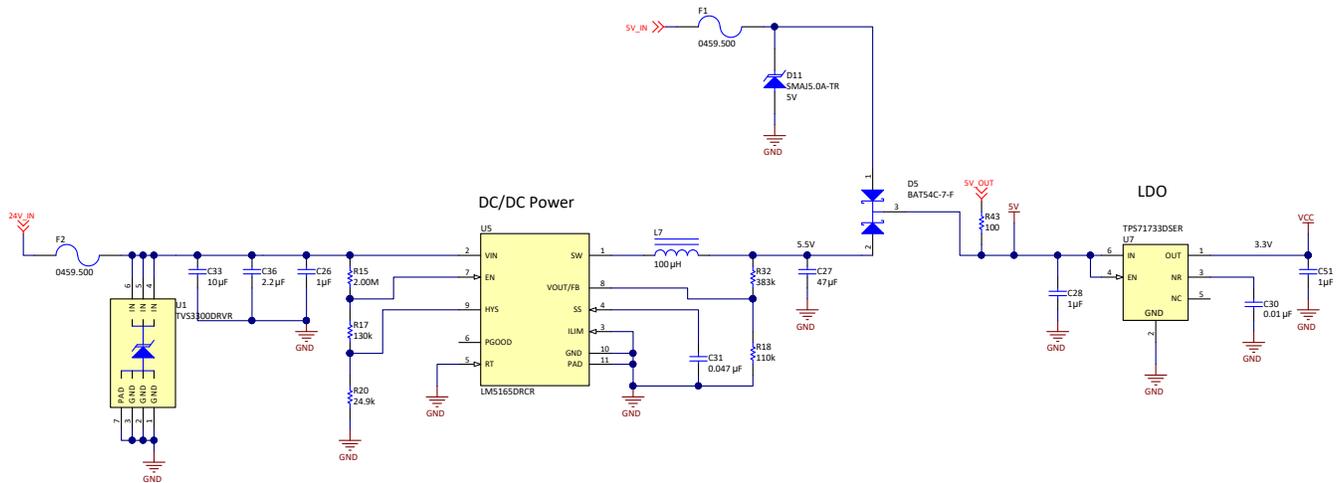
Figure 19. Power Schematics

To reduce the noise of the LM5165 output, the TPS71733 is 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 TPS71733, which is used in this reference design, is 3.3 V.

3.2.1.2 Resistance Thermometer (RTD)

The reference design has the option for an RTD. For the excitation current and to measure the RTD resistance value, this references design uses the ADS1220. Figure 20 shows the implementation of a ratiometric,three-wire RTD measurement using the excitation current sources integrated in the ADS1220. The sensor signal (that is, the voltage across the RTD) and the reference voltage for the ADC are derived from the same excitation source. Therefore, errors resulting from temperature drift or noise of the excitation source cancel out because these errors are common to both the sensor signal and the reference.The excitation current from the ADS1220 is provided through the two diodes D3 and D4, which develop a reference voltage across R28. This 3.24-kΩ precision resistor has a 0.1% tolerance with a temperature coefficient of 10 ppm/°C and generates the reference voltage for the ADC, which enables a ratiometric measurement.
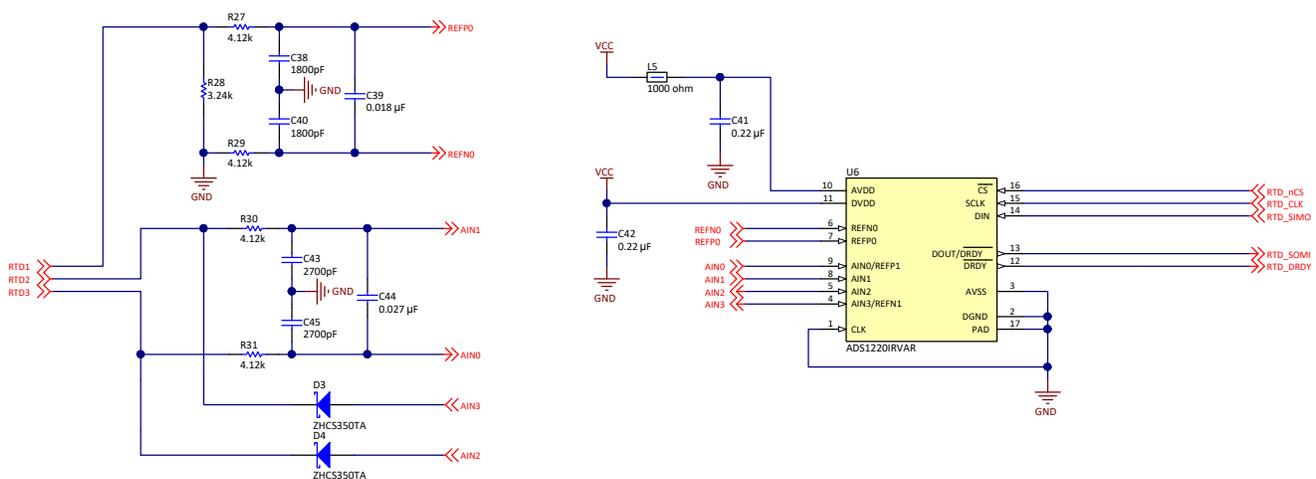
Figure 20. Three-Wire RTD Measurement

3.2.1.3 Programming and Debugging

To program or debug the reference design hardware, it is necessary to power the design board on terminal J5 with typ. 24 V.

The reference design hardware is programmed by connecting a 10-pin mini-ribbon cable from J3 or J6 to the XDS200 debugger. J3 is used to program the CC2650, and J6 is used to program the MSP432P401. Figure 21 and Figure 22 show the correct setup for connecting the reference design hardware to the XDS200 debugger. Alternatively other debuggers like the XDS110, which support the MSP432P401 and the CC2650, can be used as well.
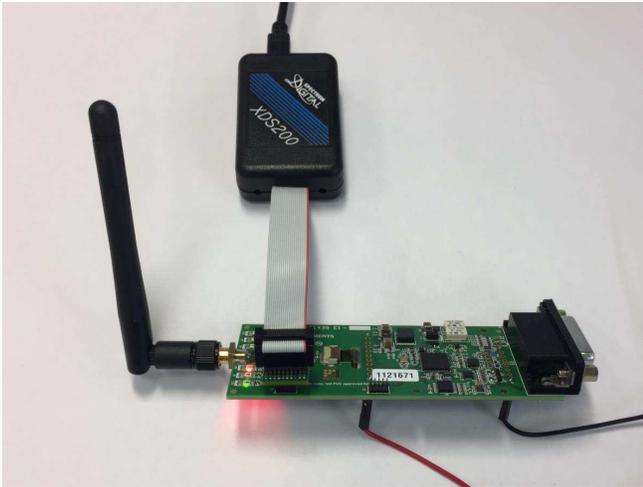
Figure 21. Debugging CC2650
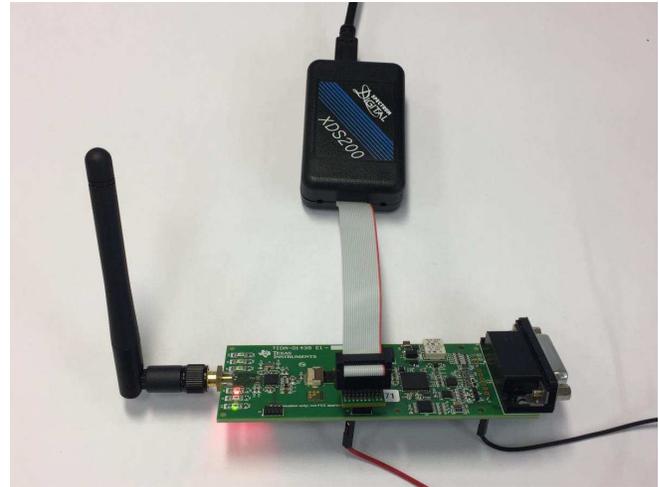
Figure 22. Debugging MSP432P401

3.2.2 Test Results

As an example the design boards are connected through the RS485 interface to several vacuum pumps (Busch Cobra DS) in a semiconductor fabrication plant. The Busch vacuum pumps provide permanent measurement data of the casing temperature, motor current, nitrogen flow, and water flow. Furthermore, the vacuum pumps provide the 24 V to power the design board. These vacuum pumps must be closely monitored to ensure uninterrupted operation. To avoid downtime, technicians must manually check the status of the pumps on a daily base. However, with this reference design board connected to the vacuum pumps, the permanent measurement data can now be centrally collected and easily accessed through the Internet. This collection enables the possibility for trend analysis and predictive maintenance.
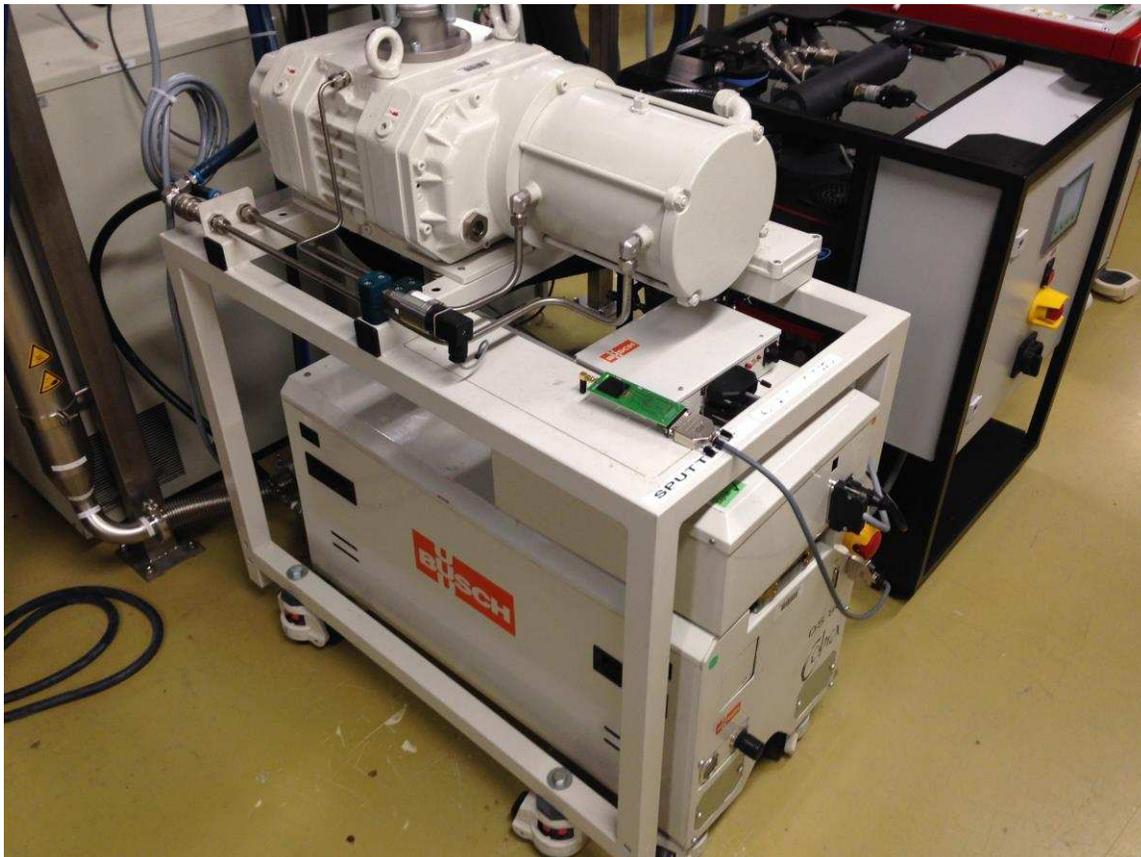
Figure 23. Design Board Connected to Vacuum Pump

To test the stability of this wireless meshed network in an industrial environment,ten nodes and one gateway were installed in a noisy environment where hundreds of different machines, like vacuum pumps, steppers for photolithography, etching, cleaning, doping, and dicing machines, are running. Figure 24 shows a picture of one node, which is connected to a pump and reads out the data of the vacuum pump.
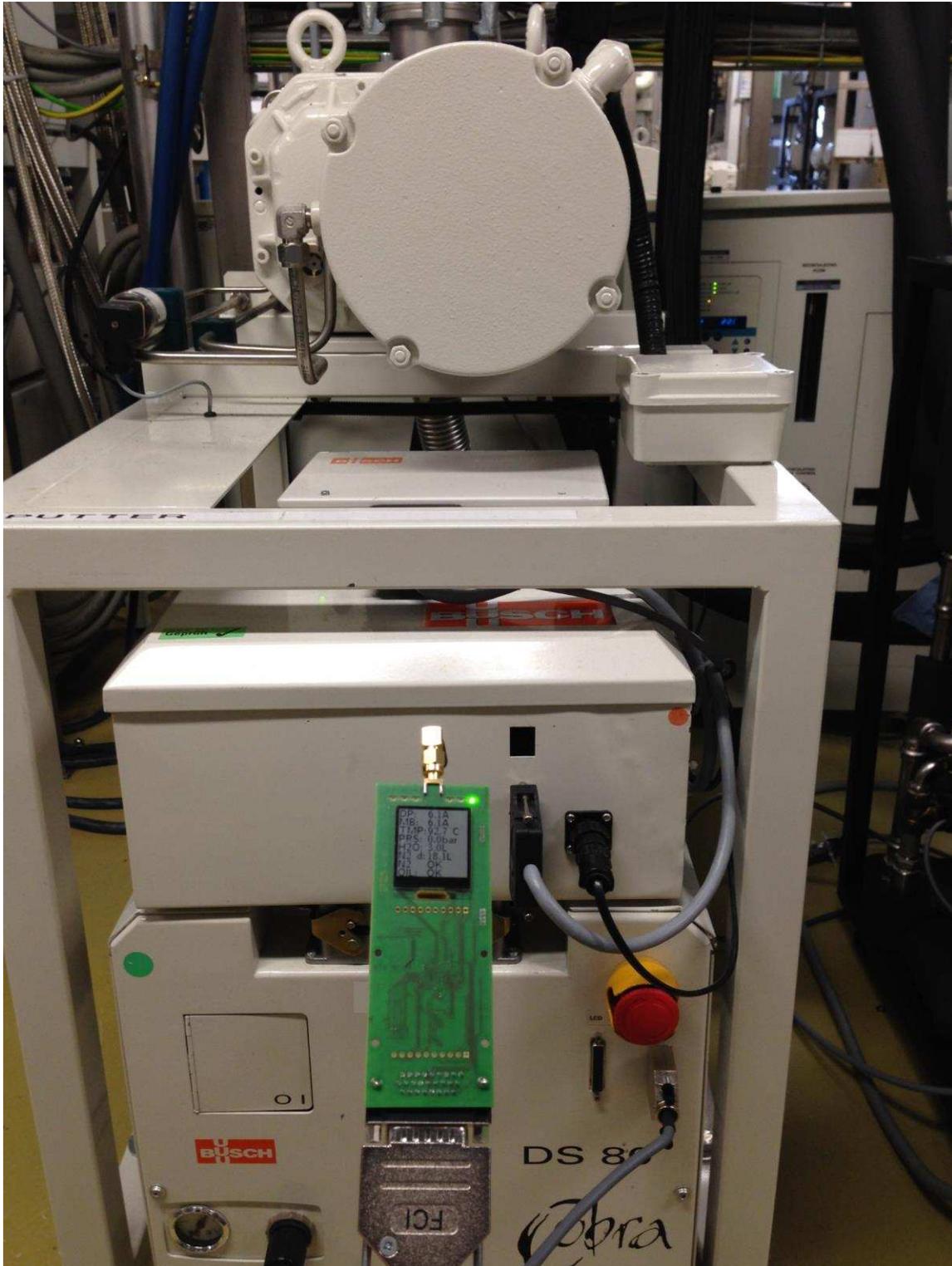
Figure 24. Design Board Showing Vacuum Pump Data

Figure 25 shows the actual connection of the nodes in the meshed network and the data of the vacuum pump, which is connected to node three. With the 6LoWPAN network this data can be easily accessed through the Internet and continuously monitored and analyzed. This access allows operators of the pumps' insight into failures before they happen. Defective components that could soon lead to a system shutdown can be identified independently of the usual maintenance schedule and replaced before damage actually occurs.
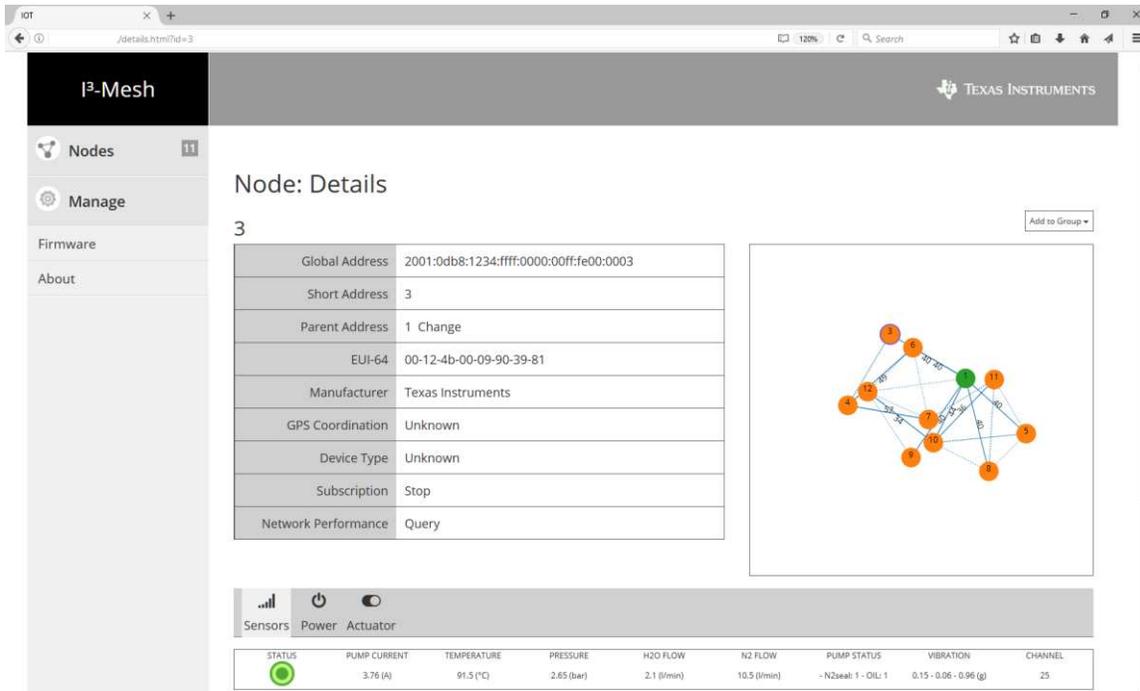
Figure 25. Details of Node Three in Meshed Network

4   Design Files

4.1   Schematics

To download the schematics, see the design files at TIDA-01439 .

4.2   Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01439 .

4.3   Layout Prints

To download the layer plots, see the design files at TIDA-01439 .

4.4   Altium Project

To download the Altium project files, see the design files at TIDA-01439 .

4.5   Gerber Files

To download the Gerber files, see the design files at TIDA-01439 .

4.6   Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01439 .

5   Software

The TIDA-01439 software is composed of multiple elements subject to several licensing types. Most of the tools such as IDE, compiler, TI-RTOS and software examples are available on www.ti.com. The TIDA-01439 is an exemplary software stack for hardware evaluation and have not been validated as production-ready. In the case of the network processor protocol stack, various alternatives can be found, like the open-source implementation supported by the community project Contiki. Other software stacks such as BLE, ZigBee, etc. can be utilized for hardware evaluation as well.

6   Related Documentation

1. Texas Instruments, *CC2650 SimpleLink Multistandard Wireless MCU Data Sheet, CC2650 Data Sheet*
2. Texas Instruments, *CC13x0, CC26x0 SimpleLink Wireless MCU Technical Reference Manual*
3. Texas Instruments, *MSP432P401R, MSP432P401M SimpleLink Mixed-Signal Microcontrollers Data Sheet*
4. Texas Instruments, *MSP432P4xx SimpleLink Microcontrollers Technical Reference Manual*
5. Texas Instruments, *LM5165 3-V to 65-V Input, 150-mA Synchronous Buck Converter with Ultra-Low I_Q Data Sheet*
6. Texas Instruments, *TPS717 Low-Noise, High-Bandwidth PSRR, Low-Dropout, 150-mA Linear Regulator Data Sheet*
7. Texas Instruments, *ADS1220 4-Channel, 2-kSPS, Low-Power, 24-Bit ADC with Integrated PGA and Reference Data Sheet*
8. Texas Instruments, *SN65HVD7x 3.3-V Full-Duplex RS-485 Transceivers With ±12-kV IEC ESD Data Sheet*
9. Texas Instruments, *MAX3232 3-V to 5.5-V Multichannel RS-232 Line Driver/Receiver With ±15-kV ESD Protection Data Sheet*
10. Texas Instruments, *TVS3300 33-V Precision Surge Protection Clamp Data Sheet*
11. Texas Instruments, *SimpleLink SensorTag*
12. Beagleboard.org, *Getting Started*
13. Busch, *Vacuum Pumps and Systems: COBRA DS 0080/0160 G*

6.1 *Trademarks*

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