TI Designs: TIDA-01228
Low-Power Water Flow Measurement With Inductive Sensing Reference Design

![TEXAS INSTRUMENTS]

Description

The TIDA-01228 reference design demonstrates a highly-integrated solution for this application using an inductive sensing technique enabled by the CC1350 SimpleLink™ Wireless MCU and FemtoFET™ MOSFET. This TI Design also provides the platform for integration of wireless communications such as wireless M-Bus, Sigfox™, or a proprietary protocol. Water utility providers who wish to add Automatic Meter Reading (AMR) capability face the choice of replacing all of their existing meters or installing a simple electronic add-on module, which will accurately measure the water flow rate and wirelessly transmit the results. Such add-on modules can provide the least expensive solution to provide AMR features to consumers.

Resources

TIDA-01228	Design Folder
CSD23285F5	Product Folder
CSD23280F3	Product Folder
CC1350	Product Folder

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Features

- Meets Measurement Accuracy Requirements of ISO4064-1:2014-11 (Class 1)
- Accurate Measurement at a Distance of 4.2 mm to a Wheel (11-mm Diameter)
- Accurate Flow Measurement as low as 11.25 Liters per Hour
- Consumes Only 4 µA With 12-Hz Sampling Rate
- Supports ISM Bands in 431- to 527-MHz and 861- to 1054-MHz Range Plus *Bluetooth*® Low Energy at 2.4 GHz

Applications

- Electronic AMR Add-on Modules:
  - Water Meters
  - Heat Meters
  - Gas Meters

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Low-Power Water Flow Measurement With Inductive Sensing Reference Design

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1 System Description

The TIDA-01228 design uses TI's CC1350 SimpleLink Ultra-Low-Power Dual-Band Wireless MCU and the FemtoFET CSD23285F5 P-channel transistor to implement an LC-sensing subsystem to detect disc rotation with minimal cost and dual-band RF functionality. Mechanical flow meters with impellers are the most popular type throughout the world, and electronic add-on solutions already exist.

Low-power operation is achieved by using the CC1350's integrated Sensor Controller Engine to interface to the LC sensing circuit and calculate the flow rate based upon the pulses generated when the meter disk rotates. This allows the ARM® Cortex® M4 MCU and RF subsystem of the CC1350 to stay in low-power sleep mode for longer periods of time.

The TIDA-01228 introduces a novel approach by integrating a true dual-band wireless subsystem with low-cost LC sensors to deliver a single-chip flow measurement solution that also offers wireless communications in both the Sub-1 GHz ISM band and the 2.4-GHz band. This single-chip approach provides a highly affordable and physically compact solution for customers developing AMR modules.

Popular AMR solutions such as wM-Bus or Sigfox can now be combined with a standard Bluetooth low energy connection to a smart phone or tablet as a powerful and easy-to-use human interface for local configuration and data readout.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Input power source	Lithium-ion primary cell battery (3.6 or 3.0 V nominal)	Section 4.4
Sensor method	Inductive (or LC sensing)	Section 2.4
Average active-state power consumption	20 or 30 µA at 64 or 100 Hz (3.6-V supply)	Section 4.4
Average standby power consumption	4 µA at 12 Hz or 5 µA at 16-Hz sampling of two LC sensors (at a 3.6-V supply)	Section 4.4
Motion sensing range (distance between disc and inductor)	4.2 mm (CSD23280F3 with 800-kHz oscillation); 3.7 mm (CSD23285F5 with 500-kHz oscillation)	Section 4.1
RF protocols (TX-only code example)	Sub-1 GHz: wM-Bus C-mode (T-mode also supported)	Section 4.5

2   System Overview

2.1   Block Diagram

The TIDA-01228 is shown together with the CC1350 device in Figure 1 and is applicable to water, heat, and gas meters with an impeller-based principle, where a rotating disc tracks the actual flow volume. Two LC sensors, with either a CSD23280F3 or a CSD23285F5 FemtoFET in each sensor, sense the rotation speed and direction of a half-metal coated, half non-metal disc, as used with mechanical flow meters in many regions of the world. Though primarily targeted at mechanical water meters, the TIDA-01228 can be used with mechanical heat and gas meters as well.

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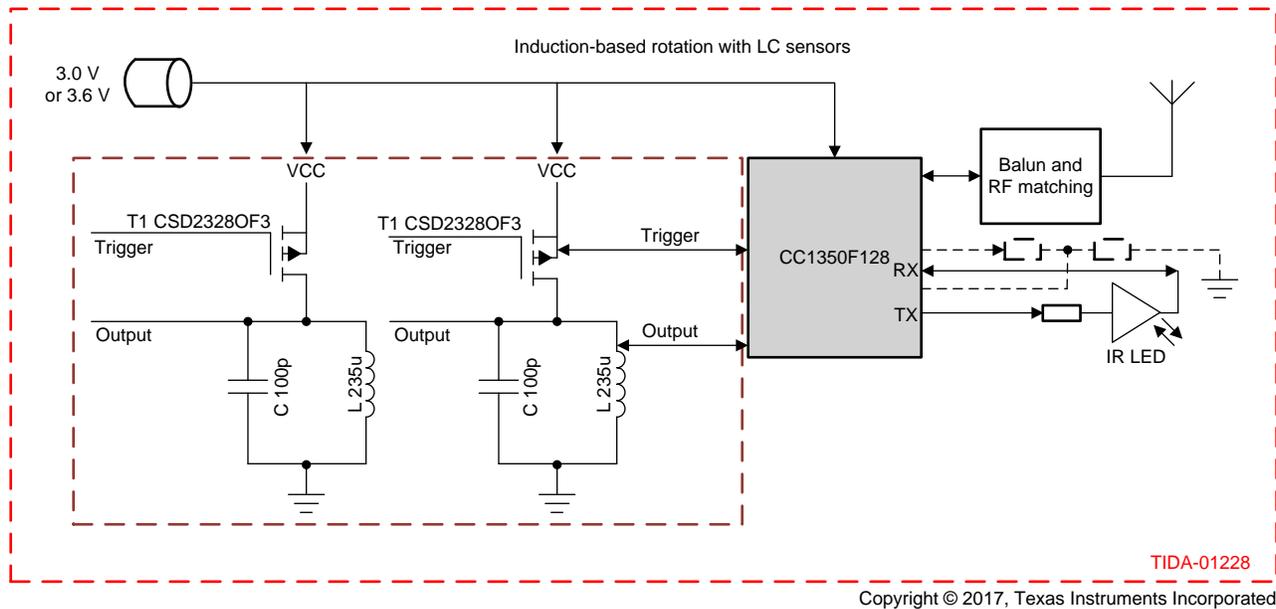
Figure 1. TIDA-01228 Block Diagram

2.2   Highlighted Products

The TIDA-01228 contains two active devices: the CC1350 wireless MCU and the FemtoFET CSD23285F5.

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2.2.1 CC1350

The CC1350 is the first device in the CC13xx and CC26xx family of cost-effective, ultra-low-power wireless MCUs capable of handling both Sub-1 GHz and 2.4-GHz RF frequencies. The CC1350 device combines a flexible, very low-power RF transceiver with a powerful 48-MHz ARM® Cortex®-M3 MCU in a platform supporting multiple physical layers and RF standards. A dedicated radio controller (Cortex-M0) handles low-level RF protocol commands that are stored in ROM or RAM, thus ensuring ultra-low power and flexibility to handle both Sub-1 GHz protocols and 2.4-GHz protocols (see Figure 2).

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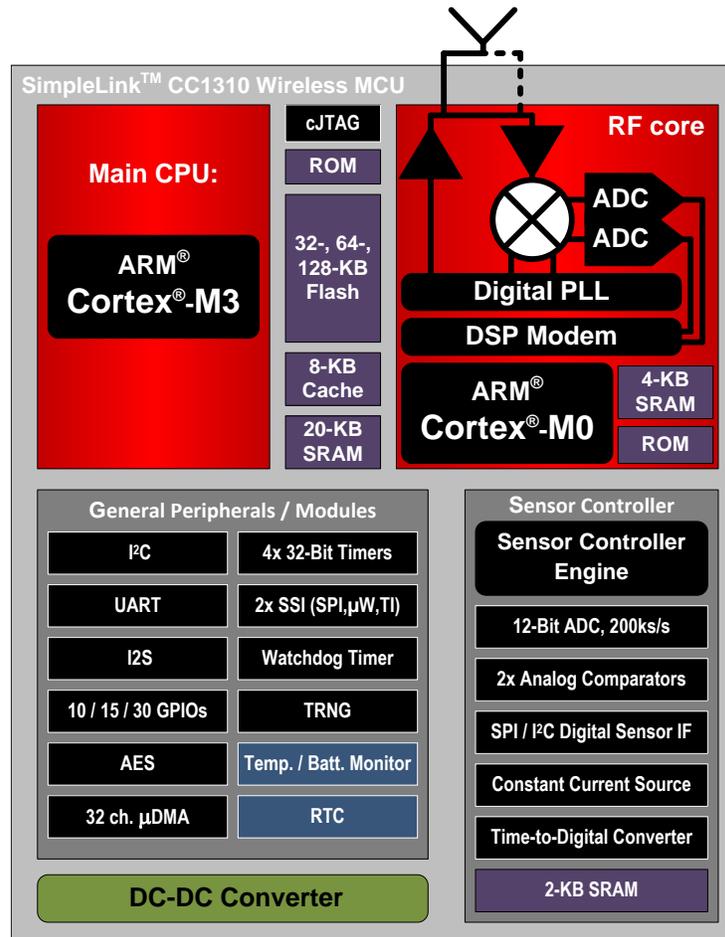
Figure 2. CC1350 Block Diagram

The ARM Cortex-M3 runs with up to 48 MHz, and there is also 128KB of in-system programmable Flash, 8KB of SRAM for cache (or as general-purpose RAM), and 20 KB of ultra-low leakage SRAM in the device. The sensor controller has been optimized for ultra-low power and can run autonomously from the rest of the system at 24 MHz, using only 0.4 mA + 8.2 μA/MHz. The sensor controller has a 16-bit architecture, a 96-MHz time-to-digital converter (TDC) and Comparator A (COMPA), and has its dedicated 2KB of ultra-low leakage SRAM for code and data. The CC1350 standby current is typically 0.8 μA at 3.6 V when using XOSC_LF (with RTC running and RAM and data CPU retention). The sensor controller uses its internal TDC and COMPA hardware blocks to deliver outstanding low-power consumption while executing various tasks.

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2.2.2 CSD23285F5 or CSD23280F3

Both FemtoFET devices have been successfully tested within the TIDA-01228, where the CSD23280F3 has an ultra-small package with a 0.36-mm pitch, which is so small that an increased PCB manufacturing and populating cost of the PCB itself has to be accounted for. The larger packaged CSD23285F5 drives lower-cost PCB manufacturing cost with its "standard" 0.5-mm pitch and provides an additional option for implementing the LC sensor. In both cases, the FETs are used as a simple, general purpose current switch to fully charge the LC tank for the desired oscillation; afterwards, the FETs are switched back to inactive mode.

The CSD23285F5 29-mΩ, –12-V, P-Channel FemtoFET is designed and optimized to minimize the footprint in many handheld and mobile applications. This technology is capable of replacing standard small signal MOSFETs while providing a significant reduction in footprint size. It features low on-resistance, an ultra-small footprint of 1.53 mm × 0.77 mm with a "standard" 0.50-mm pad pitch. The package is a 0.35-mm height low profile and is rated >4-kV HBM and >2-kV CDM.

2.3 Design Considerations

2.3.1 Physical Dimensions of Solution

The water meter rotation disc in Figure 3, which was used as a reference in the TIDA-01228 design, is only 11 mm in diameter.
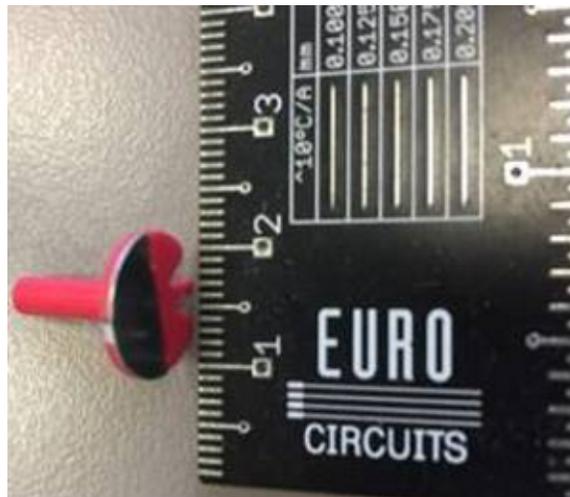
Figure 3. Rotation Disc Used for Testing, Next to Ruler With [cm] Scale

These 11 mm dictate that the inductors used for the LC sensors can not be much wider than 5 to 6 mm in diameter themselves. This is due to the quadrature encoded signal output from the two LC sensors, which can only occur when there is a position where both LC sensors (or the inductors L1 and L2) will sense the metal plate (which is one half of the full disc area) at the "same" time. Note that sensing occurs sequentially but as one sensor needs approximately 35 to 40 μs until it settles to detect the state of the disc the sensor states can be viewed as almost "simultaneous." This period of 35 to 40 μs can be extended to a certain limit to increase the detection range at the cost of additional current consumption, as the SCE of CC1350 will be active for a longer period over time. The upper limit will be defined by the maximum achievable oscillations above the selected COMPA reference threshold, depending on the supply voltage and the oscillation frequency used.

The TIDA-01228 PCB size has been optimized for a small form factor, as add-on electronic modules have to fit on top of existing mechanical meters, where the smallest form factor brass body is around 63 mm in diameter as per EN ISO 4064[7].

2.3.2 EN ISO4064-1 to ISO4064-5 Standards

In Europe, water meters are designed according to the EN ISO 4064 specifications, which are closely related to OIML R-49 documents, used in other regions of the world as well. Typically, the water meters are classified by a nominal flow range, for example Q_n = 1.5 for 1.5 m^3/h or Q_n = 2.5 with 2.5 m^3/h. The measurement error defines if the Meter is either Class 1 with ±1% maximum error or Class 2 with ±2% error from 0.1°C to 30°C. for temperatures above 30C the maximum permissible error is increased to ±2% or ±3% for Class 1 or 2 respectively.

Other important parameters in EN 4064 are the so-called permanent flow rate Q_3 and the minimum flow rate Q_1, which define the dynamic flow range of the water meter, where the ratio of Q_3/Q_1 is quite often either 80, 100, or 125 as per EN ISO 4064[7].

2.3.3 Sampling Rate for LC Sensors

For the common case, where there is no water flow at all and the disc is not rotating, often a 10-, 12-, or 16-Hz sampling rate (on both LC sensors) can be used to save power. As soon as a partial disc rotation is detected (for example, a half turn on any direction), the sampling rate must be increased to the maximum possible turning rate of the disc. These sampling rates are expected between 64 and 200 Hz (with higher sampling rate also possible), depending on the mechanical meter used.

2.3.4 Power Consumption and Battery Lifetime

As water meters are typically battery powered, one of the main target goals for the TIDA-01228 implementation is the lowest possible power consumption. Lifetime estimations for the TIDA-01228 solution are heavily dependant on the battery technology, the capacity used, and the current profile of the application. For example, more frequent RF transmissions with a higher TX power will drive the average power consumption higher. It is also essential if a water meter will report its reading over a wireless link once per minute, once per hour, or once per day. In a flow meter application, the duty cycle between "disc not turning" to "disc turning" will also have a huge effect on the lifetime estimation.

Often, the certain "worst case" scenario for this duty cycle of minimum versus maximum sampling speed of the LC sensors has to be assumed. The time with an active flow could be less than a few minutes per day in a residential home or up to several hours in a larger home or apartment. On the other hand, utilities will often demand 5 to 10 or even more years of operating time between its meter service or full replacement periods. [1] During this period, the measurement precision has to be guaranteed together with the AMR wireless operation. As add-on electronic flow modules are size constrained, this also limits also the maximum available battery capacity for water meter RF add-on modules.

[1] Due to national regulations, the maximum replacement or recalibration cycle in Germany for water meters is 5 to 6 years (but may be different in other countries).

2.4   System Design Theory

TI was the world's first vendor offering a dedicated on-chip hardware module for LC sensing with ultra-low-power consumption in the MSP430FW4xx MCU series[2].

The LC sensor is an oscillating tank circuitry, used to detect both the rotation speed and direction of a wheel (or disc), which is half-plated with metal and the other half is non-metal or non-magnetic. Such wheels are very popular in mechanical meters and enable the implementation of electronic add-on modules, which are able to measure the fluid flow and then communicate the flow meter reading wirelessly (AMR functionality).

2.4.1   Inductive (or LC) Sensor Theory

The LC sensor consists of an inductor L and a capacitor C connected in parallel. As all inductors also have an internal resistance (unless they are superconductors), the inductor can be viewed as L and R in series. The circuit analysis for this case is documented in [9].

Once the RLC circuitry is charged, the energy starts oscillating from the capacitor into the inductor.Theelectric field in the capacitor oscillates into a magnetic field in the inductor and back, with the oscillating currents decaying over time to zero due to the resistance R. Depending on the parameters of L, C, and R, the oscillation has a resonant frequency f. The higher the parameters C and L are, the lower the resulting resonant frequency is (see Equation 1):

$$f = \frac{1}{\sqrt{LC - \left(\frac{R}{L}\right)^2}} \tag{1}$$

2.4.2 Eddy Currents and Oscillations Dampening

The oscillating magnetic field created in the LC sensor induces Eddy (or also Foucault) currents in a conductor, which is the half-circle metal plate of the rotating disc, due to Faraday's law of induction. The currents build closed loops within the conductors in planes perpendicular to the magnetic field, as explained in [8]: *"The magnitude of the current in a given loop is proportional to the strength of the magnetic field, the area of the loop, and the rate of change of flux, and inversely proportional to the resistivity of the material."*

Regarding the LC sensor and the half-metal disc, this statement means that a bigger metal half-disc area, which is closer to the inductor L and faster oscillating fields (higher LC-resonant frequency), will result in larger Eddy currents and thus larger dampening of the LC sensor oscillations. Less resistivity of the metal material will also help increase the Eddy currents.
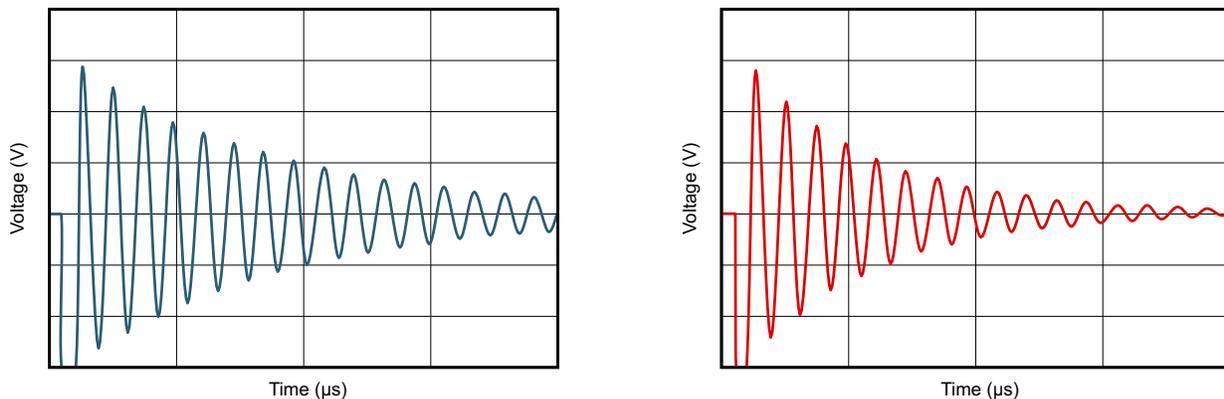
Figure 4. Dampened (to the right) and Undampened Oscillation of LC Sensor

effCounter is the effective rotation counter. UpCounter and DownCounter accumulate steps in each rotating direction. The difference of up versus down is the effCounter because water can flow also backwards (for a short period of time when the pipe pressure is equalized after a tap is closed).

The larger the dampening effect (see the red line in Figure 4), the easier it is to differentiate between dampened and undampened conditions, which correspond respectively to a metal or non-metal material being in front of the LC sensor.

The method to detect between dampened and undampened conditions in the TIDA-01228 is as follows:

1. The SCE internal reference voltage of 1.27 V is set as the COMPA reference threshold.
2. The number of full oscillations (or a full period), which crosses the selected COMPA reference, during a pre-defined time period (for example, 30 to 40 µs) are counted using the TDC module.
3. The undampened condition is when the expected number of full oscillations was achieved. The dampened condition is when the expected number of oscillations was *not* achieved.

It is easy to find out the number of full undampened oscillations based on the "worst case" distance to the disc and the inductor being used by testing with different oscillation values in the Sensor Controller Studio (SCS) debug mode. This "default" number must be then optimized for the dampened condition at the maximum desirable distance. For example, with a 4-mm distance between the disc and inductor as the "worst case" for a given flow meter, the "default" number of oscillations should *not* be achieved. This result gets reported as an error by the TDC module with a numeric value of 2 after the pre-defined time period of, for example, 39 µs elapsed. The dampened condition should be detected by both LC sensors at the maximum desired distance "simultaneously" (which means that the second LC sensor will be activated immediately after the first LC sensor has finished).

2.4.3   Flow Measurement Through Rotation Detection

Several application notes [1][2] from TI address the rotation detection and measurement using LC sensors. Section 1 of the MSP430™ application report[2] explains in detail how the undampened (non-metal in front of the L equals logical "0") and dampened (metal close to L equals logical "1") oscillations are converted into a digital coding, also known as quadrature encoded outputs, as they are 90 degrees out of phase. By implementing a simple state machine (as described in the MSP430 application report[2]) using the current and the previous state of the two LC sensors, it is possible to count the rotations of the disc with 90 degrees of resolution in both directions. Note that in a water meter, the flow can go in both directions due to the pressure change when an open tap is closed, so it is important to detect and calculate any flow in the reverse direction as well.
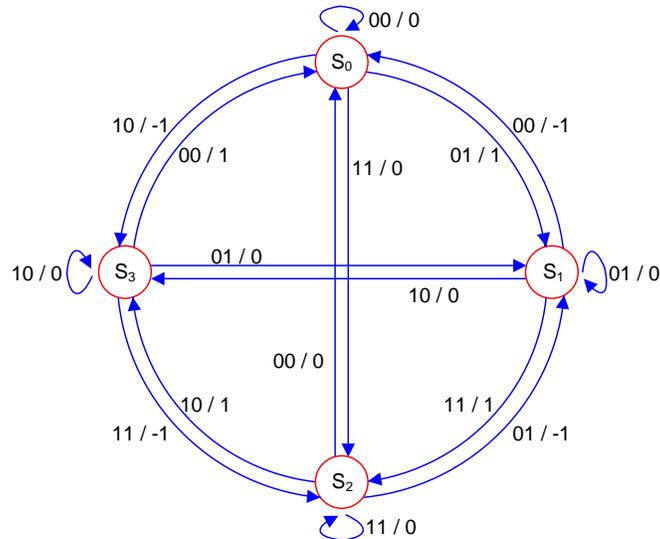
Figure 5. State Machine With 2-bit (LC Sensor 1 and LC Sensor 2) States S0 to S3

As shown in Figure 5, this state machine covers forward and backward rotation with a 90-degree or ¼ rotation resolution. The jumps between S1 and S3 or S0 and S2 must not occur and can be caused by a undersampling condition, where the sampling rate is insufficient to detect the rotation properly. Handling of such conditions has to be taken into account when calculating the disc rotation, for example by increasing the sampling rate of the Sensor Controller Engine (SCE) to the maximum.

Table 2 describes only the forward rotation case; the backward case is when the states change from S3 to S2 to S1 to S0, as indicated by the counter clockwise pointing arrows with –1 in Figure 5.

Table 2. Forward Rotation in Two LC Sensors State Machine

SENSOR	PREVIOUS STATE	CURRENT STATE	ROTATION
LC1_LC2 sensors	00	01	90 degrees = ¼ rotation clockwise
LC1_LC2 sensors	01	11	90 degrees = ¼ rotation clockwise
LC1_LC2 sensors	11	10	90 degrees = ¼ rotation clockwise
LC1_LC2 sensors	10	00	90 degrees = ¼ rotation clockwise

3 Getting Started Hardware and Software

The TIDA-01228 reference design has been designed and tested in two variants: either with CSD23280F3 or the CSD23285F5 devices. The published TIDA-01228E2 revision uses the larger (0.5-mm) pitch F5 FemtoFET device, driving a significantly lower cost for PCB manufacturing and populating the components. The TIDA-01228 design has been tested in conjunction with two commercially available TI evaluation boards: the SmartRF06 Evaluation Board combined with the CC1350EM as well as the CC1350 LaunchPad™ . Both of these evaluation boards are supported by the SCS software tool and Code Composer Studio™ (CCS) v7.1 compiler tool.

3.1 Hardware

The developed LC sensing solution has been optimized for achieving the lowest possible power and system cost with a very small PCB area, representing de-facto a single-chip RF-enabled add-on AMR capable module for electronic flow measurement. Any of these TI reference platforms can be used, as they both offer access to CC1350 GPIOs and provide GND and VDD (voltage supply for the FemtoFETs) connections on separate header pins:

- SRF06EB + CC1350EM
- CC1350 LaunchPad

The binary image, which is created by the CCS v7.1 project, can be run on both platforms after programming them with the Flash Programmer 2 Tool.

3.1.1 Peripheral Modules in CC1350

The high-precision TDC peripheral measures time between two individually selected start and stop events with high accuracy by counting on both 48-MHz clock edges, running effectively up to a speed of 96 MHz. The TDC module is able to evaluate periodic or single events due to its flexible start and stop trigger conditions in combination with the COMPA module. The SCE is a lightweight 16-bit CPU with two-clock execution for all instructions, and is effectively a 12-MHz (which is half of the 24-MHz system clock for the SCE) ultra-low-power MCU core engine. The Comparator A (COMPA) hardware module can handle input signals of up to 1 MHz, which makes it suitable for use with LC sensor oscillations, which are typically in the range of 500 kHz to 1 MHz[1].

3.1.2 FemtoFET as ON/OFF Switch for LC Sensor

The CSD23285F5 device is used as a switch to charge the LC sensor circuitry before the oscillation starts. This depends on the sampling frequency used; for example, if 100-Hz sampling is running, each FemtoFET (one per LC sensor) will be switched 100 times per second.

The length of the on-time depends on various factors such as the effective capacitance of the LC sensor and the supply voltage used while testing the value of 250 ns (or three cycles of 83.3 ns each). The most important consideration here is to ensure that the LC circuit is enabled long enough to get fully charged; the peak voltage of the first oscillation must be slightly above the VDD supply voltage and the minimum voltage a bit below 0 V. These overshoot and undershoot levels should be kept compliant with the CC1350 I/O pin specification.

3.1.3 Inductor Considerations

Important decision factors for selecting a suitable inductor have been documented in Section 1 of the application report[3]. The physical dimension or the diameter of the Inductor has to be small enough such that two inductors can fit above the metal half-plate of the rotation disc. On the other hand, larger L-values reduce the overall current consumption for each oscillation, as shown in Figure 1 of the application report[3].

As a result, a good trade-off of physical size versus a higher L value will be often in the range of 100 to 470 µH. In this TI Design, the GT1128-0 inductor from Gemphil with 235 µH has been used. The form of the inductor is also very relevant; it is essential to project the magnetic field as far as possible from the inductor top in order to maximize the field density crossing the half-metal area of the rotating disc. This is the case for inductors with a T-shaped cross-section like the GT1128-0[11], with windings around the center of the T-shape.

Based on the COMPA limit of 1 MHz (at maximum), the oscillation of the TIDA-01228 has to be below that value. The measured LC sensor frequency during testing was approximately 490 kHz, which is comparable to the 500 kHz in the MSP430FR69xx application report[1]. In summary, the LC sensing solution consists of the COMPA and TDC internal hardware modules with few external components, controlled by the SCE 16-bit CPU core.

3.2   Software

Two software projects have been designed for the TIDA-01228: the first being a SCS code for controlling the two LC sensors, whereas the second is a complete CCS example source code, which builds upon TI-RTOS and incorporates the SCS code portion. The TI SCS v1.4.1.54 or later—a TI-provided tool chain—is needed to generate the binary code for the sensor controller; the SCS software development tool can be downloaded at its product page. In SCS, it is possible to run the LC sensing project in debug mode, which has a maximum sampling rate for detecting two and a half full disc rotations per second.

The integration of correct sampling rate (up to 200 Hz was tested) with RF functionality and TI-RTOS based ultra-low-power operation is only possible inside the CCS example code, which itself includes the LC sensing task. Based on TI-RTOS, the correct sampling rate for the CCS project has been verified using the Saleae Logic PRO 16 tool.

Both firmware code projects for SCS and CCS are provided as a single-source code deliverable (TIDA-01228_SW.zip). The CCS source code project contains the SCE project, found in the install path /TIDA-01228/sce and named "TIDA01228_F285.scp," which handles the LC sensing part.

A full version of the TI CCS v7.1.x (or later) together with the TI RTOS v2.21.00.06 is required to compile and debug the TIDA-01228 firmware, which can run on both the CC1350LaunchPad and SRF06EB + CC1350EM, assuming that the proper GPIO pins of the CC1350 are wired to the TIDA-01228 design. The connections are found (and can be changed as needed by clicking the relevant DIO pin) in the I/O Map window of the SCS code project (see Figure 6).
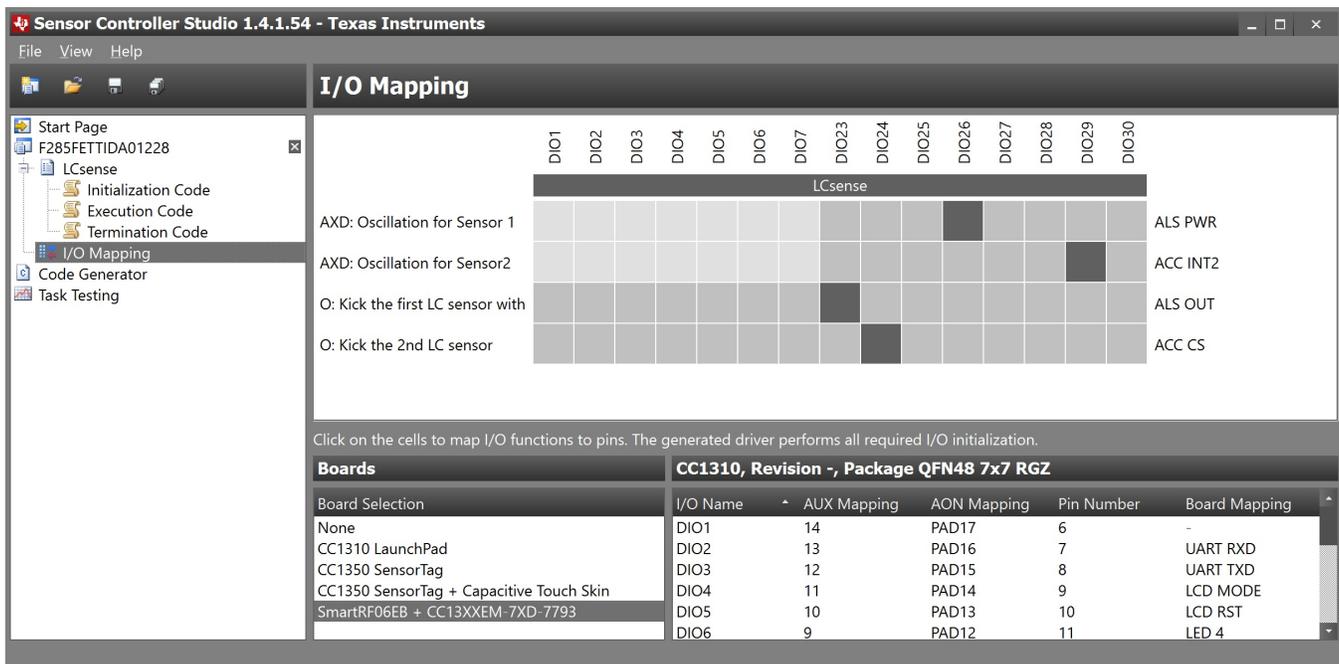
Figure 6. GPIO Map for Wiring TIDA-01228 to CC1350EM With SRF06EB

The GPIOs in use must be among the 15 I/O pins, which can be controlled by the SCE; DIO23 through DIO30 are analog capable, which means they can be used with the COMPA (or any other analog) module. Users can modify the pin allocation as they wish to accommodate any layout or other application constraints.

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3.2.1 LC Sensor Control Through SCE Code

The following nine steps are found inside the Execution Code section of the "TIDA01228_F285.scp" example:

1. Start the LC sensor oscillation with a negative pulse of three ticks = 250 ns on its respective FLOW_TRIG line (the 250-ns pulse time is the first programmable parameter).

2. Use the COMPA (< 1 MHz) to measure the number of full oscillations on the FLOW_OUTP line that pass the COMPA threshold of 1.27 V (for example, 22), which is an internal reference value in SCE. The number of full oscillations is the second programmable parameter.

3. Use the TDC module to capture the TDC value at the 39-µs timeout (the exact timeout is the third programmable parameter).

4. The TDC value will be either several thousand ticks of 10.667ns each (for example, 3000 to 4500, which means there is a "undampened" condition or state as the design has completed multiple oscillations) or 2 (meaning the expected number of oscillations never occurred during the timeout because the metal is close enough to the inductor to trigger a "dampened" condition or state).

5. Capture the state for LCsensor1 and repeat Steps 1 to 4 for LCsensor2 to detect its state.

6. Create current state "L1L2", which represents the four possible positions of the disc.

7. Use "L1L2" as the transition vector to a new state and the previous state "Lold1Lold2" to step through a state machine to the newly detected state, see Figure 5.

8. Move "L1L2" state to "Lold1Lold2" state and go to low-power or sleep mode, waiting on the TI-RTOS tick for the next sampling.

9. Based on the programmed sampling frequency (for example, 64 Hz), the CCS example code with TI-RTOS will wake-up the SCE in 15,625 ms and repeat the process starting at Step 1.

When running the SCE code the signals of the two LC sensors should look like the OUTP1 and OUTP2 in Figure 7; where the total duration of both LC sensor oscillations is about 99 µs.
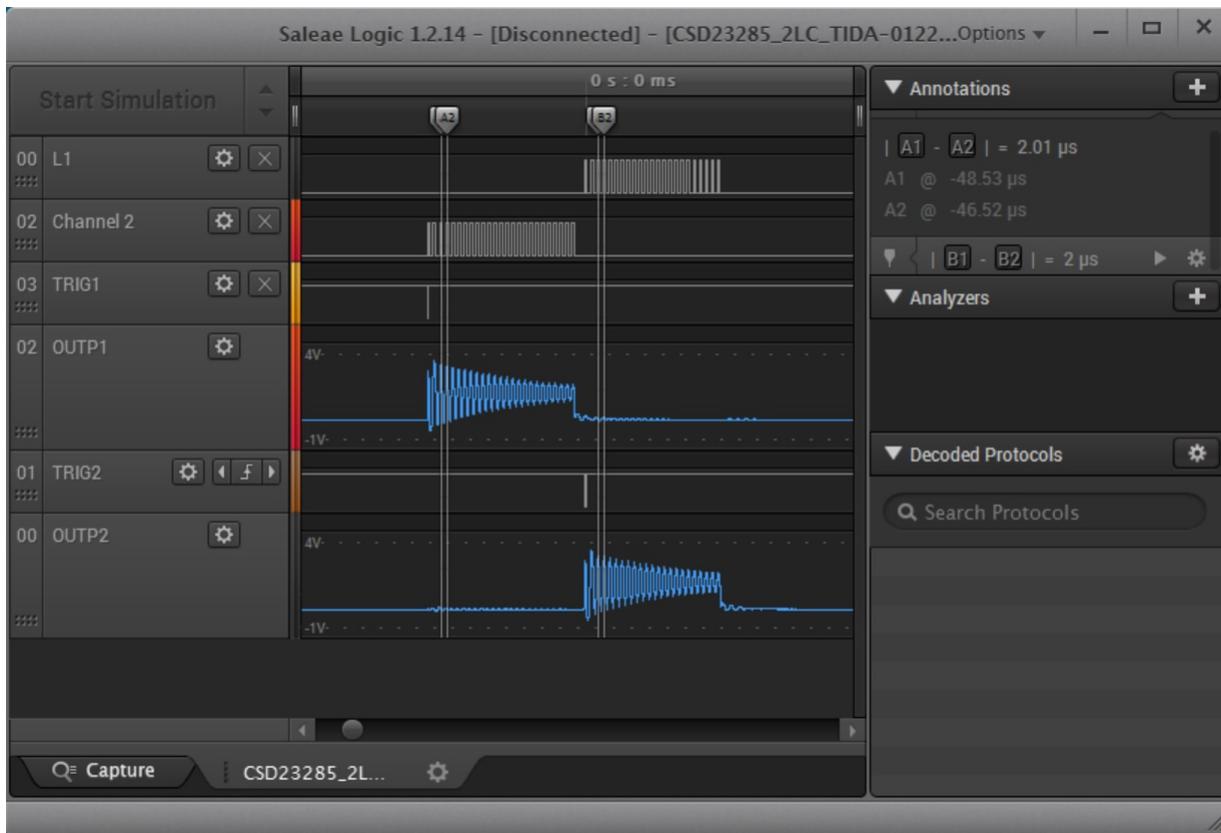
Figure 7. Undampened LCsensor1 and LCsensor2 Oscillation With Approximately 500 kHz Each

The real value for accumulating the flow (number of disc turns) is the *effCounter*, or the difference between upCounter and downCounter, which count the rotation for the forward and backward directions, respectively. There are two data structures called output and state, which contain multiple variables each. The state structure is needed for the state machine while the output structure is used to share data with the Cortex-M3 core of the application.

The Initialization Code section of the SCE project handles the Look-Up-Tables (LUT), which are used to calculate the rotation of the disc for the forward (upCounter) or backward (downCounter) direction, while the Termination Code section is not used.

3.2.2   Combining AMR With LC Sensing Functions

The code is based upon the regular "RfPacketTX" example for the CC1310DK but has been extended to support the transmission of a "water meter" C1-mode type of packet, as described in EN13757-4:2014-02, Annex C. The modifications are the usage of TI's manufacturer address and that the number of liters (in BCD) contains the number of rotations measured by the SCE, periodically report to the main application, and then wirelessly transmit.

4 Testing and Results

4.1 Rotation Measurements Setup

The DRV8846EVM with an "off-the-shelf" stepper motor with 200 steps per full turn was selected to provide a fully controlled rotation setup, simulating various speeds and rates for the rotating disc, which was glued to the motor shaft.
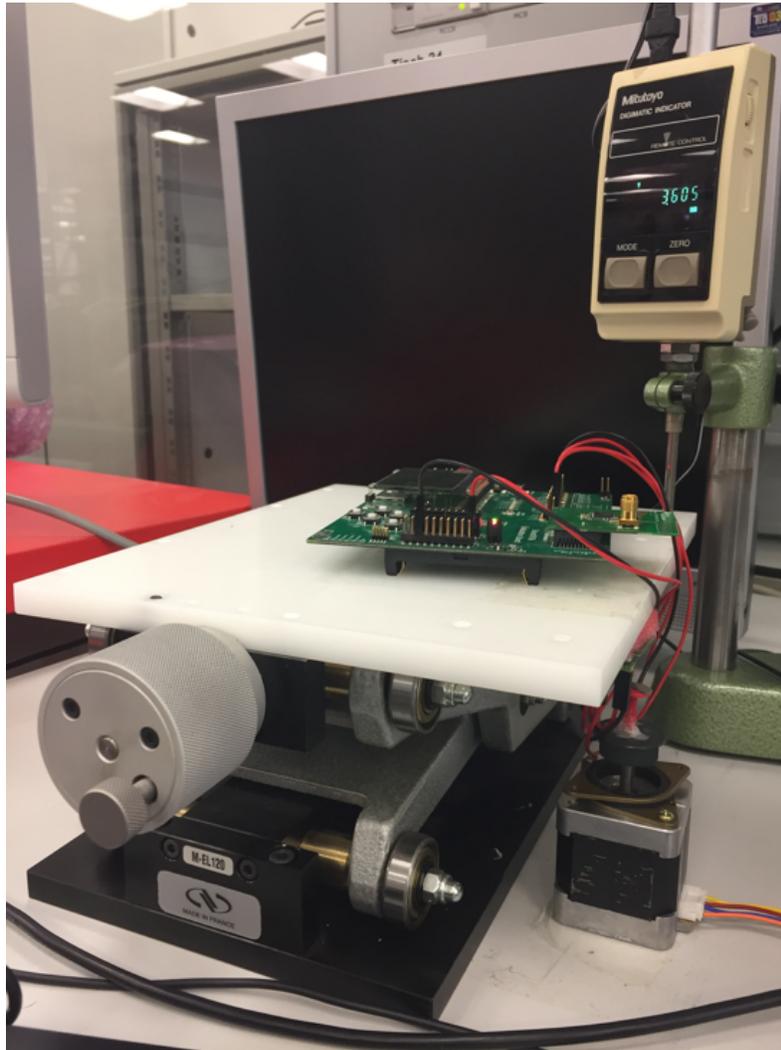
Figure 8. Stepper Motor With Disc at 3.6-mm Distance From TIDA-01228 (Face Down)

The TIDA-01228 hardware is glued with tape underneath the white elevation table with the two inductors facing down to the rotating disc, which is mounted onto the stepper motor (in up direction). The elevation table weight is multiple kilograms and thus will not move during testing; when rotating, the stepper motor is kept in a fixed position to the bench and the TIDA-01228 with double-sided glue tape.

The setup was carefully created as it has to guarantee a reproducible distance between the disc and the LC sensors, which can be precisely measured. This is achieved by the combination of an elevation table, which height above the workbench can be continuously adjusted with a turning knob. A precision "Mitutoyo" device is set to 0 mm when the disc touches the inductors and then will indicate the height or the distance to the inductors when the table is elevated to the desired testing distance using the turning knob in front. Maximizing this distance is in general one of the most important design goals. The resolution of the "Mitutoyo" device is 1 µm, which is more than sufficient as this distance in mechanical meters will often have a tolerance of 0.1 mm or more.

4.2 *Distance Between Inductors and Rotating Disc*

Often the required sensing range is somewhere between a 3- and 5-mm distance, which is mostly driven by the mechanical design of the flow meter. As the rotating disc is behind a glass or plastic cover, the LC sensor inductors will be always a few millimeters away and larger distance is the most difficult design challenge to overcome. The TIDA-01228 design achieves distances of:

1. 4.2 mm with CSD23280F3 (0.36-mm pitch FemtoFET) with a 810-kHz oscillation

2. 3.7 mm with CSD23285F5 (0.5-mm pitch FemtoFET) with a 500-kHz oscillation

To improve the distance also tests with Inductors GT1113-0 (200 µH with stranded wire) from Gemphil technologies and a few other capacitor values for the LC sensor have been run. The distance was measured multiple times with minimum and maximum disc turning rate with the target goal of less than 1% error (to meet Class 1 requirements).

Note that the 3.7-mm distance with a 500-kHz oscillation can be improved further, so far no optimization effort to increase the oscillation frequency has been done. In summary, only few discrete C-values and two types of Gemphil inductors were tested. Further fine-tuning of the solution for finding the optimum oscillation frequency and distance is strongly recommended.

The recommended optimization steps when integrating the TIDA-01228 into a custom design include:

*   Find L and C values for maximum detection range.

*   Adjust the duration of the trigger pulse (this can vary also with voltage supply).

*   Customize the duration of the TDC timeout before evaluating the LC sensor condition "0" or "1" (this can also vary with voltage supply).

*   Verify the detection distance over the full voltage supply range, based upon the available battery chemistry (thus the full voltage range between "new" and almost "drained" batteries).

4.3 *Rotation Measurement Accuracy and LC Sensor Position*

Using the DRV8846EVM and a "standard" stepper motor with 200 steps per full rotation, it was possible to test turning speeds of maximum 2.5 turns (or 500 steps) per second and minimum of 1/32 turns per second. The minimum turning rate is limited by the DRV8846 GUI control settings, while the maximum rate is limited by the SC Studio tool, which in Debug mode has an approximately 90-ms SCE task repetition period, providing an effective sampling rate of 11 Hz. As the GUI supports only 16-bit values, the maximum steps possible are 65k; for the tests 64000 steps were used resulting in 320 full turns at a maximum speed.

The turning rate was 500 steps/second or 2.5 full turns per second (which translates to 10-Hz rotation rate). Thus the 11-Hz sampling rate of the SCS tool was able to detect the 320 turns with an error of < 1%, with the test rotation itself done first in forward and then in backward direction. The measured turns for both directions were in the range of 317 to 320, which corresponds to 3/320 = 0.9375% error.

> **NOTE:** The XY-placement of the LC sensors against the rotating disc influences heavily the maximum detection distance. The test setup used is not optimized for such XY-alignment, so some fine-tuning was needed to find the best position of the disc underneath the LC sensors. In a real application, this problem can be significantly easier to solve, due to the mechanical constraints of the flow meter and its disc, such that an electronic add-on module can be designed to fit exactly above the disc.

It is also recommended to ensure that the distance between the two Inductors and their mechanical position is stable (through a fixture or similar approach). In the TIDA-01228 design, this was ensured through the soldering of the GT1128-0 inductors to the PCB. If stranded wire inductors are used, then these inductors must be somehow mechanically fixed either through plastic enclosure or some other means, which keeps them firmly fixed above the rotating disc.

4.4 *Power Consumption Measurements*

EnergyTrace™ in MSP-FET430 is used to measure Sub-1 µA power consumption. The exact wiring setup is shown in Figure 9.
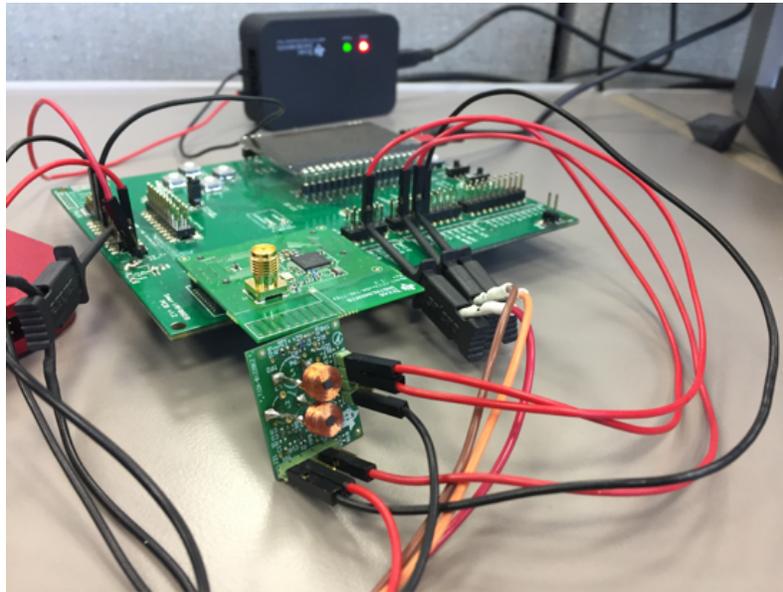
Figure 9. SRF06EB Wiring for EnergyTrace Measurements With FET430 Pro

A Saleae Logic Pro 16 (red metal box on the left) in Figure 9 is wired to the CC1350 GPIO lines for capturing the LC sensor trigger pulses, oscillations, and the sampling rate of the LC sensors. The FET430 (the black box with red and green LEDs on in the back) is powering the system through a GND (black wire) and the VDD-to-EM (red wire) of the SRF06EB. The EnergyTrace capability and precision have been verified in advance to recording the power consumption figures in Figure 10 against a simple power-down CCS code project that sets the CC1350 PG2.0 device into low-power mode under TI-RTOS. The measured 700 nA at the 3.6-V supply are consistent with the datasheet number for the CC1350 PG2.1 device used during testing.

DISCLAIMER: EnergyTrace is *not* a calibrated test and measurement equipment for measuring dynamic currents, thus the real values will be slightly different. However, by confirming the low-power sleep mode number of 700 nA, the reported consumption numbers are realistic, as the error from 25 µA up to 75 mA is ±2%(see Section 5.6.1 in [13]).
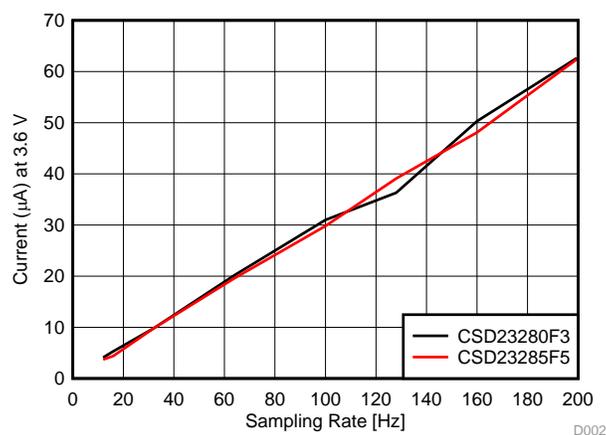
Figure 10. Power Consumption Comparison for Two FemtoFET Devices

Figure 10 shows the average current at the 3.6-V power supply for the TIDA-01228 with both FemtoFET variants. Five tests with at least a 10 second duration (this is the "active" or LC sensing mode in between RF transmissions) have been captured with the EnergyTrace tool and the mean value plotted.

Further tests with supply voltage from 2.1 up to 3.6 V have been conducted and successfully verified that the TIDA-01228's number of full oscillations will not be reduced just due to voltage changes (for example, discharging the battery). Due to the integrated DC/DC in the CC1350, the reported power consumption value (P = I × U) by EnergyTrace is almost constant in the 2.1- to 3.6-V range. The adjustment of the voltage supply is shown in Figure 11 for CCS v7.1 with EnergyTrace:
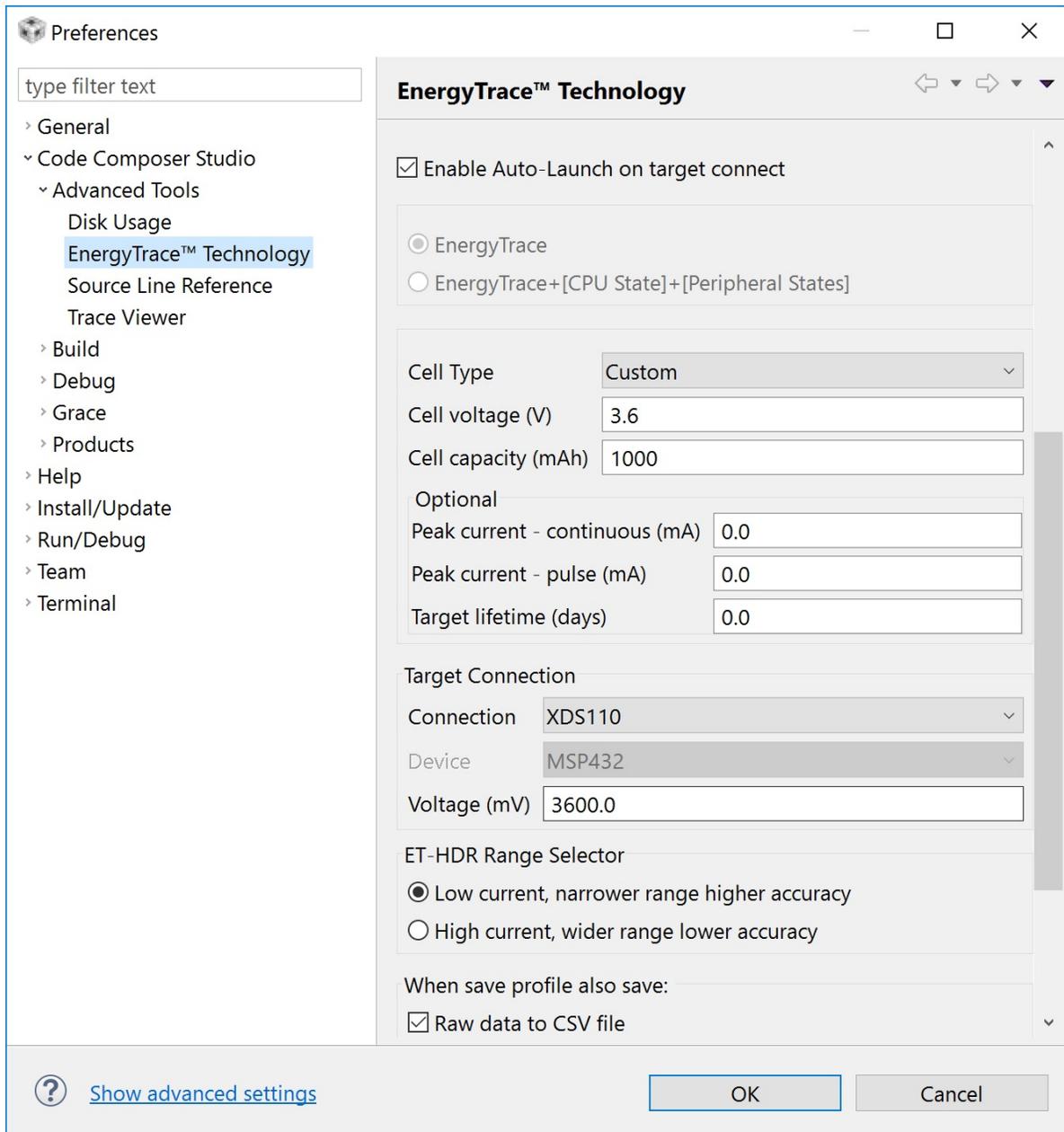
Figure 11. 3.6-V Voltage Supply to SRF06EB + CC1350EM + TIDA-01228 in "Target Connection"

The "3600 mV" voltage shown in Figure 11 was modified; tests were done for 2.1, 2.5, 3.0, 3.3 and 3.6 V as these are values delivered by either LiSoCl2 or LiMnO2 primary cells, with 3.6- or 3.0-V nominal voltage. The sampling rates tested were 12, 128, 160, and 200 Hz to confirm that both the minimal and the maximal sampling rates are supported properly.

4.5 RF Functionality

To enable AMR functionality, periodic RF transmissions are the minimum implementation. Multiple protocols exist, with wM-Bus at 868 MHz being a popular option in many EU countries for metering applications. However, multiple proprietary protocols with or without long-range modes (or also newer solutions such as Sigfox or 6LowPAN mesh networks) can be used to collect the metering data. The CC1350 can address the majority of these protocols due to its flexible radio front-end and sufficient FLASH and RAM resources for accommodating the various protocol stacks.

The TIDA-01228 CCS code example reuses the wM-Bus transmit code from the TIDA-00848 design and allows the periodic transmission of one data packet with a user programmable period. The data packet was received by the CC1350 LaunchPad under SmartRFStudio with the C-mode XML configuration file also included in the TIDA-01228 firmware image (see Section 6).

4.6 Summary

The rapidly increasing demand by utilities all over the world to add AMR to their mechanical flow meters are driving the need for electronic add-on modules with RF capabilities, which can report flow meter readings wirelessly over multiple protocols in various ISM bands. Such RF-enabled add-on modules should offer ultra-low power consumption and very low system cost without compromising on performance. The CC1350 SimpleLink Wireless MCU presents a unique opportunity to address both of these customer concerns with the TIDA-01228, demonstrating an accurate flow measurement (or rotation detection) with less than 4 µA at a 12-Hz sampling rate and a 3.6-V supply.

The TIDA-01228 design presents a highly integrated, inexpensive system solution for mechanical flow meter projects in any market in the world with a low-cost inductive sensing approach with the CC13x0's SCE and one of two TI FemtoFET devices.

The CC1350 supports dual-band wireless communications with the capability to switch sequentially between the 2.4-GHz and Sub-1 GHz ISM bands. This flexibility allows the handling of protocols such as wM-Bus or Sigfox and the Bluetooth low energy at 2.4 GHz. The implemented example for the wM-Bus C-mode at 868-MHz protocol offers support for a popular AMR implementation while an additional to-be-added Bluetooth low energy smartphone connection can enable better user experience through a smart phone or tablet application.

5   Design Files

5.1   Schematics

To download the schematics, see the design files at TIDA-01228.

5.2   Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01228.

5.3   PCB Layout Recommendations

There are no strict layout requirements to be considered; the E2 PCB revision is a two-layer PCB with standard 0.5-mm wiring resolution. The two-layer E1 revision using the CSD23280F3 drove higher costs for PCB manufacturing and populating due to the 0.36-mm pitch of the FemtoFET device. The layout was optimized for compact size, and the two inductor footprints in parallel in each LC sensor were added for testing of different part numbers and different inductors packaging options such as through-hole pins versus flexi-wire connections. It is up to the customer to select an inductor supplier (this TI Design uses Gemphil Technologies GT1128-0) and adapt the PCB to fit his or her own form factor.

5.3.1   Layout Prints

To download the layer plots, see the design files at TIDA-01228.

5.4   Altium Project

To download the Altium project files, see the design files at TIDA-01228.

5.5   Gerber Files

To download the Gerber files, see the design files at TIDA-01228.

5.6   Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01228.

6   Software Files

To download the software files, see the design files at TIDA-01228.

7   Related Documentation

1. Texas Instruments, *LC Sensor Rotation Detection With MSP430 Extended Scan Interface (ESI)*, Application Report (SLAA639)
2. Texas Instruments, *Rotation Detection With the MSP430 Scan Interface*, Application Report (SLAA222)
3. Texas Instruments, *Method to Select the Value of LC Sensor for MSP430 Extended Scan Interface (ESI)*, Application Report (SLAA642)
4. Texas Instruments, *CC1350 LaunchPad Getting Started Guide* (SWRU478)
5. Texas Instruments, *SmartRF06 Evaluation Board (EVM) User's Guide* (SWRU321)
6. Texas Instruments, *SimpleLink™ CC1310 Evaluation Module Kit Quick Start Guide* (SWRU429)
7. Beuth, EN ISO 4064-1 thru -5 Water meter specifications (2014-11 versions)
8. Wikipedia, *Eddy current* (https://en.wikipedia.org/wiki/Eddy_current)
9. Wikipedia, *RLC circuit* (https://en.wikipedia.org/wiki/RLC_circuit)
10. Texas Instruments, *SmartRF™ Flash Programmer User Manual* (SWRU069)
11. Gemphil Technologies, Inc., Inductor GT1128-0
12. Texas Instruments, *Single-chip Smart Water Meter with Dual-band RF and InfraRed port*, TI Training

13. Texas Instruments, *MSP430 Hardware Tools User's Guide*, MSP-FET430UIF User's Guide (SLAU278)

7.1 Trademarks

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8   Terminology

Water meter— Mechanical water meters with impeller and a rotating disc in their dial, which can be sensed to measure its rotation speed and direction (thus the water flow)

Inductive or LC sensing— Using an LC tank oscillation to detect a nearby metal plate (mounted on the rotating disc) through dampened oscillations due to induced eddy currents

Rotating disc— Small circular disc, with a half-round metal plate, often used as 1 liter dialindicator, found in many mechanical flow meters in the world

Class 1 or Class 2— Precision categories for water meters defined in DIN EN ISO 4064-1:2014-11

EnergyTrace— Feature to measure power consumption integrated into the MSP-FET tool, from several hundred nA up to 100 mA

9   About the Author

MILEN STEFANOV (M.Sc.E.E) is a system engineer at TI, working in the Grid Infrastructure field and an expert in RF communication technologies and metering applications. After graduating, he spent 5 years as a research assistant at the University of Chemnitz (TUC) and 3.5 years in the semiconductor industry in high-speed optical and wired communications as a system engineer. He joined TI in 2003 to become a Wi-Fi® expert and support TI's Wi-Fi products at major OEMs. Since 2010, he has focused on metering and Sub-1 GHz RF solutions for the European Grid Infrastructure market. Mr. Stefanov has published multiple articles on wM-Bus technology in Europe and presented technical papers at the Wireless Congress and Smart Home & Metering summits in Munich.

Revision History

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

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