TI Designs
Smart Plug with Remote Disconnect and Wi-Fi Connectivity

TEXAS INSTRUMENTS

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Design Resources

TIDC-SMARTPLUG-WIFI	Tool Folder Containing Design Files
MSP430i2040	Product Folder
CC3200	Product Folder
UCC28910	Product Folder

TI E2E™ Community

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Design Features

- SimpleLink™ Wi-Fi connectivity over IEEE-802.11 b/g/n networks from any smart phone, tablet, or computer through a standard web broswer.
- Single-phase energy measurement that calculates RMS current, RMS voltage, active and reactive power and energies, power factor, and frequency
- Solid-state relay provides remote connect and disconnect capability
- Compact physical design with minimal BOM components
- Low-power components and efficient power supply provide low system-power consumption
- System design is tested and includes firmware for energy measurement, Wi-Fi connectivity, and relay control along with an Android-based demo application and user's guide.

Featured Applications

- Smart Plugs or Power Strips
- Metering
- Home Appliances / White Goods
- Home Monitoring
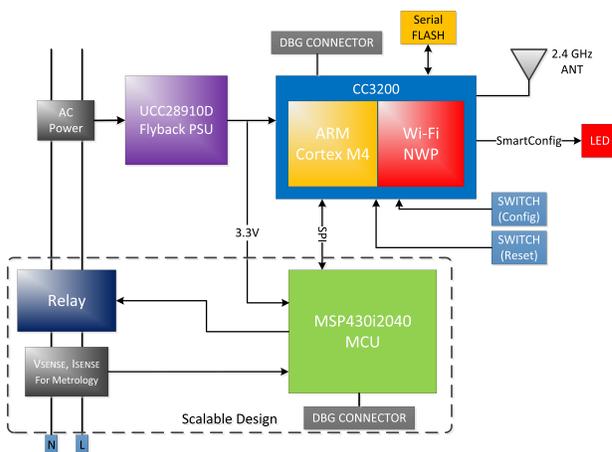
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1 System Description

1.1 Introduction

Increasingly, applications require WiFi-enabled energy measurement and control, particularly in end-products such as Smart Plugs and Smart Receptacles, and in general application spaces such as home appliances, Smart Grid, and building automation. This guide offers a form-factor reference design and application software for the Smart Plug, while also addressing application requirements in connected energy measurement and any Cloud-connected device.

2 Design Features

The Wi-Fi Enabled Smart Plug showcases TI's ability to provide full system solutions that cannot be offered from a single competitor. Leveraging portfolio competitiveness and breadth enables innovative system features and cost savings.

The Smart Plug utilizes an MSP430i2040 to monitor the energy consumption for a single load and control the high-voltage side of the design. This data is then passed to a CC3200 to communicate the data over Wi-Fi to both another device in the LAN and to a Cloud server. The system is powered from a highly compact and efficient primary side regulated flyback PSU using the UCC28910D. A solid state relay enables the application to control the load, based on its energy consumption.

The final design of the Smart Plug also includes male and female connections to a NEMA 15 type North American power outlet. This makes it easy to connect in series with a device to measure the live power consumption. In addition to the PCB mounted high voltage connections, a simple enclosure has been designed and provided to insulate the user from potential exposure to high voltages. The electronics are pre-designed for international voltages; only the mechanics need to be changed.

3 Block Diagram

Figure 1 shows a high-level overview of the connections between the the various devices in the Smart Plug reference design. The only physical connections from the system are the AC voltage input and the output for an AC load. On this high-voltage line, the flyback power supply, load control relay, and metrology sensors are connected.
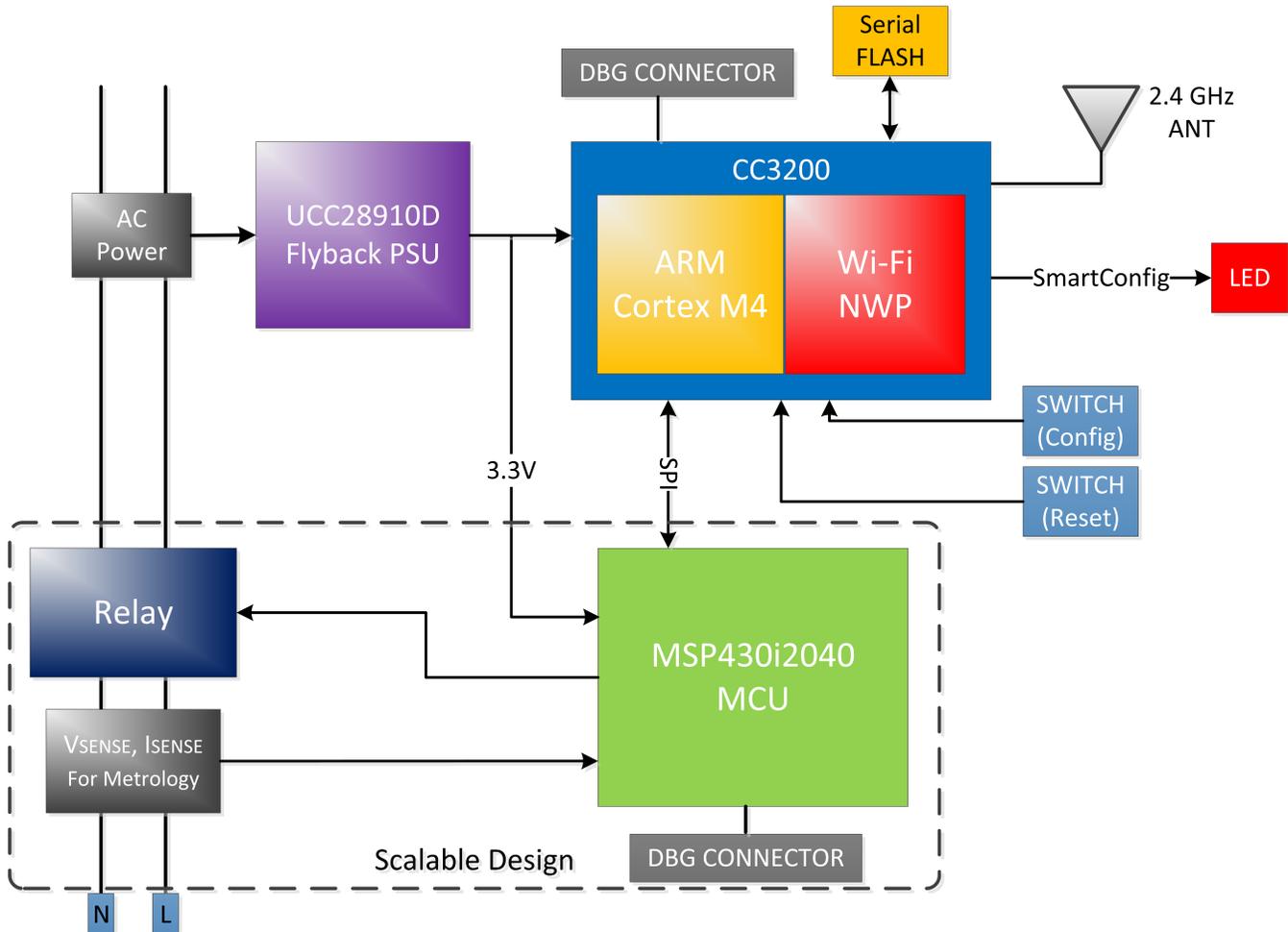
Figure 1. Smart Plug Block Diagram

4 Circuit Design and Component Selection

4.1 Embedded Metrology – Analog Inputs

The analog front-end of the MSP430i204x, which consists of the ΣΔ ADC, is differential and requires that the input voltages at the pins do not exceed ±928 mV (gain = 1). To meet this specification, the current and voltage inputs must be scaled down. Additionally, the ΣΔ24 allows a maximum negative voltage of -1 V. Therefore, the AC current signal from mains can be directly interfaced without the need for level shifters. This section describes the analog front end used for the voltage and current channels.

4.1.1 Voltage Inputs

The voltage from the mains is usually 230 V or 120 V, and must be scaled down to within 928 mV. The analog front end for voltage consists of spike protection varistors followed by a voltage divider network, and an RC low-pass filter that acts as an anti-alias filter.
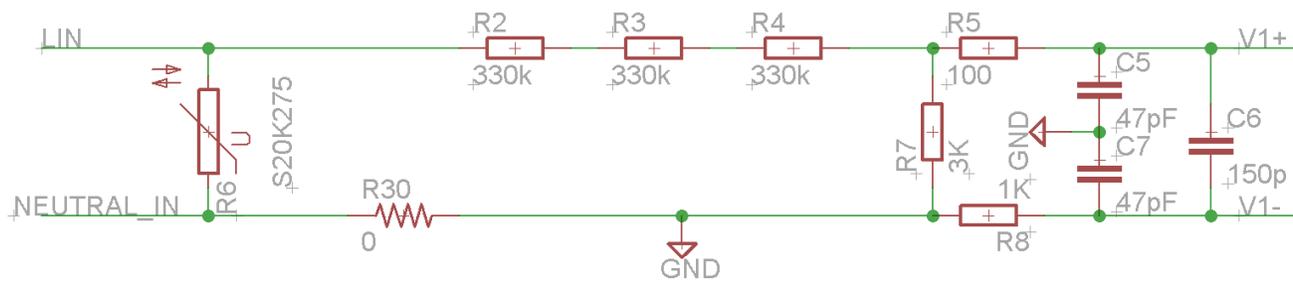
Figure 2. Analog Front End for Voltage Inputs

Figure 2 shows the analog front end for the voltage inputs for a mains voltage of 230 V. In this circuitry, the voltage is brought down to approximately 626mV RMS, which is 885mV peak, and fed to the positive input of the convertor. Note that the anti-alias resistors on the positive and negative sides are different because the input impedance to the positive terminal is much higher; therefore, a lower value resistor is used for the anti-alias filter. If this is not maintained, a relatively large phase shift could result between voltage and current samples.

4.1.2 Current Input

The analog front-end for current inputs is slightly different from the analog front-end for the voltage inputs. Figure 3 shows the analog front-end used for a current channel.
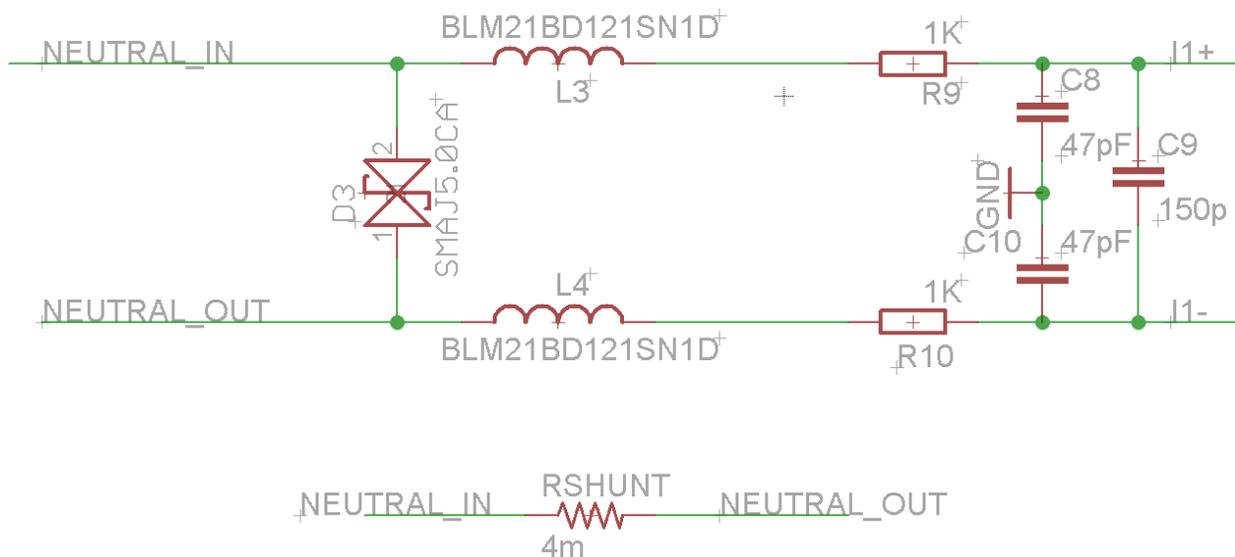
Figure 3. Analog Front End for Current Inputs

In the figure, resistor RSHUNT is the shunt sense resistor that is selected based on the current range used. The value of the resistor for this design is 4 mΩ. The antialiasing circuitry, consisting of resistors and capacitors, follows the shunt resistor. Based on the 15 A maximum current of this EVM and the 4 mΩ shunt, a voltage of ±85 mV will be detected by the msp430i2040 ADC. To increase the dynamic sense range, the built-in PGA must be set to 8x, enabling ±680 mV to be measured by the converter.

For the EVM430-i2040, footprints for suppressant inductors are also available. These inductor footprints are shown below as L8 and L9 and by default are populated with 0 ohm resistors.

4.2   Embedded Wi-Fi

The Smart Plug uses two primary design considerations for the CC3200 Wi-Fi SoC, the antenna design and the power management sections. Each of these are documented thoroughly via the CC3200 Datasheet, and the *SimpleLink Wi-Fi LaunchPad Hardware User's Guide* (SWRU372). The following sections outline specific considerations taken for the Smart Plug hardware concerning these two elements. For additional design considerations and requirements, reference the Hardware User's Guide.

4.2.1   Antenna Landing

As with many RF designs, the placement and control of the antenna and matching circuit is critical to ensure peak performance. By utilizing the work already done on the Simple Link Wi-Fi Launchpad, this process is highly simplified. The only modification necessary is the removal of the UFL connector to save space.

In addition to the Launch Pad design files, the particular antenna manufacturer provides specific antenna land patterns for the selected device, as shown in Figure 4. The element that is not preset is the 50 ohm input to the antenna landing area.
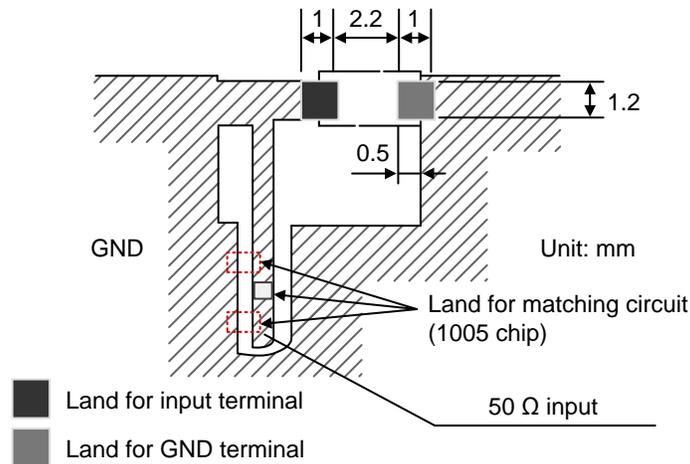
Figure 4. Antenna Manufacturer Landing

The final implementation on the Smart Plug design uses a 10 pF capacitor (C33) and the TDK filter to work as a band pass filter for the Wi-Fi transmission and reception, and a 6.2 pF cap and 5.6 nH inductor to serve as a 50 ohm matching network, as shown in Figure 5. This matching network is designed based on real word measurements, a process further described in the CC3200 User's Guide.
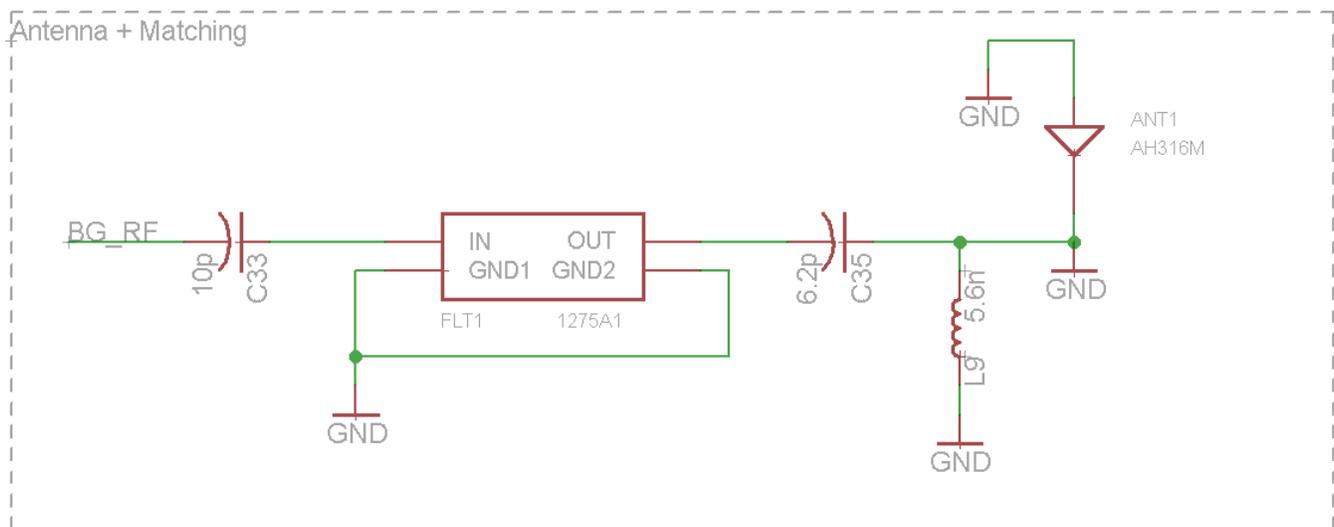
Figure 5. Antenna and Matching Schematic

4.2.2 Power Management

The CC3200 SoC provides a wide range of potential power options to the designer, including wide input voltage ranges and battery power support. For the Smart Plug, however, the design has only a single 3.3 V power rail, so the power management system needs to be tweaked from the standard design.

As a starting point, the Smart Plug uses the reference schematic from the CC3200 Data Sheet, presented here in Figure 6.
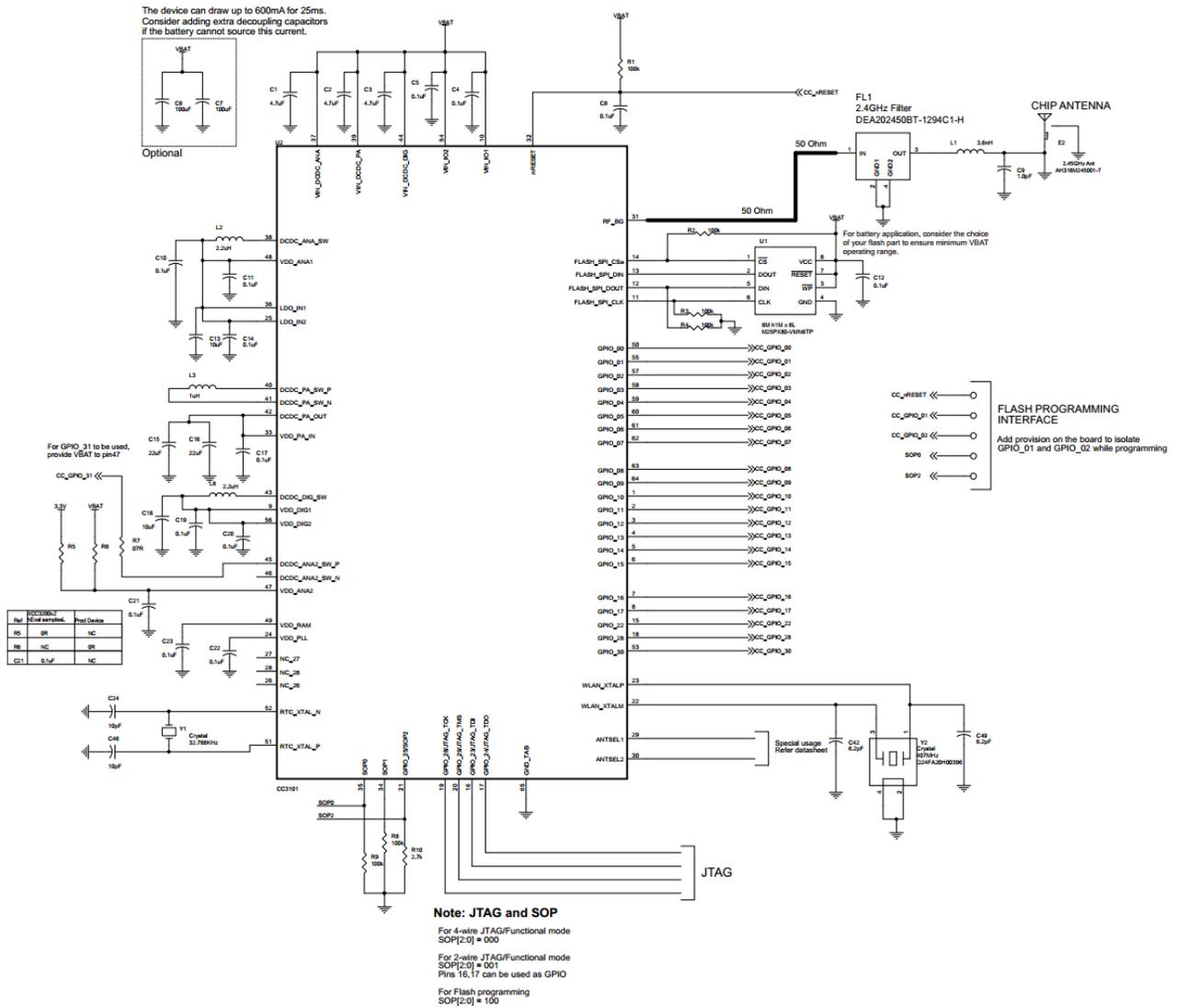
Figure 6. Schematics for CC3200 Wide-Voltage Mode Application

The CC3200 has several built-in buck converters to power the device subsystems. These include the core, the antenna power amp, and the digital and analog subsystems. As shown in the reference schematic, most of these can be powered from the wide input range source VBAT. VBAT can be anywhere within the range of 2.1 V to 3.6 V, which fits well with the 3.3 V flyback power supply onboard the Smart Plug. For the final version of the power management design, refer to Section 8.1.

5 Software Description

5.1 Energy Library

The software is described n the following subsections. The first subsection describes the setup of various peripherals of the MSP430. The metrology software is divided into two major processes: the foreground process and background process.

5.1.1 Start Up Code for Device Security and Peripheral Calibration

In each i20xx device, device-specific calibration values are stored in INFO memory. These values affect items such as clock accuracy, SD24 operation, and reference voltage operation. For proper functionality of this device, these values must be loaded to the proper calibration and trim registers, as mentioned in the TLV and Start-Up Code chapter of the *MSP430i2xx User's Guide* (SLAU335). In addition, a decision whether to secure or unsecure the i204x must be made in the first 64 MCLK cycles after RESET. Both of these functions are accomplished in the low_level_init function (in low_level_init.c), which runs before the main function is called.

CAUTION

Because the device-specific peripheral calibration is stored in INFO memory, do not change the project settings to erase INFO memory as it would erase these values. Also note that meter calibration data is stored in the same segment as the peripheral calibration information.

5.1.2 ΣΔ24 Setup

The i204x has four sigma delta data converters to measure the voltage and currents in the system. For the i20xx, the clock to the ΣΔ24 ADCs (fM) is fixed at 1.024000 MHz. In the software, an OSR of 256 is used, which results in a sampling frequency of 4.000 ksps for the converters. At every sampling instance, the ΣΔ24s are configured to generate regular interrupts. For the single phase shunt mesurment, the following channel association is used:

- A0.0+ and A0.0- → Voltage V
- A1.0+ and A1.0- → Current I
- A2.0+ and A2.0- → Not used
- A3.0+ and A3.0- → Not used

5.1.3 Foreground Process

The foreground process includes the initial setup of the MSP430 hardware and software immediately after a device RESET. Figure 7 shows the flowchart for this process.
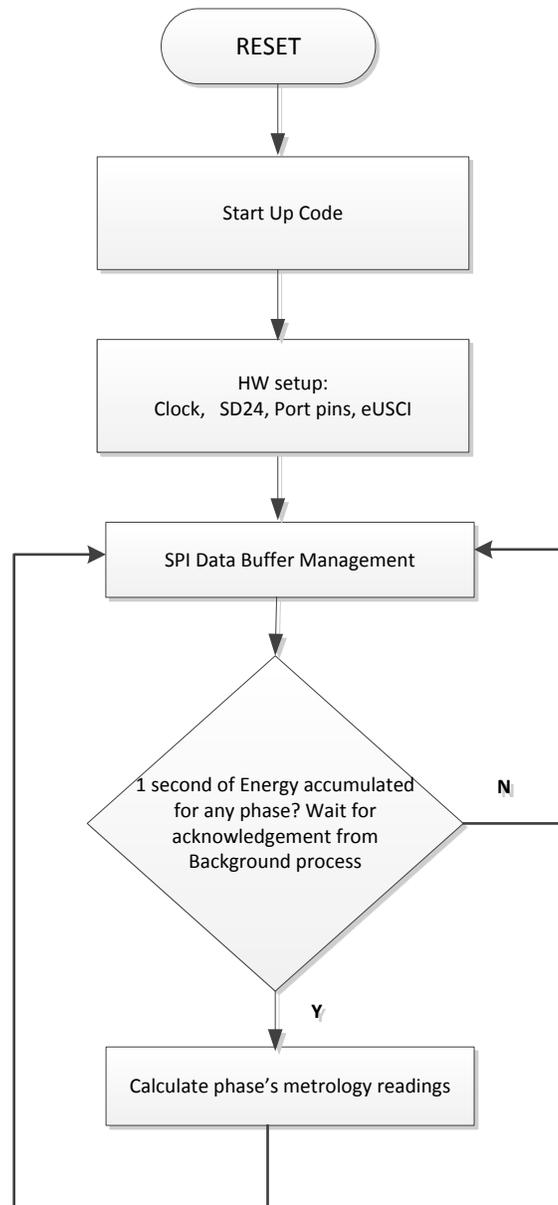
Figure 7. Foreground Process

The initialization routines involve the setup of the analog to digital converter, clock system, general purpose input/output (port) pins, and the USCI_A0 for UART functionality. After the hardware is setup, any received frames from the GUI are processed. Subsequently, the foreground process checks whether the background process has notified it to calculate new metering parameters. This notification is done through the assertion of the PHASE_STATUS_NEW_LOG status flag whenever a frame of data is available for processing. The data frame consists of the processed dot products accumulated for one second in the background process. This is equivalent to accumulation of 50 or 60 cycles of data synchronized to the incoming voltage signal. In addition, a sample counter keeps track of how many samples are accumulated over this frame period. This count can vary as the software synchronizes with the incoming mains frequency.

The processed dot products include the VRMS, IRMS, active power, and reactive power. These dot products are used by the foreground process to calculate the corresponding metrology readings in real-world units. Processed voltage dot products are accumulated in 48-bit registers. In contrast, processed current dot products, active energy dot products, and reactive energy dot products are accumulated in separate 64-bit registers to further process and obtain the RMS and mean values. Using the foreground's calculated values of active and reactive power, the apparent power is calculated. The frequency (in Hertz) and power factor are also calculated using parameters calculated by the background process using the formulas in Section 5.1.3.1.

5.1.3.1 Computation Formulas

This section briefly describes the formulas used for the voltage, current, energy, and temperature calculations.

5.1.3.1.1 RMS Voltage and Current

As described in previous sections, voltage and current samples are obtained from the ΣΔ converters at a sampling rate of 4000 Hz. All of the samples that are taken in 1 second are kept and used to obtain the RMS values for voltage and current for each phase. The RMS values are obtained by the following formulas:

$$V_{RMS,ph} = K_{v,ph} * \sqrt{\frac{\sum_{n-1}^{Sample\ count} v_{ph}(n) * v_{ph}(n)}{Sample\ count}} - v_{offset,ph}$$

$$I_{RMS,ph} = K_{i,ph} * \sqrt{\frac{\sum_{n-1}^{Sample\ count} i_{ph}(n) * i_{ph}(n)}{Sample\ count}} - i_{offset,ph}$$

(1)

Where,

ph = The voltage-current association with parameters being calculated. For the neutral-monitoring and two-phase configuration, that is, Phase A(=1), and Phase B (=2). For the common-voltage configuration, that is Current Channel A (=1), Current Channel B (=2), and Current Channel C (=3).

$v_{ph}(n)$ = Voltage sample at a sample instant n

$v_{offset,\ ph}$= Offset used to subtract effects of the Additive White Gaussian Noise from the voltage converter

$i_{ph}(n)$ = Each current sample at a sample instant n

$i_{offset,\ ph}$= Offset used to subtract effects of the Additive White Gaussian Noise from the current converter

Sample count = Number of samples in one second

$K_{v,ph}$ = Scaling factor for voltage

$K_{i,ph}$ = Scaling factor for each current

5.1.3.1.2   *Power and Energy*

Power and energy are calculated for one frame's worth of active and reactive energy samples. These samples are phase-corrected and passed on to the foreground process, which uses the number of samples (sample count) to calculate channel/phase active and reactive powers by the formulas in Equation 2.

$$P_{ACT,ph} = K_{ACT,ph} \frac{\sum_{n-1}^{Sample\ count} v(n) \times i_{ph}(n)}{Sample\ count} \quad P_{REACT,ph} = K_{REACT,ph} \frac{\sum_{n-1}^{Sample\ count} v_{90}(n) \times i_{ph}(n)}{Sample\ count}$$

(2)

Where,

$v_{90,ph}(n)$ = Voltage sample at a sample instant n shifted by 90 degrees, and

$K_{ACT,ph}$ = Scaling factor for active power

$K_{REACT,ph}$ = Scaling factor for reactive power

For reactive power, the 90° phase shift approach is used for two reasons:

- It allows accurate measurement of the reactive power for very small currents.
- It conforms to the international specified measurement method.

The calculated mains frequency is used to calculate the 90 degrees-shifted voltage sample. Because the frequency of the mains varies, first measure the mains frequency accurately to phase shift the voltage samples accordingly.

To get an exact 90° phase shift, interpolation is used between two samples. For these two samples, use a voltage sample slightly more than 90° before the current sample, and a voltage sample slightly less than 90° before the current sample. The application's phase shift implementation consists of an integer part and a fractional part. The integer part is realized by providing an N samples delay. The fractional part is realized by a one-tap FIR filter. In the software, a lookup table provides the filter coefficients used to create the fractional delays.

After calculating the active and reactive power, the apparent power is calculated by the following formula:

$$P_{APP,ph} = \sqrt{P_{ACT,ph}^{2} + P_{REACT,ph}^{2}}$$

(3)

In addition to calculating the per-phase active, reactive, and apparent powers, the cumulative sum of these parameters are calculated for the two-phase configuration. These cumulative parameters are calculated by the below equations:

$$P_{ACT,\ Cumulative} = \sum_{ph-1}^{2} P_{ACT,ph} \quad P_{REACT,\ Cumulative} = \sum_{ph-1}^{2} P_{REACT,ph} \quad P_{APP,\ Cumulative} = \sum_{ph-1}^{2} P_{APP,ph}$$

(4)

For each of the three configurations, the calculated powers for each phase are then converted to energy by the following equations:

$$E_{ACT,\ ph} = P_{ACT,\ ph} \times Sample count$$
$$E_{REACT,\ ph} = P_{REACT,\ ph} \times Sample count$$
$$E_{APP\ ph} = P_{APP\ ph} \times Sample count$$

(5)

For the two-phase configuration, they are also accumulated to calculate the cumulative energies, as shown by the below equations:

$$E_{ACT, Cumulative} = \sum_{ph=1}^{2} E_{ACT,ph} \quad E_{REACT, Cumulative} = \sum_{ph=1}^{2} E_{REACT,ph} \quad E_{APP, Cumulative} = \sum_{ph=1}^{2} E_{APP,ph}$$

(6)

The calculated energies are then accumulated into buffers that store the total amount of energy consumed since meter reset. Note that these energies are different from the working variables used to accumulate energy for outputting energy pulses. There is one set of buffers for each voltage-current association, and if applicable, one set of buffers for the cumulative of the phases. Within each set of buffers, the following energies are accumulated:

- Active import energy (active energy when active energy >= 0)
- Active export energy (active energy when active energy < 0)
- React. Quad I energy (reactive energy when reactive energy >=0 and active power >=0; inductive load)
- React. Quad II energy (reactive energy when reactive energy >=0 and active power < 0; capacitive generator)
- React. Quad III energy (reactive energy when reactive energy < 0 and active power < 0; inductive generator)
- React. Quad IV energy (reactive energy when reactive energy < 0 and active power >=0; capacitive load)
- App. import energy (apparent energy when active energy>=0)
- 8. App. export energy (apparent energy when active energy < 0)

5.1.3.1.3 *Frequency (Hz)*

The background process calculates the frequency in terms of samples per mains cycle. The foreground process then converts this to Hertz by Equation 7.

$$\text{Frequency (Hz)} = \frac{\text{Sampling Rate (samples/ second)}}{\text{Frequency (samples/ cycle)}}$$

(7)

5.1.3.1.4 *Power Factor*

After the active power and apparent power are calculated, the absolute value of the power factor is calculated. In the meter's internal representation of power factor, a positive power factor corresponds to a capacitive load/generator and a negative power factor corresponds to an inductive load/generator. The sign of the internal representation of power factor is determined based on the sign of the active and reactive power. Therefore, the internal representation of power factor is calculated by the following formula:

$$\text{Internal Representation of Power Factor} = \begin{cases} \dfrac{|P_{Act}|}{P_{Apparent}}, \text{if capacitive load/generator} \\ -\dfrac{|P_{Act}|}{P_{Apparent}}, \text{if inducitive load/generator} \end{cases}$$

(8)

5.1.4 Background Process

The background function deals mainly with timing-critical events in software. The function uses the ΣΔ interrupt as a trigger to collect voltage and current samples. The ΣΔ interrupt is generated when a new voltage sample is ready. Once the voltage sample is obtained, sample processing is done on the previously-obtained voltage and current samples. This sample processing is done by the per_sample_dsp() function. After sample processing, the background process uses the per_sample_energy_pulse_processing() for the calculation and output of energy-proportional pulses. Figure 8 shows the flowchart for this process.
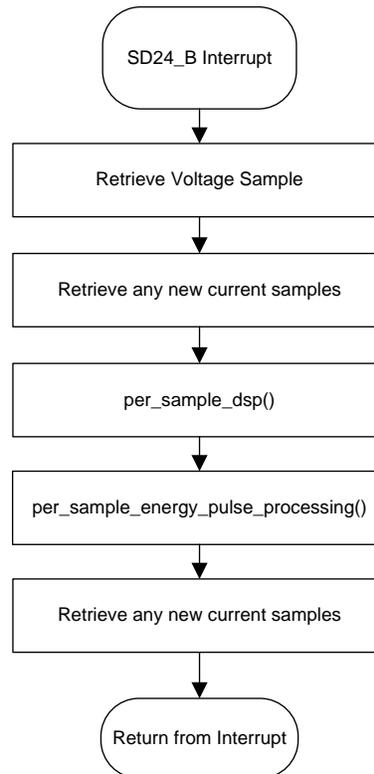
Figure 8. ADC Interrupt

5.1.4.1 *per_sample_dsp()*

The flowchart for the per_sample_dsp function is shown in Figure 9. The per_sample_dsp function calculates the intermediate dot product results fed into the foreground process for the calculation of metrology readings. Since 16-bit voltage samples are used, the voltage samples are further processed and accumulated in dedicated 48-bit registers. In contrast, since 24-bit current samples are used, the current samples are processed and accumulated in dedicated 64-bit registers. Per-phase active power and reactive power are also accumulated in 64-bit registers.

After sufficient samples (approximately one second's worth) have been accumulated, the foreground function is triggered to calculate the final values of VRMS, IRMS, active, reactive, and apparent powers; active, reactive, and apparent energy; frequency, temperature, and power factor. In the software, there are two sets of dot products: at any given time, one is used by the foreground for calculation and the other used as the working set by the background. After the background process has sufficient samples, it swaps the two dot products so that the foreground uses the newly acquired dot products that the background process just calculated, and the background process uses a new empty set to calculate the next set of dot products.

Whenever there is a leading-edge zero-crossing (– to + voltage transition) on a voltage channel, the per_sample_dsp function updates the frequency of the corresponding phase (in samples/cycle) and voltage sag/swell conditions. For the sag conditions, whenever the RMS voltage is below a certain user-defined threshold percentage, the number of mains cycles where this condition persists is logged as the sag duration. The number of periods in time with a sag condition is logged as the sag events count. Note that the sag duration corresponds to the total number of cycles in a sag condition since reset, and is therefore not cleared for every sag event. Also, when the RMS voltage is above a certain threshold percentage, swell events and duration are logged in a similar way.
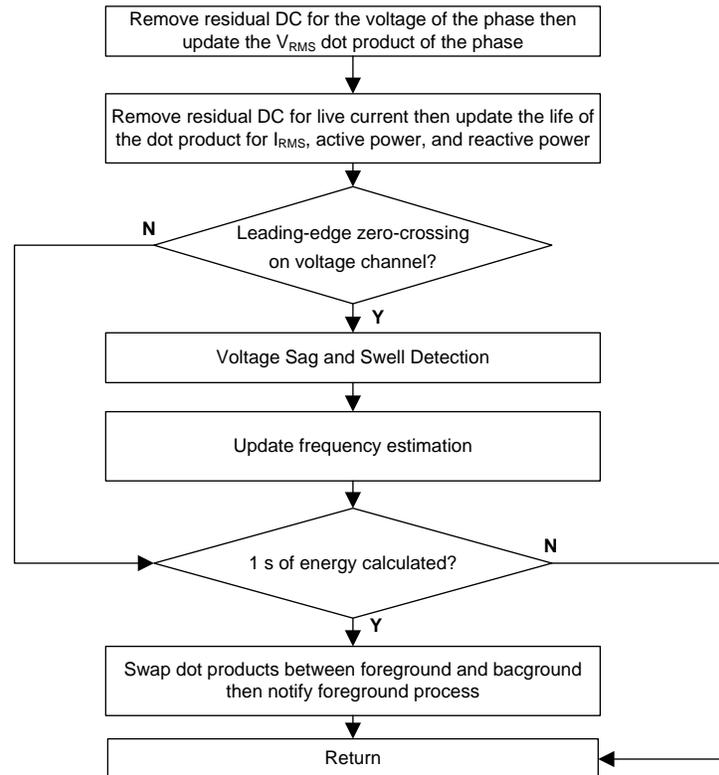
Figure 9. per_sample_dsp() for Single Phase Configuration

The following sections describe the various elements of electricity measurement in the per_sample_dsp function.

5.1.4.2   *Voltage and Current Signals*

The output of each $\Sigma\Delta$ converter is a signed integer, and any stray DC or offset value on these converters is removed using a DC tracking filter. Separate DC estimates for all voltages and currents are obtained using the filter and voltage and current samples, respectively. These estimates are then subtracted from each voltage and current sample.

The resulting instantaneous voltage and current samples are used to generate the following intermediate dot product results:

- Accumulated squared values of voltages and currents, used for VRMS and IRMS calculations, respectively.
- Accumulated energy samples to calculate active energies.
- Accumulated energy samples using current and 90° phase shifted voltage to calculate reactive energies.

These accumulated values are processed by the foreground process.

5.1.4.3   Frequency Measurement and Cycle Tracking

The instantaneous voltage of each phase is accumulated in 48-bit registers. In contrast, the instantaneous current, active power, and reactive power are accumulated in 64-bit registers. A cycle tracking counter and sample counter keep track of the number of samples accumulated. When approximately one second's worth of samples are accumulated, the background process switches the foreground and background, then notifies the foreground process to produce the average results such as RMS and power values. Cycle boundaries trigger the foreground averaging process, as it produces stable results.

For frequency measurements, a straight line interpolation is used between the zero crossing voltage samples. Figure 10 shows the samples near a zero cross and the process of linear interpolation.
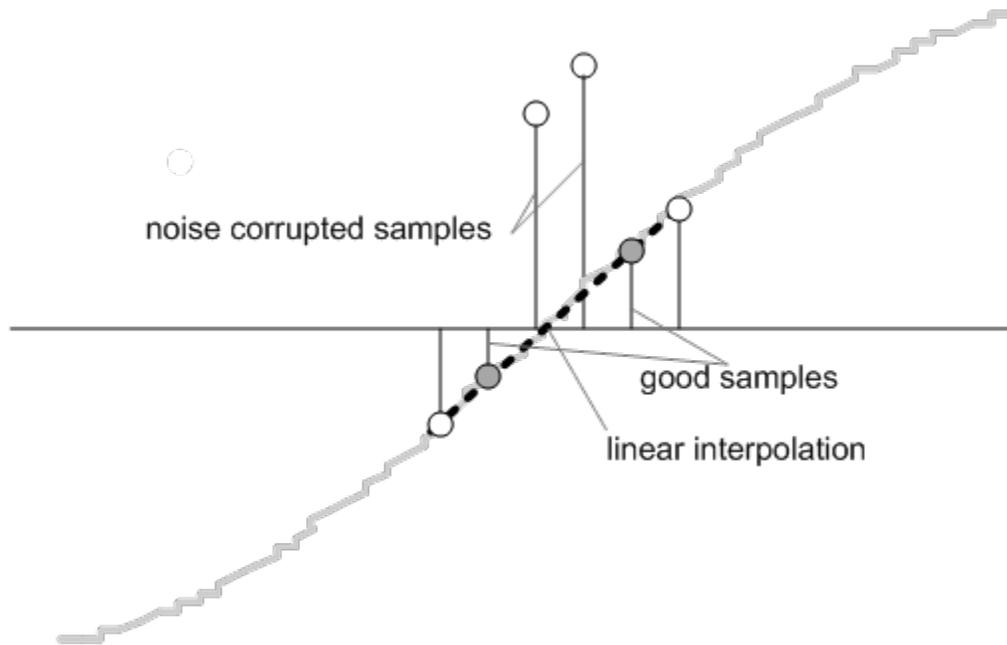
Figure 10. Frequency Measurement

Because noise spikes can also cause errors, the application uses a rate of change check to filter out the possible erroneous signals, and to ensure that the two points interpolated from are genuine zero crossing points. For example, with two negative samples, a noise spike can make one of them positive, and therefore make the negative and positive pair appear as if there is a zero crossing.

The resultant cycle-to-cycle timing goes through a weak low-pass filter to further smooth out cycle-to-cycle variations. This results in a stable and accurate frequency measurement that is tolerant of noise.

5.2   Embedded Wi-Fi

The M4 core available in the CC3200 allows a significant amount of flexibility that can be leveraged in any application. For the Smart Plug, the CC3200 queries metrology data from the MSP403i2040, forms it into packets, and broadcasts it to the companion Android application. It also monitors and controls auxiliary function, and provides bidirectional communication to increase the user experience with the reference design.

The software developed for the CC3200 is based on FreeRTOS, which is available with the getting started documentation via the *CC3200 SimpleLink Wi-Fi and IoT Solution Programer's Guide* (SWRU369A). FreeRTOS is based on tasks added to the scheduler by the application to run at specific priorities to facilitate the TCP communication. These tasks leverage the network stacks provided by the CC3200 development environment to simplify the communication. The following sections outline the critical tasks associated with the Smart Plug application code.

5.2.1 SmartPlugTask

The primary function of the SmartPlugTask is to begin and maintain the connection to the network, and facilitate the status broadcast to the host device. These are broken into a simplified flow chart in Figure 11.
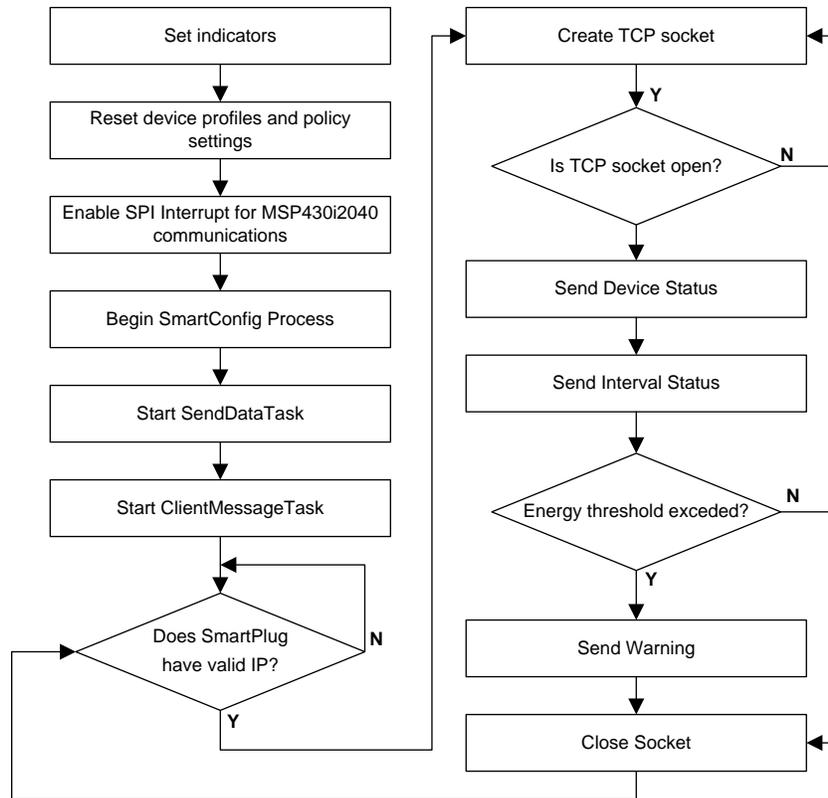
Figure 11. SmartPlugTask

On power up, the Smart Plug clears out all old profiles to prepare for a new connection to the Android device. At this point, all of the SPI interface settings are also prepared and an interrupt enabled to facilitate retrieval of information from the MSP430i2040.

The SmartConfig process starts here, as defined in the CC3200 programmer's guide. This process checks for an existing connection configuration in NVRAM, and connects to the existing configuration if it exists. This can be overridden if the CC3200 detects that the user button is pressed during startup, which forces the device into Smart Config mode. Operation of the Smart Config is then handled by the libraries provided.

There are two associated FreeRTOS tasks that are started at this point, the SendDataTask and the ClientMessageTask, which are described in the following sections.

Once the device is connected to a Wi-Fi network and has a valid IP address, the SmartPlugTask has several status messages that it will periodically send to the host device via a TCP channel. This TCP socket is opened and validated over port 1204 using the same process as defined in the programmer's guide. The socket is then used to send up to three status messages:

- Device Status, which is the current set value of the power relay on the Smart Plug.
- Interval Status, which contains power saving status information, and the running internal time.
- Warning Status, which is only sent when the Smart Plug has detected excessive energy consumption.

When the CC3200 has sent the statuses, it then closes the socket and waits for the task to be restarted, after which it can open the socket and transmit the status messages again.

5.2.2   SendDataTask

The SendDataTask is the primary mechanism in the CC3200 to transfer metrology data from the background ISR-driven SPI routine to the the host device via TCP. Despite its core functionality, the operation is fairly linear, and described in Figure 12.
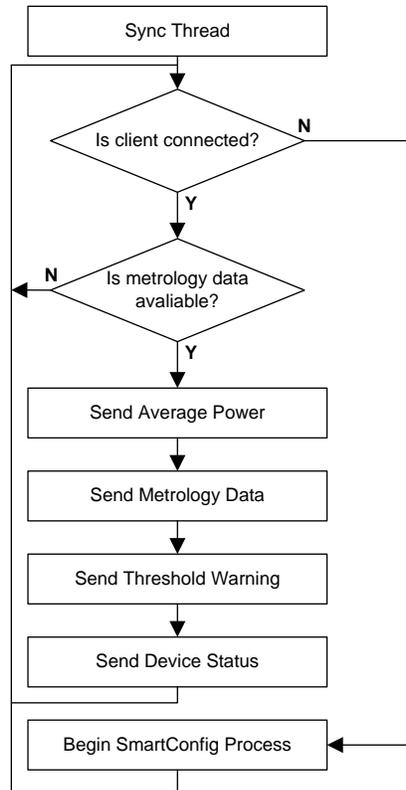
Figure 12. SendDataTask

The SendDataTask synchronizes itself with the FreeRTOS host, and then validates the connection to the host device on the network. If there is no valid connection, this task reinitializes the SmartConfig process from the NVRAM parameters, ensuring that the Smart Plug stays connected to the Wi-Fi network.

Once a connection is validated, the task checks for metrology data from the SPI communication protocol running in the background. Each piece of metrology data is then pulled from the SPI buffer and packetized to be transmitted via TCP to the host. These packet structures are defined in the following tables.

Table 1. Average Power Packet

Byte	1	2-5	6-9
Use	0x02	Average Power	Timestamp

Table 2. . Metrology Data Packet

Byte	1	2-5	6-9	10-13	14-17	18-21	22-25	26-29	30-33	34-37
Use	0x01	Power	Voltage	Current	Freq	VAR	Cos()	VA	KWh	Timestamp

Table 3. Over Power Warning Packet

Byte	1	2-5
Use	0x08	Timestamp

Table 4. Device Status Packet

Byte	1	2	3-6
Use	0x04	Device Turned Off/On (0/1)	Tiemstamp

5.2.3   ClientMessageTask

The ClientMessageTask processes any data that the host device sends to the Smart Plug. The received messages are placed into a buffer as they arrive, and are then processed when this task is called.

1. Turn On/Off attached load
2. Set power threshold for warning message
3. Set power savings mode
4. Reset/clear all stored metrology data

The packet structure for each of these simple commands is shown in the following tables. For each received command, and appropriate call is made into the configuration data of the CC3200 application.

Table 5. Turn On/Off Attached Load

Byte	1	2
Use	0x01	Turn Off/On Device

Table 6. Set Power Warning Threshold

Byte	1	2-5
Use	0x02	Power threshold value

Table 7. Set Power Savings Mode

Byte	1	2	3
Use	0x04	Disable/Enable Power saving mode (0/1)	Time interval for periodic update in seconds

Table 8. Reset/Clear Metrology Data

Byte	1
Use	0x08

5.2.4   SPI Communication Handler

Communication from the CC3200 to the MSP430i2040 is handled through an SPI link. This process is interrupt-driven, not task-driven like the packet handlers. The MSP430i2040 asserts an IO line to alert the CC3200 that a new set of data is available for retrieval. The CC3200 then acts as the master SPI device to pull the data. This interrupt is set up in the SmartPlugTask called for device initialization. Once set up, the interrupt then calls AefInterruptHandler(), which in turn calls into Read_AEF_Data(), where the SPI transmission is handled.

The communication between the CC3200 and the MSP430i2040 is a simple series of single byte commands, followed by four blank bytes to clock data out of the MSP430i2040 slave device. All of the commands used in the application are described in Table 9.

Table 9. SPI Commands

Command	Data Requested
0x60	Active Power
0x62	Apparent Power
0x64	Reactive Power
0x66	Vrms
0x67	Frequency
0x68	Irms
0x6A	Power Factor
0x6C	Active Energy

The received data is placed into a buffer to be retrieved by the SendDataTask, and placed into a packet to transmit to the host device over TCP.

6 Application Demo

1. Install both provided applications onto the Android device.
2. Connect the Android device to the access point.
3. Plug the Smart Plug onto a power strip.
   - The red LED blinks twice, indicating that the CC32000 initialized properly.
   - The green LED blinks, indicating that the Smart Plug is in SmartConfig mode.
4. Launch the Wi-Fi starter (SmartConfig) Android app.
   (a) Based on the AP settings, enter the password or leave the field empty. **Do not change the device name and token**.
   (b) Option to add the device name.
      - Smart plug broadcasts itself using this name.
      - By default, the device broadcasts its MAC address as the name.
5. Start SmartConfig.
6. If the connection is successful, the green LED will become steady, indicating that the board is configured, connected to the AP with an IP address, and now ready to monitor values.
7. Press the back button on the Android device to return to the Smart Plug app.
8. Open the Smart Plug Android application.
9. Connect to a Smart Plug device by clicking on Searching Devices in the menu.
   - Once the device is found, a screen as shown in Figure 13 appears.
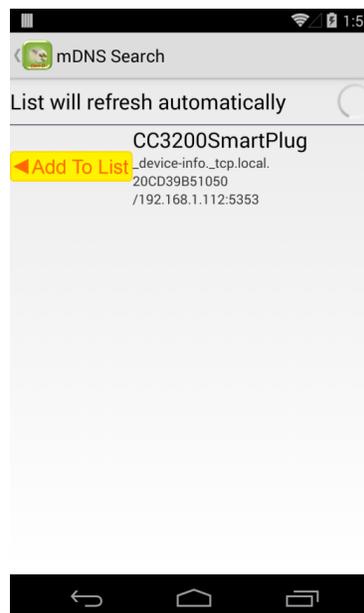
Figure 13. mDNS Search Results

   - Select Add To List to add the discovered Smart Plug to the main Smart Plug application. If multiple Smart Plugs are present, wait for a minute until all of them appear. Once finished, press Back to return to the list. The items just added will appear.
10. Click on an item in the list.
11. To start a connection, slide the Connection Status switch to ON.
12. Once connected, a message indicates whether the device is powered or not, followed by progress updates. An example is shown in Figure 14.
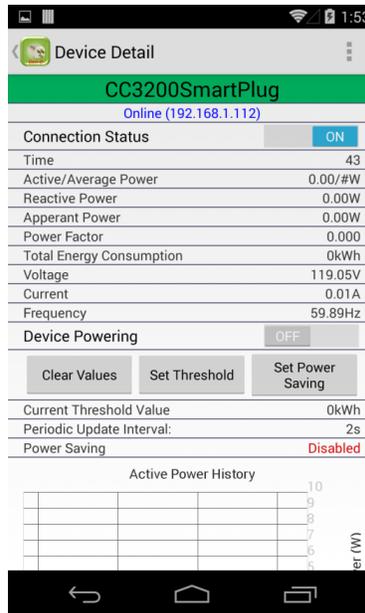
Figure 14. Android Metrology Results

13. While in connection, the following operations are allowed:

- Power on/off the device – Powers on or off any electronic devices plugged into the Smart Plug.
- Clear Values – Clears values stored on the Smart Plug.
- Set Threshold
- Enable/Disable power saving mode – The default update interval is 2 seconds. Change the update interval by enabling power saving mode.
- Add another device to monitor.

7   Test Results

As shown in the Application demo, the functionality of the Smart Plug has been tested successfully. A graph of the device's energy reading accuracy, Figure 15, shows errors below 0.5% across a wide dynamic range, making it suitable for many applications.
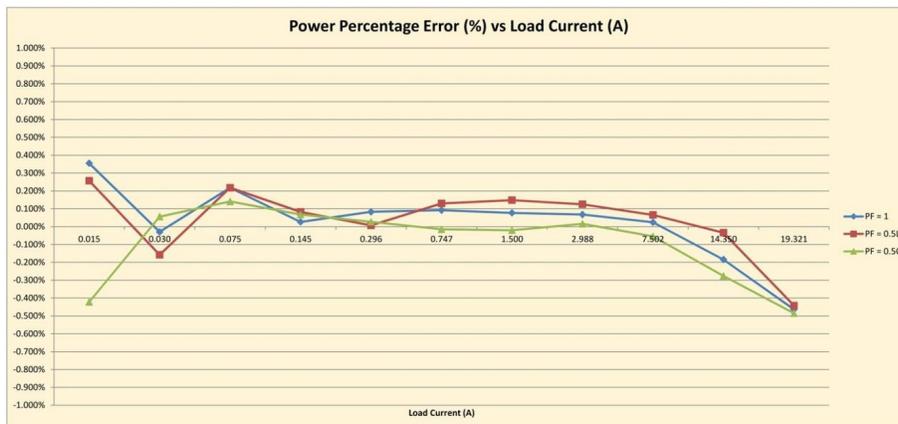
Figure 15. Energy Reading Accuracy

8 Design Files

8.1 Schematics

CC31xx

VCC VCC TP2 TP1

Antenna + Matching

GND ANT1 AHG16M

BG_RF

IN   OUT
GND1 GND2
FLT1   1275A1

GND

GND

CC31xx JTAG

5PinHeader
CC_TMS   1
CC_TCK   2
CC_TDO   3
CC_TDI   4
5
CC3101JTAG

GND

CC31xx UART

5PinHeader
CC_TX   1
CC_RX   2
CC_RTS   3
CC_CTS   4
5
CC3101UART

GND

VDD_RAM 49
CC_RTS   50
RTC_XTAL 51
52
53
54
VBAT_IO2 55
CC_RX   56
VDD_DIG 57
58
DEBUG1   59
DEBUG2   60
61
CC_CTS   62
63
RELAY_IO 64

VDD_RAM
GPIO0
RTC_XTAL_P
GPIO32
GPIO30
GPIO1
VDD_DIO2
GPIO2
GPIO3
GPIO4
GPIO5
GPIO6
GPIO7
GPIO8
GPIO9

NRESET
RF_BG
GPIO27
GPIO28
NC9
NC7
NC8
LDO_IN2
VDD_PLL
WLAN_XTAL_P
WLAN_XTAL_N
GPIO25
TMS
TCK
GPIO28
TD0

32 CC_RESET
31 BG_RF
30
29 BTN1
28
27
26
25 LDO_IN
24 VDD_PLL
23 WLAN_XTAL_P
22 WLAN_XTAL_N
21
20 CC_TMS
19 CC_TCK
18
17 CC_TDO

U2
CC31XX

GND

CC31xx Oscillator/Crystal

40MHz X1
WLAN_XTALN WLAN_XTALP
C15   C14
6p   6p
GND   GND

VCC
NC OUT RTC_XTAL
NC   GND
OCS1   ECS-327SMD
C36
0.1u
GND

Push Button

VCC
S1 DTSM-3
GND 100k R18
BTN1

SPI Flash

VCC   VCCVCC

W25Q16V U3
VCC   DI_IO0
DO_IO1   CLK
HOLD_IO3 CS
GND   WP_IO2

FL_MISO
FL_MOSI
FL_CLK
FL_CS

C11
0.1u
GNDGND

GND

Power Access

VCC
1
2
3
GND PWR

CC31xx Bypass

VCC

C13 C32 C31 C30 C29
4.7u 4.7u 4.7u 0.1u 0.1u

C28 C27 C26 C17
10u 0.1u 0.1u 0.1u

C25 C24 C23
22u 22u 1u

GND GND GND

VDD_PLL VDD_DIG
C16 C20 L6 2.2u C19 C12
0.1u 10u   0.1u 0.1u
GND GND DIG_SW GND GND

Notification LEDs

VCC VCC
R16 1k R17 1k
LED1 LED2
LED1 LED2

CC Reset

VCC
R15 100k
CC_RESET 1k R29 CC_RESET DTSM-3
C37 10000p
GND GND

CC31xx + Antenna

TITLE: Smart_Plug_v1.6

Document Number: REV:

Date: not saved!   Sheet: 2/2

8.2 Bill of Materials

Table 10. Bill of Materials

Qty	Value	Device	Parts	Type of Component	Digikey Part no.
1	AH316M	AH316M	ANT1	AH316M	587-2200-1-ND
1	10u	C-EUC0603	C1	C0603	445-4112-1-ND
3	0.1u	C-USC0402	C11, C27, C36	C0402	445-1265-1-ND
8	0.1u	C-USC0201	C12, C16, C17, C19, C26, C29, C30	C0201	445-7318-1-ND
3	4.7u	C-USC0402	C13, C31, C32	C0402	445-7395-1-ND
2	6p	C-USC0402	C14, C15	C0402	445-4885-1-ND
2	0.1u	C-EUC0603	C2, C3	C0603	445-1316-1-ND
1	10u	C-USC0402	C20	C0402	445-8920-1-ND
1	1u	C-USC0201	C23	C0201	445-8008-1-ND
1	22u	C-EUC0603	C24	C0603	445-8028-2-ND
1	22u	C-EUC0603	C25	C0603	445-8028-2-ND
1	10u	C-USC0402	C28	C0402	445-8920-1-ND
1	10p	C-USC0201	C33	C0201	445-5565-1-ND
1	10u / 400V	CPOL-USE5-10.5	C34	E5-10,5	P5939-ND
1	6.2p	C-USC0201	C35	C0201	445-7060-1-ND
1	10000p	C-USC0201	C37	C0201	445-1793-1-ND
1	0.1u	C-EUC0603	C38	C0603	478-5052-1-ND
1	18u	CPOL-USE5-5	C39	E5-5	P15284CT-ND
1	0.47u	C-EUC0603	C4	C0603	445-1320-1-ND
1	820u	CPOL-USE3.5-8	C40	E3,5-8	565-1629-ND
1	10u	C-USC1210	C41	C1210	445-1434-1-ND
1	0.1u	C-USC0805	C42	C0805	478-3755-1-ND
4	47pF	C-EUC0603	C5, C7, C8, C10	C0603	445-1277-1-ND
2	150p	C-EUC0603	C6, C9	C0603	445-1283-1-ND
2	DTSM-3	DTSM-3	CC_RESET, S1	DTSM-3	679-2307-1-ND
2	5PinHeader	MA05-1	CC3101JTAG, CC3101UART	MA05-1	609-3462-ND
1	B130LB-13-F	DIODE-DO214AA	D10	DO214AA	B130LB-FDICT-ND
1	SMAJ5.0CA	SMAJ	D3	DO-214	SMAJ5.0CABCT-ND
1	US1J-E3/5AT	DIODE-DO-214AC	D6	DO-214AC	US1J-E3/5ATGICT-ND
1	1SMB5954BT3G	DIODE-DO-214AC	D7	DO-214AC	1SMB5954BT3GOSCT-ND
1	US1M-13-F	DIODE-DO-214AC	D8	DO-214AC	US1M-FDICT-ND
1	BAS20HT1G	DIODE-SOD323-R	D9	SOD323-R	BAS20HT1GOSCT-ND
1	S212S01F	S212S01F	K1	S212S01	425-2412-5-ND
2	BLM21BD121SN1D	L-USL2012C	L3, L4	L2012C	P0.0GCT-ND
2	2.2u	LQM2MPN2R2MG0	L5, L8	2016	445-6373-1-ND
1	1u	LQM2HPN1R0MJC	L7	2520	445-6370-1-ND
1	5.6n	LQM2HPN1R0MJCL0201	L9	L0201	445-1579-1-ND
1		LEDCHIP-LED0603	LED1	CHIP-LED0603	475-2506-1-ND
1		LEDCHIP-LED0603	LED2	CHIP-LED0603	475-2709-2-ND
1	14PinHeader	MA07-2	MSP430JTAG	MA07-2	609-3491-ND
1	ECS-327SMO	ECS-327SMO	OCS1	ECS-327SMO	XC777CT-ND
2	3PinHeader	MA03-1	PWR, PWR_SEL	MA03-1	609-3461-ND
1		PNP-TRANSISTOR_SOT23	Q1	SOT23	ZXTP08400BFFCT-ND
1	4.7k	R-EU_R0603	R1	R0603	P4.7KGCT-ND
2	10k	R-US_R0402	R11, R12	R0402	P10KJCT-ND
1	39	R-US_R0603	R13	R0603	P39GCT-ND
6	100k	R-US_R0201	R15, R18, R25, R26, R27, R28, R31	R0201	P100KAGCT-ND
2	1k	R-US_R0402	R16, R17	R0402	P1.0KJCT-ND
1	2.87k	R-US_R0603	R19	R0603	541-2.87KHCT-ND
4	330k	R-EU_R0603	R2, R3, R4	R0603	P330KGCT-ND
1	30.1k	R-US_R0603	R20	R0603	541-30.1KHCT-ND
1	76.8k	R-US_R0603	R21	R0603	541-76.8KHCT-ND
1	10	R-US_R0603	R22	R0603	541-10.0HCT-ND
1	2.0k	R-US_R0603	R23	R0603	541-2.0KGCT-ND

Submit Documentation Feedback

Table 10. Bill of Materials (continued)

Qty	Value	Device	Parts	Type of Component	Digikey Part no.
1	0	R-US_R0805	R24	R0805	P0.0ACT-ND
1	1k	R-US_R0201	R29	R0201	P1.0KAGCT-ND
1	0	R-US_R0603	R30	R0603	P0.0GCT-ND
1	100	R-US_R0603	R5	R0603	P100GCT-ND
1	S20K275	S20K275	R6	S20K275	495-1417-ND
1	3K	R-US_R0603	R7	R0603	P3.0KGCT-ND
4	1K	R-US_R0603	R8, R9, R10, R14	R0603	P1.0KGCT-ND
2	10K	R-US_R0201	R32, R33	R0201	P10KAGCT-ND
1	DNP	R-US_R0201	R34	R0201	
1	4m	R-US_R4527	RSHUNT	R4527	WSRB-.004CT-ND
1	W25Q16V	W25Q16V	U3	8PINWSON	W25Q16DWZPIG-ND
1		MOUNT-PAD-ROUND3.0	GROUNDOUT	3,0-PAD	
2	MALE_BLADE	MALE_BLADE	L_IN, N_IN	BLADE_MALE	
2	BLADE_FEMALE	BLADE_FEMALE	L_OUT, N_OUT	BLADE_FEMALE	
1	40MHz	40.0000MF15Z	XT1	FA-20H	FA-20H, 40MHZ, 10PPM, 12PF
1	1275A1	1275A1	FLT1	1275A1	Custom TDK Filter
1	CUSTOMTRANS	CUSTOMTRANS	T1	TRANS	Custom Renco Trans
1	MSP430I2040XPW	MSP430I2040XPW	U1	TSSOP28	
1	CC31XX	CC31XX	U2	S-PVQFN-N64	296-38011-ND
1	UCC28910D	UCC28910D	U4	SOIC(D)	296-37829-1-ND

8.3 Layout Guidelines
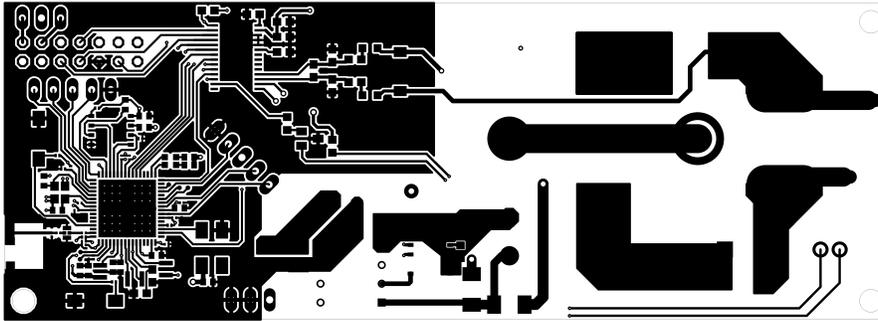
Figure 16. Top Copper
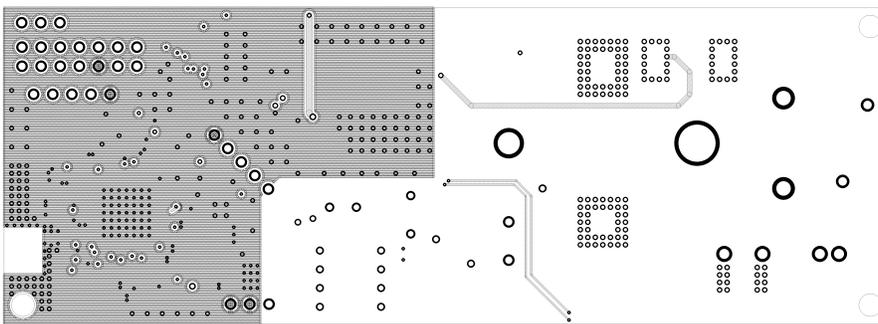
Figure 17. Inner Ground
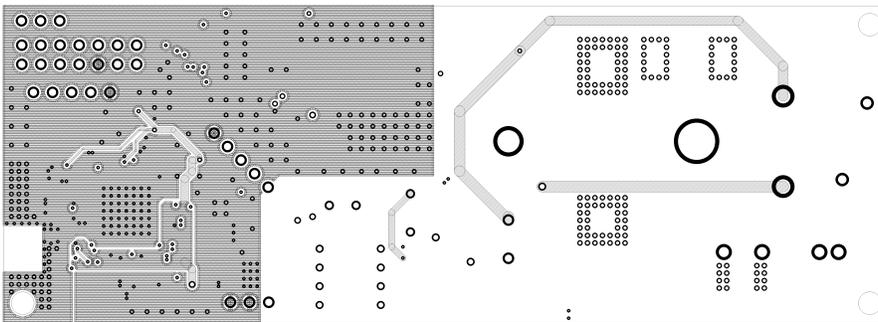
Figure 18. Inner Power
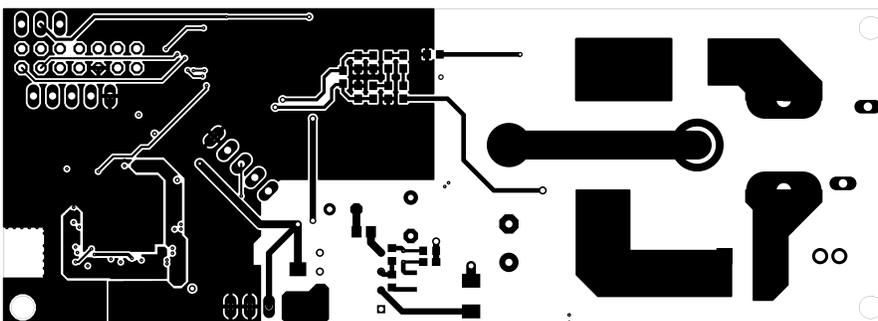
Figure 19. Bottom Copper

8.4 CAD Project

To download the CAD project files for each board, see the design files at http://www.ti.com/tool/TIDC-SMARTPLUG-WIFI

8.5 Gerber Files

To download the Gerber files for each board, see the design files at http://www.ti.com/tool/TIDC-SMARTPLUG-WIFI

9 Software Files

To download the software files for this reference design, see the link at http://www.ti.com/tool/TIDC-SMARTPLUG-WIFI

10 About the Author

BART BASILE is a systems and applications engineer in the Texas Instruments Smart Grid Solutions Team, focusing on the e-metering and grid infrastructure industries. Bart works across multiple product families and technologies to leverage the best solutions possible for system level application design. Bart received his Bachelors of Science in Electronic Engineering from Texas A&M University.

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