Application Report

SWRA494 – December 2015

CC2640 Wireless MCU DC Supply Evaluation

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ABSTRACT

This application report evaluates CC2640 Wireless MCU DC power supply. CC2640 is TI SimpleLink™ *Bluetooth*® Smart Wireless MCU that offers exceptional RF performance with ultralow-power consumption. CC2640 incorporates linear and switching voltage regulators and this application report details the performance and evaluation of these regulators.

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1 Introduction

Voltage regulators are the basic building blocks of any DC power supply. CC2640 wireless MCU incorporates an on-chip internal DC-DC converter. Figure 1 shows CC2640 SoC (system-on-chip) block diagram, which contains blocks for ARM® Cortex®-M3 CPU, RF core, sensor controller, general peripherals, memory, and a DC-DC converter.

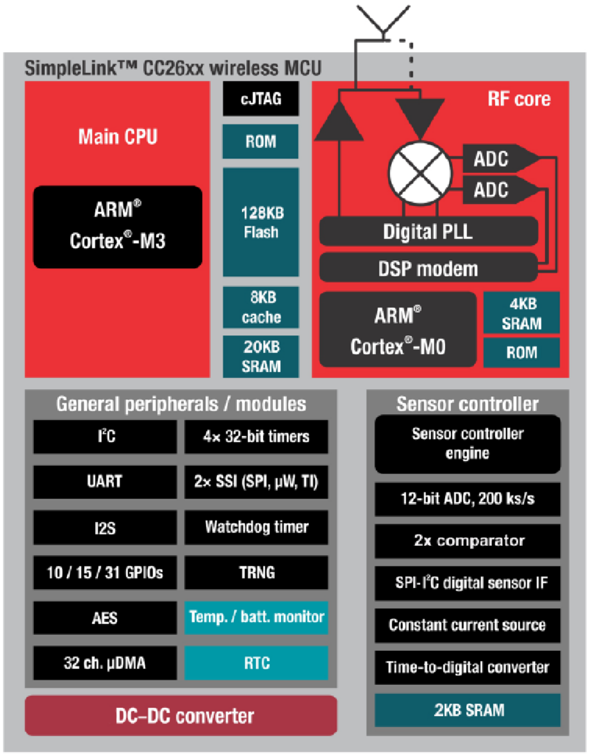

Figure 1. CC2640 Block Diagram

One of the core advantages of the CC2640 SoC is that it has an integrated DC-DC converter block. The CC2640 DC-DC converter incorporates both switching and linear regulators that support all power modes and power-management features. Figure 2 shows how the CC2640 device uses a parallel DC-DC switching regulator and low-dropout linear regulator (LDO).

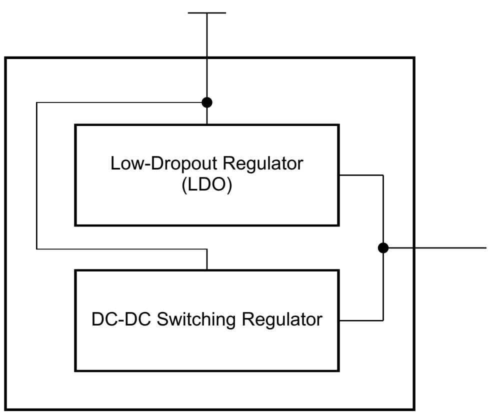

Figure 2. CC2640 DC-DC Converter

2 Basics on Linear and Switching Regulators

Most of the CC2640 applications are battery powered. As the battery drains over a period of time, efficient and clean voltage regulators are essential to provide a constant DC output to the respective subcircuits maintaining the regulated voltage irrespective of any changes in input voltage and load currents. The CC2640 uses LDOs and a DC-DC switching regulator to provide clean and regulated supply with the highest efficiency.

2.1 Low-Dropout Voltage Regulator

LDO regulators are linear regulators with low-dropout voltage. Dropout voltage is the minimum voltage required across the regulator to maintain output voltage regulation. Figure 3 shows a simplified LDO circuit.

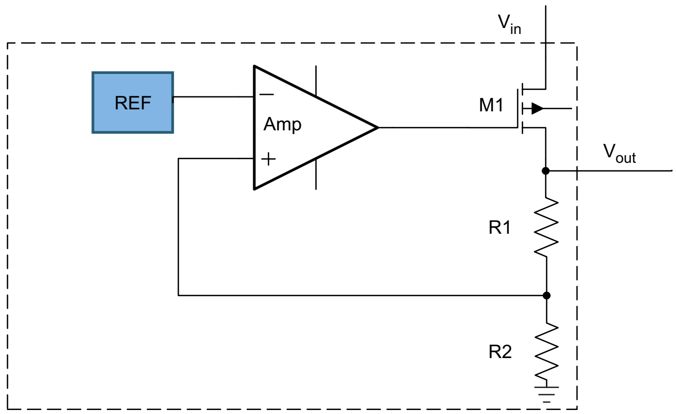

Figure 3. Linear LDO

The R1 and R2 resistors sense the output voltage which appears as a sense signal at the amplifier (Amp) input. This error amplifier drives the pass transistor (M1) to constantly regulate the output voltage (V_{out}) through the negative feedback loop by forcing the sense voltage equal to the reference (REF) voltage.

2.2 Switching DC-DC Regulator

The CC2640 has a built-in DC-DC switching regulator that offers higher efficiency and flexibility to support different internal voltage supplies. Figure 4 shows a simple diagram of buck DC switching voltage regulator.

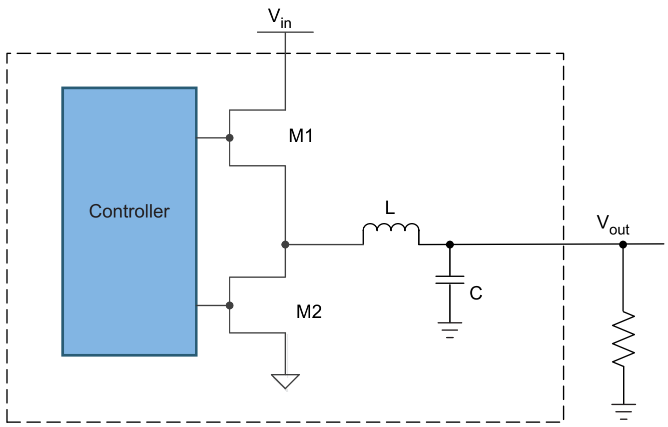

Figure 4. Buck DC Switching Regulator

Buck regulators reduce input DC level to lower levels. The controller switches the switch on and off, and equivalent DC output voltage level is determined based on its pulse-switching duty cycle. The high-side switch transistor (M1) alternately connects and disconnects input voltage (V_{in}) to the inductor (L). When the high-side switch is on, the voltage drop across inductor induces increased current within the inductor (current ramps up), which flows through the load (R_L) and charges the capacitor (C). During switchoff time current within inductor ramps down. The resultant DC load current is the average of these ramp up and ramp down inductor currents and the time that no current flows through the inductor; these determine the regulated output voltage level. See *Linear and Switching Voltage Regulator Fundamental Part 1* Application Report (SNVA558).

Two characteristics determine what type of DC-DC is used based on the conducted inductor current. When the current is continuously conducted through the inductor, the DC-DC is a continuous current mode (CCM) DC-DC. Noncontinuous conduction DC-DCs are discontinuous current mode (DCM) DC-DC. DC-DC controllers may use either pulse frequency modulation (PFM) or pulse width modulation (PWM). The CC2640 uses a PFM DCM DC-DC.

3 Supply Efficiency

3.1 Background Information

Figure 5 shows the basic regulator configuration. Supply efficiency is the ratio of power output (P_{out}) by a regulator to the power inputted (P_{in}) to the regulator. See Equation 1.

$$\eta\,(\%) = \frac{P_{out}}{P_{in}} \bullet 100 \tag{1}$$

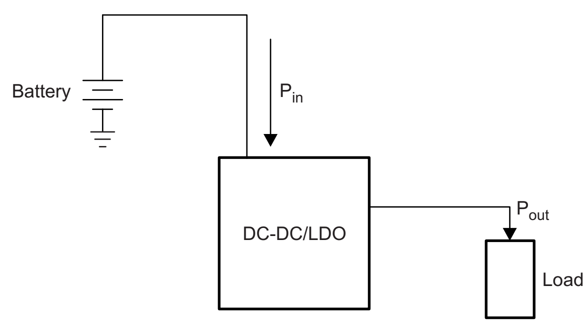

Figure 5. Basic Regulator Configuration

3.2 LDO Efficiency

To calculate efficiency, you must measure P_{out} and P_{in}. For an LDO, efficiency is theoretically limited to the ratio of the output to the input voltage. Consider that most power in an LDO is used by the pass transistor and delivered to the load. If the pass device is a PMOS with its drain connected directly to the load and if all input current is delivered to the load, the same current that flows into the pass device also flows out to the load. The ratio of power out to power in for an LDO is approximately V_{out}/V_{in}.

3.3 Switching Regulators Efficiency

For a switching DC-DC regulator, the output current and the input current are different. Due to the switching of the inductor in the DC-DC regulator, the average current from the battery supply to the DC-DC regulator is scaled by the duty cycle of the inductor switch. If the inductor of the DC-DC regulator is connected to the supply only 25% of the time, the average current into the DC-DC regulator from the battery supply is only 0.25 times the output current (assuming no losses). A buck DC-DC converter can have a higher efficiency than an LDO because the current from the battery supply is reduced (if no losses occur, a buck DC-DC regulator is 100% efficient).

3.4 Evaluation Setup and Measurement Results

Figure 6 shows basic DC-DC and LDO configuration in CC2640, V_{IN} is the main supply to CC2640, I_{IN} is the current through the main supply. Some of the CC2640 circuitry is directly powered by main supply. This current in other circuits is designated as I_{OTHER}. The bias current in LDO is I_{BIAS} and is obtained from simulations. $I_{IN\_ LDO}$ and I_{IN_DCDC} are the input currents through LDO and DC-DC, respectively. $I_{OUT\_ LDO}$ and $I_{OUT\_ DCDC}$ are the output currents from LDO and DC-DC, respectively. R is the external pullup resistor at output of DC-DC and LDO whose value could be around 100 Ω. I_{PU} is the current through the external pull resistor when the output is pulled up. V_{OUT} is the output voltage with I_{OUT} current through the output load, which is CC2640 circuitry powered by the regulator.

NOTE: The pullup resistor is used only for measuring efficiency and is not generally present in an application using the CC26XX and CC13XX.

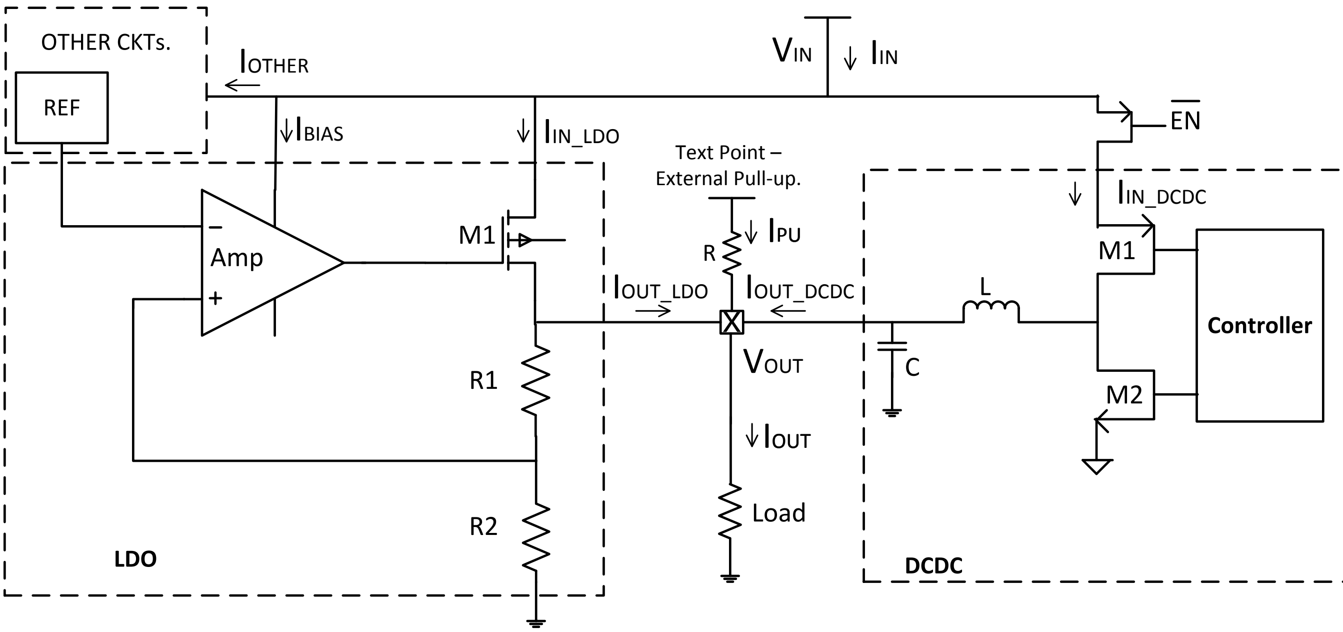

Figure 6. DC-DC and LDO Configuration in CC2640

The first task in measuring efficiency is to measure I_{OTHER}. When the DC-DC is turned off and the output of the LDO is pulled up, which disables LDO, the total current drawn from the main supply is equivalent to sum of I_{OTHER} and LDO bias current after pullup I_{BIAS_AP}. I_{BIAS_AP} is obtained from simulations.

The following steps summarize the DC-DC efficiency calculation procedure in CC2640.

1. Calculate the DC-DC output current.
   (a) Turn off the DC-DC converter.
   (b) Measure the input current through the main supply before DC-DC and LDO output are pulled up ($I_{IN} = I_{IN\_BP}$). (See Equation 2 and Equation 3.)

NOTE: With DC-DC turned off, the DC-DC input current (I_{IN_DCDC}) is negligible.

$$I_{IN\_BP} = I_{OTHER} + I_{BIAS\_BP} + I_{IN\_LDO} + I_{IN\_DCDC} \tag{2}$$

$$I_{IN\_BP} = I_{OTHER} + I_{BIAS\_BP} + I_{IN\_LDO\_BP} \tag{3}$$

(c) Measure the input current through the main supply after DC-DC is turned off and LDO and DC-DC output is pull up ($I_{IN} = I_{IN\_AP}$). (See Equation 4 and Equation 5.)

NOTE: With DC-DC turned off, DC-DC input current (I_{IN_DCDC}) is negligible. With the LDO output pulled up, the LDO input current (I_{IN_LDO}) is also negligible.

$$I_{IN\_AP} = I_{OTHER} + I_{BIAS\_AP} + I_{IN\_LDO} + I_{IN\_DCDC} \tag{4}$$

$$I_{IN\_AP} = I_{OTHER} + I_{BIAS\_AP} \tag{5}$$

(d) Calculate $I_{IN\_LDO\_BP}$ as follows from Equation 3 and Equation 5.

$$I_{IN\_AP\_BP} = (I_{IN\_BP} - I_{IN\_AP}) - (I_{BIAS\_BP} - I_{BIAS\_AP}) \tag{6}$$

(e) Measure the drop across pullup resistor while the DC-DC converter is off ($V_{R\_DCDC\_OFF}$).

(f) Measure the drop across pullup resistor while the DC-DC converter is on ($V_{R\_DCDC\_ON}$).

(g) Calculate the additional current draw when the DC-DC converter is on with the R pullup resistor using Equation 7.

$$I_{PU} = \frac{\left(V_{R\_DCDC\_ON} - V_{R\_DCDC\_OFF}\right)}{R} \tag{7}$$

(h) Calculate the total load current which can be assumed as current from LDO and is equivalent to LDO input current (see Equation 8 and Equation 9).

$$I_{OUT} = I_{OUT\_DCDC} + I_{OUT\_LDO} + I_{PU} = I_{OUT\_LDO} + I_{PU} \tag{8}$$

$$I_{OUT} = I_{IN\_LDO\_BP} + I_{PU} \tag{9}$$

(i) Calculate the total DC-DC output current or load current (I_{OUT}) from Equation 7, Equation 8, and Equation 9 as follows.

$$I_{OUT} = (I_{IN\_BP} - I_{IN\_AP}) - (I_{BIAS\_BP} - I_{BIAS\_AP}) + \frac{(V_{R\_DCDC\_ON} - V_{R\_DCDCOFF})}{R} \tag{10}$$

2. Measure the DC-DC input current.

(a) Calculate the current in other circuits as follows from Equation 5.

$$I_{OTHER} = I_{IN\_AP} - I_{BIAS\_AP} \tag{11}$$

(b) Turn on the DC-DC converter.

(c) Measure the DC-DC input voltage (V_{IN}).

(d) Measure the DC-DC and LDO output voltage (V_{OUT}).

(e) Measure the total input supply current (I_{IN}).

NOTE: This input current from Equation 4 with the DC-DC converter turned on is as follows.

$$I_{IN} = I_{OTHER} + I_{BIAS\_BP} + I_{IN\_LDO} + I_{IN\_DCDC} \tag{12}$$

(f) Calculate the total input current in DC-DC and LDO with the DC-DC converter on from Equation 12. (See Equation 13 and Equation 14.)

$$I_{IN\ DCDC} + I_{IN\ LDO} + I_{BIAS\ BP} = I_{IN} - I_{OTHER} \tag{13}$$

$$I_{IN\_DCDC} + I_{IN\_LDO} + I_{BIAS\_BP} = (I_{IN} - I_{IN\_AP}) - I_{BIAS\_AP} \tag{14}$$

3. Calculate efficiency using Equation 15 and Equation 16.

$$\eta\,(\%) = \frac{P_{OUT}}{P_{IN}} \times 100 = \frac{V_{OUT} \times I_{OUT}}{V_{IN} \times (I_{IN\_DCDC} + I_{IN\_LDO} + I_{BIAS\_BP})} \times 100 \tag{15}$$

$$\eta\,(\%) = \frac{V_{OUT} \times (I_{IN\_BP} - I_{IN\_AP}) - (I_{BIAS\_BP} - I_{BIAS\_AP}) + \frac{(V_{R\_DCDC\_ON} - V_{R\_DCDC\_OFF})}{R}}{V_{IN} \times ([I_{IN} - I_{IN\_AP}] - I_{BIAS\_AP})} \times 100 \tag{16}$$

Figure 7 shows the typical characteristics of the CC2640 regulator. At typical device operation when the DC-DC effiency is enabled, most the input current is through DC-DC, that is, $I_{IN\_DCDC} + I_{IN\_LDO} + I_{BIAS\_BP}$ is equivalent tp I_{IN_DCDC}.

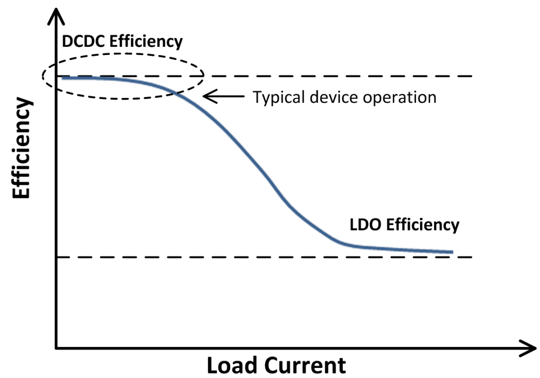

Figure 7. CC2640 Typical Efficiency Characteristics

For example, calculate the efficiency of CC2640 with V_{IN} = 3 V, V_{OUT} = 1.7 V, measured I_{IN} = 10.5 mA. Bias currents I_{BIAS_BP} = 62 µA and I_{BIAS_AP} = 15 µA. Voltage across a 100-Ω pullup resistor is 380 mV and 400 mV when the DC-DC converter is off and on, respectively. The DC-DC input current is 15.3 mA and 2.3 mA previously to and prior to DC-DC and LDO output being pulled up, respectively. For more information, see Equation 17.

$$\eta\,(\%) = \frac{1.7 \times ([15.3 - 2.3] - [0.062 - 0.015] + \frac{[400 - 880]}{100})}{3 \times ([10.5 - 2.3] - 0.015)} \times 100 = 91.06\% \quad (17)$$

Figure 8 shows a typical set of efficiency curves of a DC-DC converter.

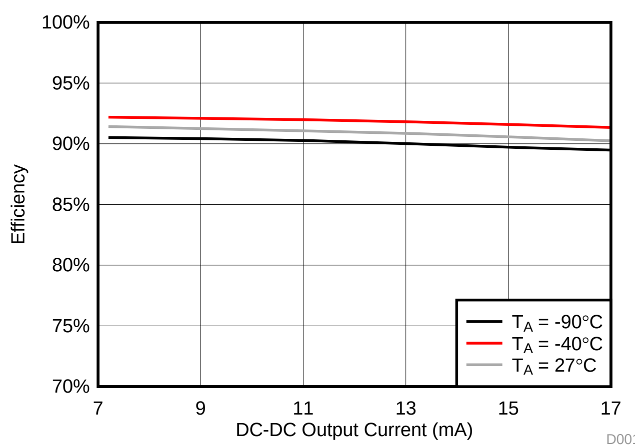

Figure 8. CC2640 Efficiency Across Temperature and Load Currents

4 Load Regulation

4.1 Background Information

Load regulation is the ability of a regulator to maintain a given output voltage with respect to any load current variations. Load regulation is defined as change in output voltage (ΔVout) divided by the change in output load current (ΔIout). See Figure 9 for more information.

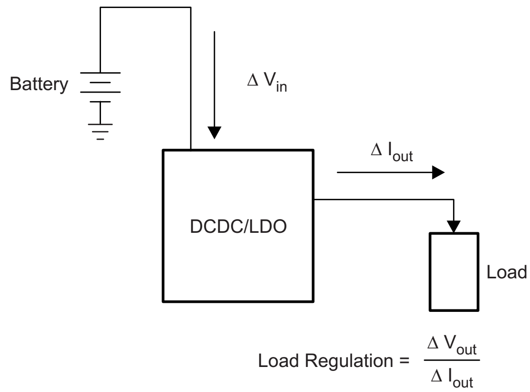

Figure 9. Load Regulation

4.2 Evaluation Setup and Measurement Results

To measure load regulation, apply a load step to the output of the regulator and observe the output voltage. To achieve a switching load, a switch board is used with a PNP switch as shown in Figure 10.

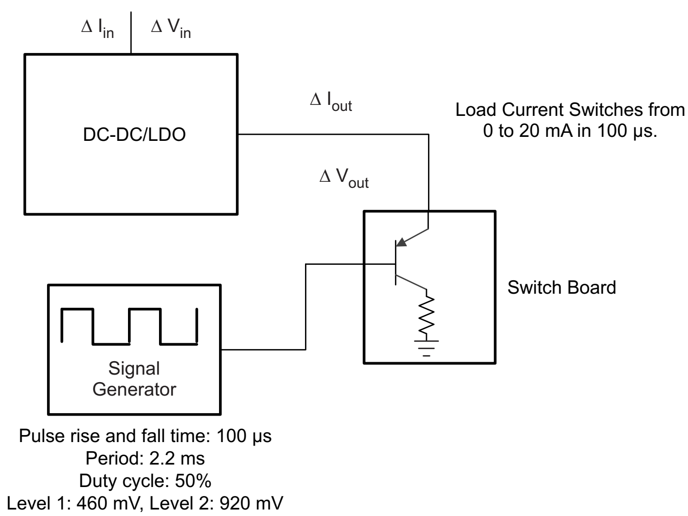

Figure 10. Load Regulation Evaluation Setup

To switch DC-DC and LDO output load current from 0 to 20 mA (ΔIout = 20 mA) in 100 µs, a pulse signal is used with a 100-µs rise and fall time, a 2.2-ms period, and a 50% duty cycle. In Figure 11, this pulse signal is a yellow curve and drives the base of the switch. The DC-DC output voltage variation (ΔVout) is the blue line. The total peak-peak change in output voltage is 5.8 mV, and approximately maximum overshoot, that is, with the change output voltage (ΔVout) could be estimated to about 4 mV. The typical load regulation is given less than 4 mV for change in output current from 0 mA to 20 mA. See Equation 18 and see Figure 12 for the results of the measurement.

$$Load\,regulation = \frac{\Delta Vout}{\Delta Iout} = \frac{4\,mV}{20\,mA} = 0.2V/A \quad (18)$$

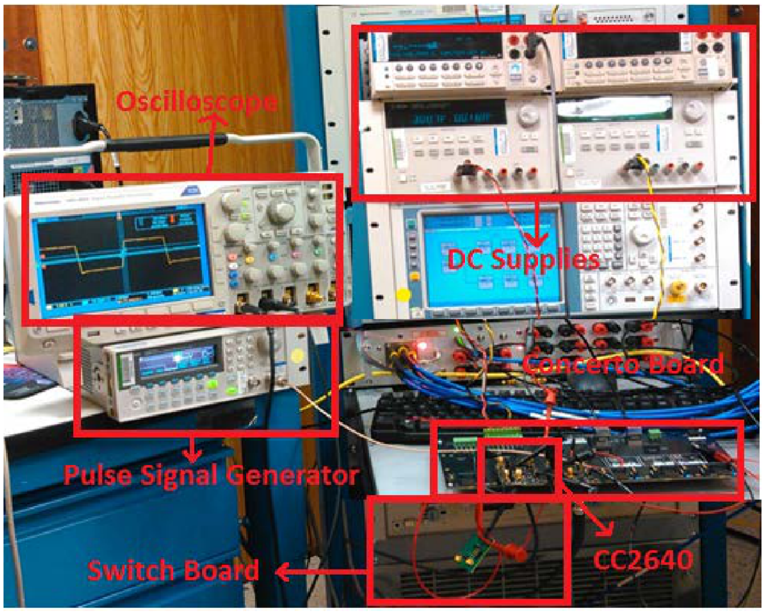

Figure 11. Load Regulation Setup Picture

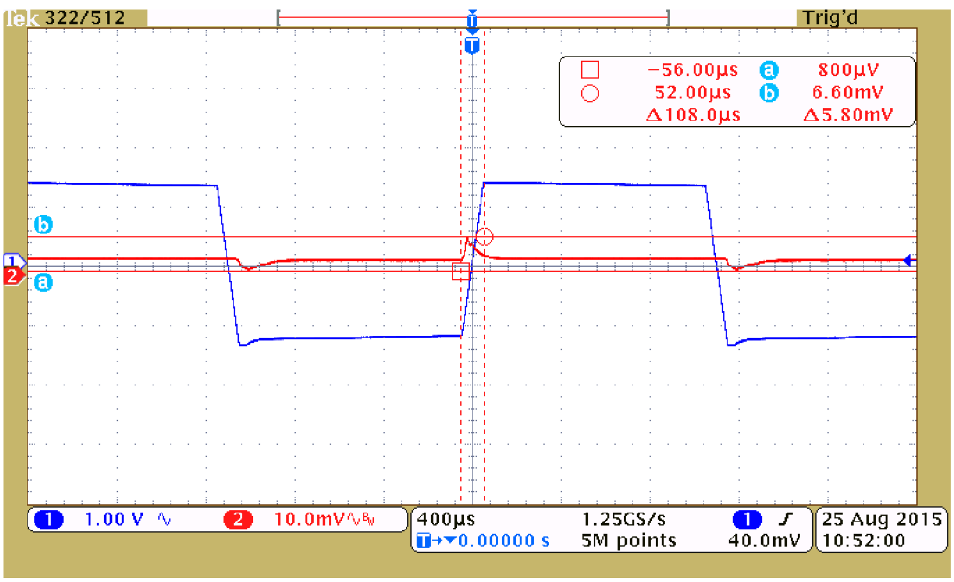

Figure 12. Load Regulation Measurement Result (The red curve is the output of the LDO.)

5 Line Regulation

5.1 Background Information

Line regulation is the ability of a regulator to maintain a specified output voltage with respect to any input voltage variations. Line regulation is defined as change in output voltage (ΔVout) divided by change in input voltage (ΔVin). See Figure 13 for more information.

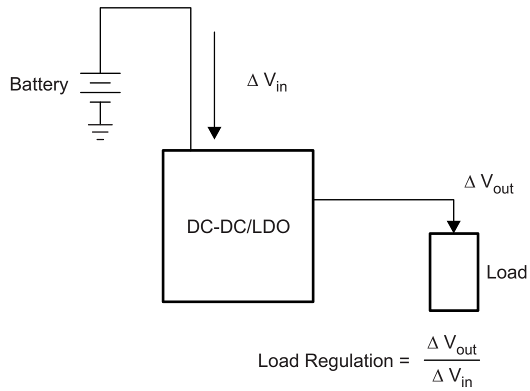

Figure 13. Line Regulation

5.2 Evaluation Setup and Measurement Results

To measure line regulation, apply a voltage step to the input of the regulator and observe the output. The challenging part of measuring line regulation is providing a voltage step from a power supply. A high-speed amplifier connected to a function generator is used to generate the voltage step. See Figure 14.

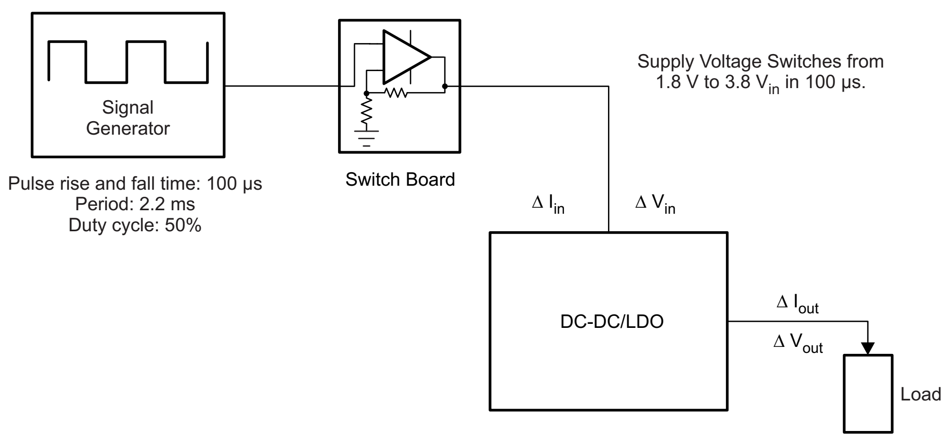

Figure 14. Line Regulation Evaluation Setup

To switch DC-DC and LDO input supply voltage from 1.8 V to 3.8 V (ΔVin = 2 V) in 100 µs, a pulse signal is used with a 100-µs rise and fall time, a 2.2-ms period, and a 50% duty cycle. In Figure 15, Input supply voltage to DC-DC and LDO is the blue curve. The LDO (with the DC-DC converter turned off) output voltage variation (ΔVout) is the red line. The total peak-peak change in output is approximately 8 mV. Equation 19 gives the typical line regulation.

$$LDO\ Line\ regulation = \frac{\Delta Vout}{\Delta Vin} = \frac{8\,mV}{2\,V} = 0.004 \tag{19}$$

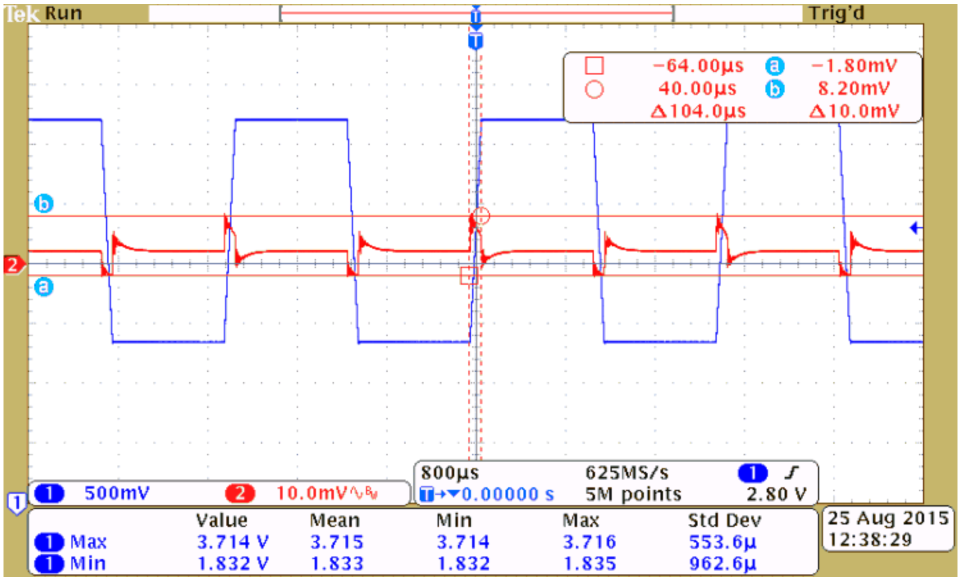

Figure 15. LDO Line Regulation Measurement Result

\When the DC-DC converter is turned on, the DC-DC output voltage variation (ΔVout) is the red line in Figure 16. The total peak-peak change in output voltage is 55.4 mV, and approximately maximum overshoot, that is, with the change output voltage (ΔVout) could be estimated to about 35 mV. Equation 20 gives the typical line regulation.

$$\text{DC}-\text{DC Line Regulation} = \frac{\Delta\text{Vout}}{\Delta\text{Vin}} = \frac{35\text{ mV}}{2\text{ V}} = 0.0175 \qquad (20)$$

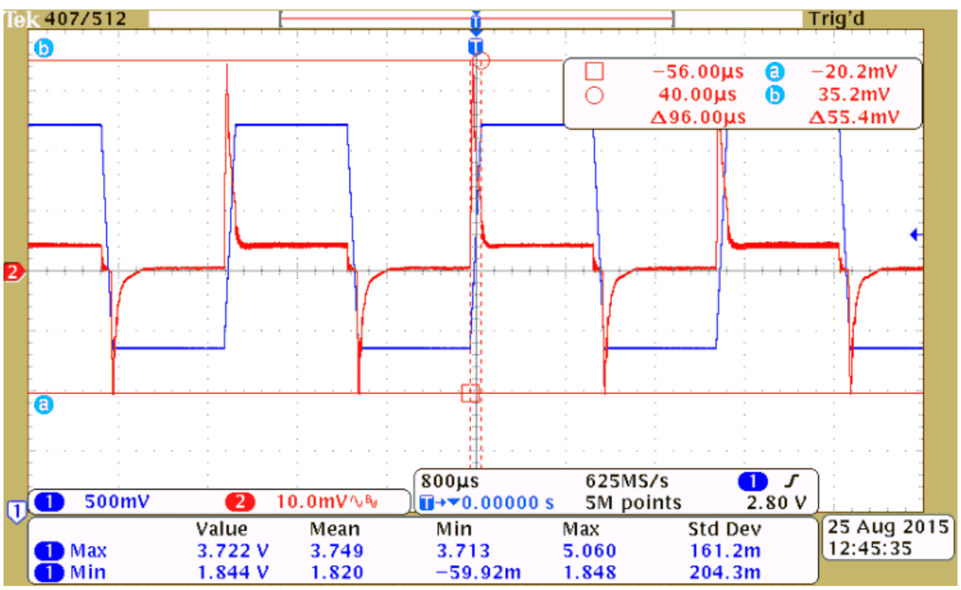

Figure 16. DC-DC Line Regulation Measurement Result

6 Power Supply Rejection Ratio

6.1 Background Information

Power supply rejection ration (PSRR) is the ability of a regulator to maintain the regulated output voltage free of any input voltage fluctuations. PSRR could be considered similar to line regulator but inclusive of frequency spectrum. For more information, see Equation 21 and Figure 17.

$$PSRR = 20.\log 10\left(\frac{Vin(w)}{Vout(w)}\right) \tag{21}$$

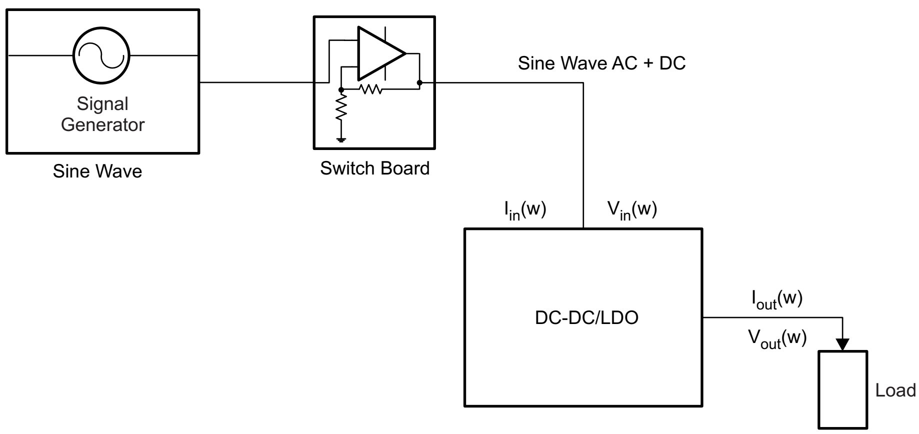

Figure 17. PSRR Measurement Setup

6.2 Evaluation Setup and Measurement Results

To measure PSRR, a sine wave is applied on top of the supply voltage of the regulator (the input voltage). The sine wave generator produces a sine wave with a nonzero DC value. Amplitude of the sine wave is kept low at first and then increased until it is measurable at the output. The ratio of the input sine wave amplitude to the output sine wave amplitude is the PSRR.

Figure 17 shows the PSRR measurement setup. This setup is the same as for line regulation. Figure 18, Figure 19, and Figure 20 show the measurement results of CC2640 LDO and DC-DC PSRR. In these figures, blue curves are DC-DC/LDO sine wave applied at input and red curves are DC-DC/LDO output sine wave. Sine waves of frequencies 1 kHz and 10 kHz were considered. DC-DC and LDO PSRR are calculated in Equation 22, Equation 23, and Equation 24.

$$PSRRLDO1KHz = 20.\log 10\left(\frac{Vin(w)}{Vout(w)}\right) = 20.\log 10\left(\frac{1.846}{0.00325}\right) = 55dB \tag{22}$$

$$PSRRLDO10KHz = 20.\log 10\left(\frac{Vin(w)}{Vout(w)}\right) = 20.\log 10\left(\frac{1.514}{0.0193}\right) = 37.89dB \tag{23}$$

$$PSRRDCDC10KHz = 20.\log 10\left(\frac{Vin(w)}{Vout(w)}\right) = 20.\log 10\left(\frac{1.487}{.0258}\right) = 35.21dB \tag{24}$$

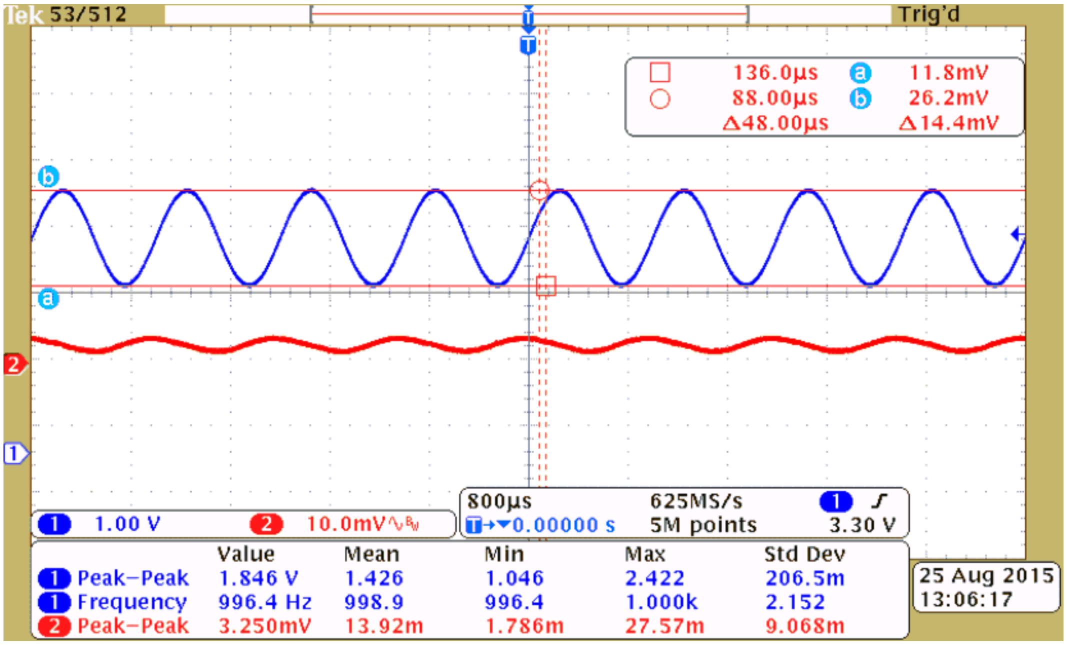

Figure 18. LDO PSRR Measurement Result, Frequency 1 kHz

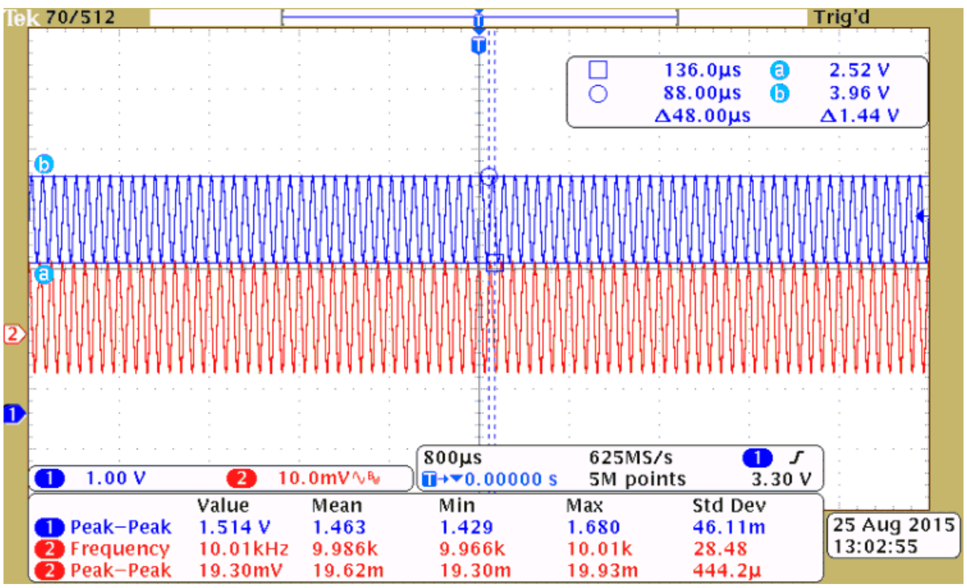

Figure 19. LDO PSRR Measurement Result, Frequency 10 kHz

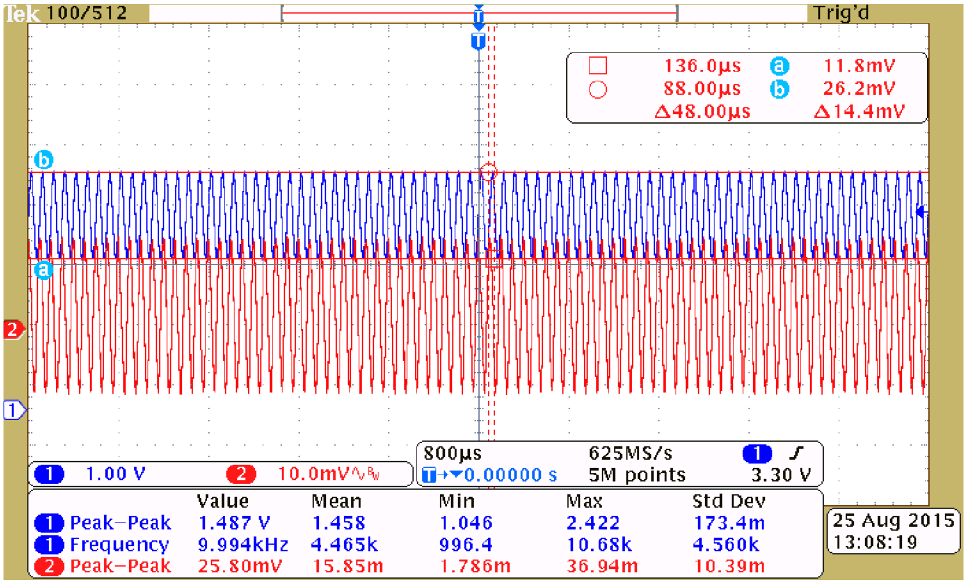

Figure 20. DC-DC PSRR Measurement Result, Frequency 10 kHz

7 Summary

CC2640 Wireless MCU DC power supply is evaluated in this application report. Major specifications of a DC supply are discussed. Procedure to calculate CC2640 supply efficiency is detailed along with the load regulation, line regulation, and power supply rejection ratio parameters. CC2640 DC-DC regulator typically shows more than 90% efficiency. CC2640 LDO has 0.2 V/A of load regulation and .004 line regulation, with PSSR of 55 dB at 1 kHz and more than 37 dB at 10 kHz.

8 References

1. *CC2640 SimpleLink™ Bluetooth® Smart Wireless MCU* data sheet (SWRS176)
2. *Linear and Switching Voltage Regulator Fundamental Part 1* Application Report (SNVA558)

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