# TI Designs 16-Ch Status LED Driver for PLC Modules

# UTEXAS INSTRUMENTS

# **TI Designs**

TI Designs provide the foundation that you need including methodology, testing, and design files to quickly evaluate and customize the system. TI Designs help *you* accelerate your time to market.

# **Design Resources**

TIDA-00560	Tool Folder Containing Design Files
TLC5928	Product Folder
SN74LVC2G86	Product Folder
SN74LVC1G332	Product Folder
BeagleBone Black Wiki	BeagleBone Resource Folder



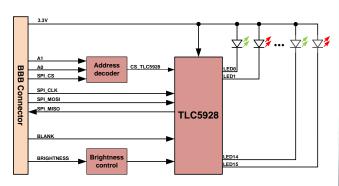
ASK Our E2E Experts WEBENCH® Calculator Tools

# **Design Features**

- 16-Channel Shift Register With Wide Range Constant Current Sinks (2 mA to 35 mA)
- Two-Level Brightness Setting for Light-Emitting Diode (LED) to Compensate for Ambient Light
- Diagnostic Features: LED Open and LED Shorted to GND
- Standardized SPI Connects Seamlessly to Standard Processors
- Number of Channels Increasable by Daisy-Chaining Multiple LED Driver Devices
- BeagleBone Cape Support for Easy Evaluation

# **Featured Applications**

- Programmable Logic Controller (PLC)
- PLC Analog Input and Output modules
- PLC Digital Input and Output modules





An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

All trademarks are the property of their respective owners.

# 1 Key System Specifications

PARAMETER	SPECIFICATION	DETAILS				
LED channels	Number of LED channels: 16	See TLC5928 data sheet (SBVS120)				
V <sub>cc</sub>	Supply voltage range: 3.0 V to 5.5 V	See Section 5.1.1				
ILED	Brightness signal low or high: 2 mA or 5 mA	See Section 5.1.3				
	I <sub>CC</sub> (LEDs off), 3.3 V, no data transfer: 0.535 mA					
I <sub>cc</sub>	$I_{\text{CC}}$ (LEDs on, 2 mA), 3.3 V, no data transfer: 31.89 mA	See Section 8.3.4				
	I <sub>CC</sub> (LEDs on, 5 mA), 3.3 V, no data transfer: 79.9 mA					
	Red: 20 mcd at 2 mA, 50 mcd at 5 mA	See Section 4.1.3				
Luminous intensity	Green: 4 mcd at 2 mA, 10 mcd at 5 mA	See Section 5.1.3				
HW brightness control	Changing forward current in two steps	See Section 5.1.3				
LED fault simulation	LEDs D1-D8	See Section 5.1.4				
System control	Any host processor using serial peripheral interface (SPI) or general purpose input and output (GPIO)	See Section 7				
Board integration	Compatible with BeagleBone Cape specification	See Section 5.2				
Operating conditions	-40°C to +85°C	See TLC5928 data sheet (SBVS120)				



# 2 System Description

This TIDA-00560 TI design demonstrates a way to control up to 16 LEDs independently as required in systems with multiple channels, such as analog or digital PLC I/O modules. The very small board space of the core components and the standard interface of the LED driver allow seamless integration into small form factor modules.



Figure 1. TIDA-00560 Board Image

# 2.1 TLC5928

The main part of this TI design, the TLC5928 [1], is a 16-channel, constant-current LED driver with fault detection. The current is selectable with a resistor and can be in the range of 2 mA to 35 mA. The channel-to-channel accuracy is typical at 1%. The daisy-chain feature allows cascading of multiple TLC5928 devices in a chain. The device-to-device accuracy is also typical at 1%. While the digital part works in the range of 3.0 V to 5.5 V, the current-sink input voltages can be as high 17 V supporting multiple LEDs per current sink in series. A dedicated BLANK pin allows the sudden shut off of all LEDs without SPI communication.



Block Diagram

# 3 Block Diagram

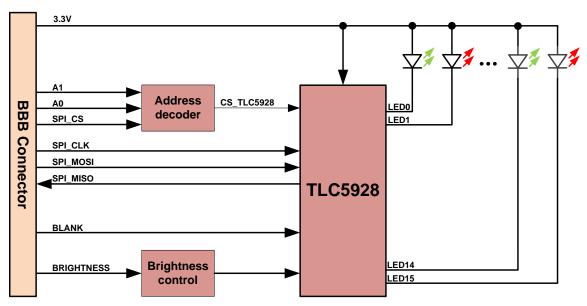


Figure 2. TIDA-00560 Block Diagram

# 3.1 Highlighted Products

The TI design for a 16-channel LED driver features the following device:

- TLC5928
  - 16 channels, constant-current sink output
  - 35-mA capability (constant-current sink)
  - 10-ns high-speed constant-current switching transient time
  - LED power-supply voltage (up to 17 V)
  - V<sub>CC</sub> = 3.0 V to 5.5 V
  - Constant-current accuracy:
    - Channel-to-channel = ±1%
    - Device-to-device = ±1%
  - 35-MHz SPI data transfer rate
  - Readable error information:
    - LED open detection (LOD)
    - LED short to GND
    - Pre-thermal warning
    - Operating temperature: -40°C to +85°C

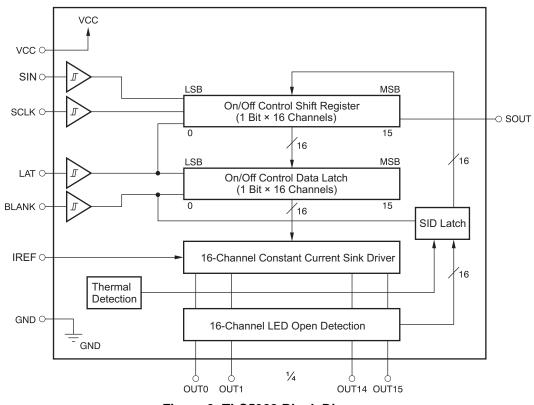


Figure 3 shows the block diagram for the TLC5928 device.

Figure 3. TLC5928 Block Diagram

For more information see the respective product folder at: <u>www.ti.com/product/tlc5928</u>.

# 4 System Design Theory

# 4.1 Methods of Driving LEDs

Designers currently use different methods to drive an LED. The system environment and performance requirements dictate which method to use. For example, if an LED just indicates that a voltage is available (actual brightness is secondary), the LED simply connects to the observed voltage with a resistor in series. However, this approach is insufficient where brightness control is a requirement. To better describe each approach, the following paragraph provides a brief description of the LED characteristics.

Every LED (and every other diode) has a U-I characteristic similar to what Figure 4 shows. As an example, Figure 4 shows the curve of a Wurth Elektronik LED (part number 150120VS75000) as used in this TI design.

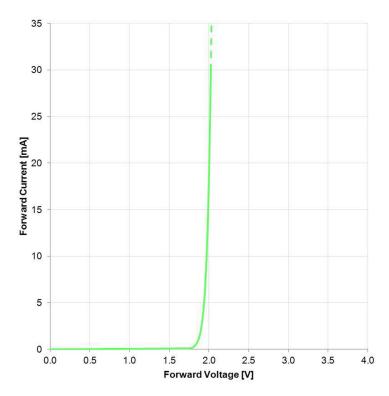


Figure 4. Forward U-I Curve of LED



Given the steepness of the curve in the area of interest (here: 1.9 V to 2.0 V), the user can discern that small changes in the forward voltage result in a larger change of the forward current. Rather than trying to set the voltage, a more practical way is to inject the current and let the voltage follow. Setting the forward current also enables better control of the brightness because the forward current and the luminous intensity are almost linear dependent (see Figure 5).

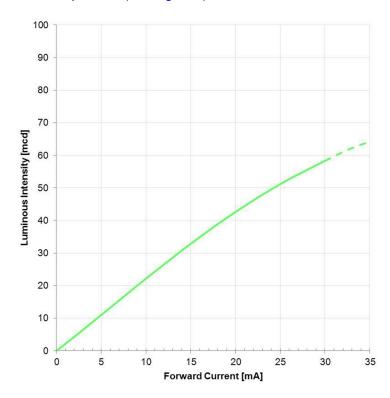


Figure 5. Forward Current — Luminous Intensity Curve

# 4.1.1 Driving Single LED Using GPIO

The simplest way to turn an LED on or off is to use a general-purpose input or output (GPIO) pin (see Figure 6).

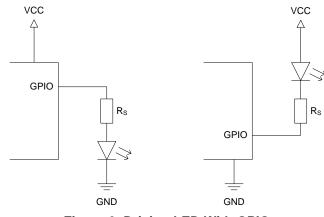


Figure 6. Driving LED With GPIO

# TEXAS INSTRUMENTS

## System Design Theory

www.ti.com

The circuit just requires a resistor in series to limit the current. Equation 1 calculates the value of the resistor:

$$R_{S} = \frac{V_{GPIO} - V_{LED}}{I_{LED}}$$

(1)

However, R<sub>s</sub> cannot be calculated precisely due to reasons such as:

- Production-related deviation in V<sub>LED</sub> (at a given I<sub>LED</sub>)
- Current-dependent V<sub>GPIO</sub>

In addition to these reasons, the calculated value of  $R_{\rm S}$  might not be available. Selecting the next available value also adds an error.

The standard GPIOs of microcontrollers and microprocessors are not designed to drive higher currents, in that the  $R_{DSON}$  of their high-side and low-side MOSFETs are not optimized. As more current flows through the MOSFET, the voltage drop over its source-drain increases, which results in a voltage shift at the GPIO pin. The datasheet of the device usually specifies this characteristic. As examples, Figure 7 (sinking current) and Figure 8 (sourcing current) show the plots for the MSP430G2553 low-power microcontroller [2].

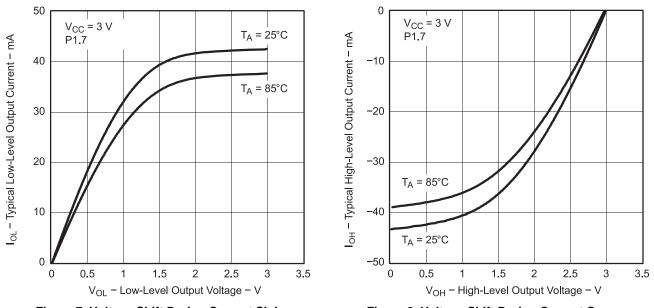


Figure 7. Voltage Shift During Current Sink



The attentive reader may notice that the voltage drops are not similar for a certain current. Taking the 30-mA point from the 25°C curve: the ground shift caused by the low-side MOSFET is around 0.9 V (see Figure 7), while the voltage drop induced by the high-side MOSFET for the same current is around 3.0 V - 1.9 V = 1.1 V (see Figure 8). This difference in voltage drops means that the right-side circuit in Figure 6 performs slightly better than the left-side option. If a user desires better control over the voltage drop or requires driving a higher current, TI recommends using an external MOSFET.

# 4.1.2 Driving Multiple LEDs With GPIOs

The previous solution that Section 4.1.1 outlines requires one GPIO per LED channel. If the number of LEDs that must be driven are more than the number of GPIOs available, the user can implement a GPIO expander. Expanders usually have a standard serial interface as an input and multiple GPIOs as outputs. A commonly used serial interface for this type of device is the I<sup>2</sup>C bus. Because the I<sup>2</sup>C bus is shareable among multiple devices (memory, sensor, and so forth), adding GPIOs does not require an additional pin. A good example of this is the PCF8574 device [ 3].



Another way to add GPIOs is to use a standard logic device, such as the SN74HC595 [4] with an SPIcompatible serial port. The values for the 8-bit output are serially clocked into the shift register and transferred to the storage register with a separate signal to avoid an unintended GPIO state change during the time of new data arrival.

# 4.1.3 Driving LED With Integrated Current Source

The more efficient way to drive an LED is to control it using a current source. The forward voltage is the result of the current being injected; therefore, the current source must be able to provide the expected forward voltage. By supporting higher voltages, multiple LEDs can be connected in series while maintaining the same brightness because the same current flows through this string of LEDs.

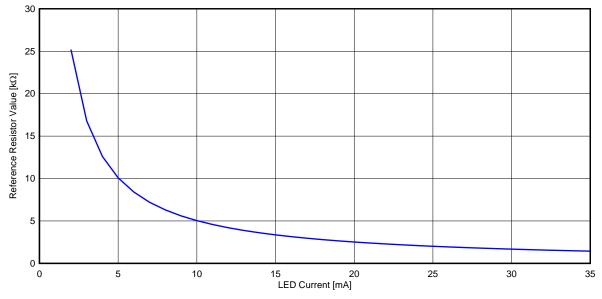
A designer can simply create current sources with a few components, but the bill of materials (BOM) and real estate requirements increase with multiple channels. This TIDA-00560 TI design shows the simplicity of a multi-channel current-driven LED design using the TLC5928 device.

The current limit for the sources is set by an external resistor connected to the TLC5928 device. The formula to set the current limit can be calculated using the following Equation 2:

$$R_{IREF} = \frac{V_{IREF}}{I_{LED}} \times 42$$

(2)

With a constant  $V_{IREF}$  of 1.2 V, the R-I curve can be calculated. Figure 9 shows the plot over the entire supported LED current range of 2 mA to 35 mA.





## 4.1.4 Board Space

Another important aspect of the TIDA-00560 design is the real estate required by the solution. While this design is mechanically compatible with the specifications listed for the BeagleBone Cape, the actual LED driver solution can be much smaller. The TLC5928 device comes in a 4 mm × 4 mm QFN-24 package and the absolute minimum of required additional components are the current-limiting reference resistor and the bypass cap. Because no additional resistors for the LEDs are required, this design is the most physically compact with the shortest BOM among all of the previously mentioned options.

# 5 Getting Started Hardware

# 5.1 Running the TI Design

Although the TIDA-00560 TI design is designed to run on a BeagleBone Black Cape, connecting to any other processor with SPI or without SPI (emulation required through GPIO) is possible. Table 1 shows the assignments of headers J8 and J9.

PIN ON BOARD	SIGNAL	DESCRIPTION	MANDATORY FOR OPERATION				
J8.11	CAPE_A1	Cape address decoding	No				
J8.12	CAPE_A0	Cape address decoding	No				
J9.19	I2C_SCL	Cape identification	No				
J9.20	I2C_SDA	Cape identification	No				
J9.25	BRIGHTNESS	Brightness adjust	No				
J9.27	BLANK	Blank signal	Yes				
J9.28	SPI_CS	SPI chip select	Yes				
J9.29	SPI_MISO	Data from TLC5928	Only for diagnostics				
J9.30	SPI_MOSI	Data to TLC5928	Yes				
J9.31	SPI_SCLK	SPI shift clock	Yes				

### Table 1. Pin Assignments

The signals CAPE\_A0 and CAPE\_A1 are pulled-high by resistors R7 and R9 (see Figure 14). For proper operation of the address decoder logic, the user must set both S1 switches to "off" if the CAPE\_A0 and CAPE\_A1 signals are not driven. This assures that the I<sup>2</sup>C address (set by S1) matches the address of CAPE\_A0/CAPE\_A1 and the SPI chip select (CS) signal is passed to the TLC5928.

The optional I<sup>2</sup>C bus is required in conjunction with the specification designated by the BeagleBone Cape; Section 5.2 describes this in further detail. This feature is not required for proper operation, though.

The optional signal BRIGHTNESS selects between the default LED current of 2 mA (BRIGHTNESS set low) or 5 mA (BRIGHTNESS set high). If this signal is not driven, an LED current of only 2 mA is supported.

The diagnostic features of the TLC5928 device (*LED open, LED short to ground*, and *thermal*) is optional. If not required, the signal SPI\_MISO can be omitted.

The TIDA-00560 design requires a three-wire SPI and the BLANK pin at the minimum for proper operation.



# 5.1.1 Voltage Range

The TLC5928 requires two different voltages:

- V<sub>cc</sub>: 3.0 V to 5.5 V
- V<sub>o</sub>: up to 17 V

In a digital environment, from where the TLC5928 is driven, a common voltage for  $V_{cc}$  is 3.3 V. Setting  $V_o$  to also run from this voltage is also effective to save the second voltage rail; therefore, check for the minimum  $V_o$  for this design. To obtain the supported voltage range, the user must know that each current sink in the TLC5928 requires a certain voltage drop over the OUTx pin to properly regulate the sink current (see Figure 10).

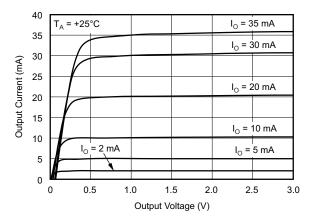


Figure 10. Required Voltage Drop for Stable Current Regulation

Figure 10 clearly shows that the amount of voltage drop is dependent on the target sink current. This TI design is optimized for 2-mA and 5-mA sink currents. According to Figure 10, the regulation is stable at around the 0.5-V voltage drop. By adding the working point voltage drop ( $V_{LED}$ ) of the LED (conservatively 2.0 V—see Figure 4), a  $V_0 \ge 2.5$  V is required. The comparatively lower forward voltage for colored LEDs (compared to blue or white LEDs) as used in PLC I/O modules is an advantage here. As a result, the design works in the full range of the digital supply of the TLC5928 ( $V_{CC}$ ), including the target of 3.3 V.

The difference between the minimum  $V_o$  ( $V_{O_{-MIN}}$ ) and the applied  $V_o$  must be consumed by the current sinks, increasing the power dissipation. The closer the applied  $V_o$  gets to  $V_{O_{-MIN}}$  the better. Just generating a new voltage rail for  $V_o$  may not be economical, but if a voltage rail closer to  $V_{O_{-MIN}}$  is available, the user should consider using this closer voltage rail to minimize the power consumption of the circuit.

# 5.1.2 Power Dissipation

As with every thoroughly designed circuit, the user must calculate the power dissipation, followed by any appropriate actions, if required. The used QFN-24 package is capable of dissipating 1615 mW at 85°C. The maximum power of the TLC5928 device with the given parameter is calculated in Equation 3:

$$P_{D_{MAX}} = 16 \times (V_{OUT} \times I_{LED}) + V_{CC} \times I_{CC_{MAX}(est)}$$

$$P_{D_{MAX}} = 16 \times ((3.3 \text{ V} - 2.0 \text{ V}) \times 5 \text{ mA}) + 3.3 \text{ V} \times 5 \text{ mA}$$

$$P_{D_{MAX}} = 120.5 \text{ mW}$$

(3)

A  $P_{D_MAX}$  of 120.5 mW for this design is far below the limit of 1615 mW. This number applies with the use of a soldered power pad. TI highly recommends to always solder the power pad for proper heat dissipation and mechanical stability reasons.



#### Getting Started Hardware

#### 5.1.3 Brightness Control

The current limit for the output channels is set with a single resistor from pin IREF to GND. This TIDA-00560 TI design features an optional two-step brightness approach. This approach is useful in conjunction with an ambient light sensor such as the HDC1000 [ 5] to compensate for ambient light changes. Figure 11 shows the circuit.

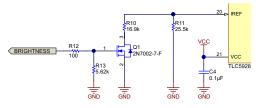


Figure 11. Brightness Circuit

In default configuration, the digital signal BRIGHTNESS is low and Q1 is not conducting. The IREF pin of the TLC5928 device is connected to GND by R11 only. The value of 25.5 k $\Omega$  sets the current limit for each channel to about 2 mA. If BRIGHTNESS is set high, Q1 is conducting and puts R10 parallel to R11, which results in a resistance of about 10.16 k $\Omega$  registered by the TLC5928 device. In this case the current limit rises to about 5 mA.

#### 5.1.4 Simulating Fault Detection

In addition to switching the LEDs, each current sink can be observed for an *LED open* or *short to GND* event. The TLC5928 device internally senses the voltage drop across each OUTx pin to GND. If the nominal voltage is less than 300 mV, the devices assumes a fault and reports it to the processor over the MISO line during SPI communication. Both fault conditions can be tested with this TI design (see Figure 12).

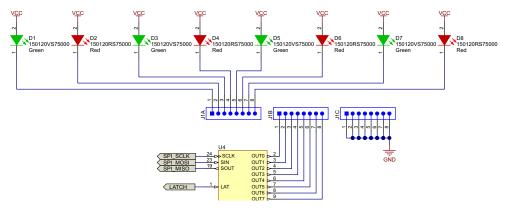


Figure 12. Fault Simulation

All of the sixteen channels support the *LED open* and *short to GND* features, although only the first eight channels (OUT0 through OUT7) utilize these features in this TIDA-00560 TI design. The behavior is understood for OUT0 (D1) but also applies to the remaining seven channels; the default jumper setting is a shorted J1A.1 and J1B.1, which connects the cathode of D1 to the OUT0 pin of the TLC5829 device. If no jumper is inserted, the *LED open fault* is simulated. Finally, if J1B.1 and J1C.1 is shorted, the OUT0 pin is connected to GND, simulating the *short to GND* fault. Additionally, the TLC5928 device can also report an *over temperature* condition, setting all bits of the 16-bit status word to "1".

# 5.2 BeagleBone Cape Concept

This TIDA-00560 TI design is compatible with the BeagleBone Cape concept. The design allows a seamless connection to the BeagleBone and BeagleBone Black development platforms for easy evaluation. The implemented handshake mechanism allows for an automatic adaption of the BeagleBone GPIOs using device tree overlay files. The mandatory hardware for each cape is an EEPROM that stores all of the relevant information of the cape. The EEPROM is connected to the serial interface I<sup>2</sup>C of the AM3359 device [ 6] used with the BeagleBone platform. During Linux startup, the AM3359 device scans the address range 0x54 to 0x57 for any cape board extensions (as up to four capes can be supported at a time). The address is selected by switch S1. Table 2 shows the mapping.

I <sup>2</sup> C ADDRESS	S1.1	\$1.2
0x54	On	On
0x55	Off	On
0x56	On	Off
0x57	Off	On

Table 2	2. S1	to	I <sup>2</sup> C	Address	Mapping
---------	-------	----	------------------	---------	---------

Figure 13 shows the circuit for the cape identification. This EEPROM is not protected here, which means it can be written to at any time.

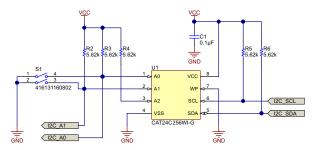


Figure 13. Cape Identification

Now imagine a scenario where four boards of this TIDA-00560 TI design are stacked. All TLC5928 devices would connect to the same SPI port and the AM3359 would not be able to distinguish between these devices. To solve this issue, this design implements an additional address decoding logic for the SPI CS signal. The SPI CS signal of the SPI is routed to the TLC5829 as the signal LATCH, but only if the signal CAPE\_A0 (J8.12) matches the signal I20\_A0 (set by S1.1) and the signal CAPE\_A1 (J8.11) matches the signal I20\_A1 (set by S1.2). If the addresses do not match, signals SPI\_SCLK and SPI\_MOSI still reach the TLC5928 device, but they have no impact because the SPI CS stays high. More importantly, the address logic assures that only one TLC5928 drives the SPI\_MOSI at a time.

Driving more than one output may destroy the output buffer of a TLC5829 DOUT pin (connected to SPI\_MOSI), and in the worst-case scenario, this damage may be irreversible. See Figure 14 for the implementation in hardware.



Getting Started Hardware

www.ti.com

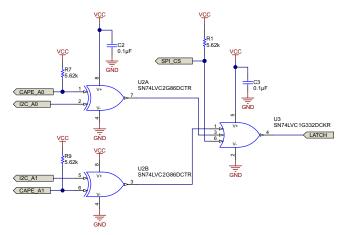


Figure 14. Address Decoder Logic

The full BeagleBone Cape specification is available in the *BeagleBone Black System Reference Manual* [7].



# 6 Getting Started Firmware

### 6.1 Software Flow

A simple program for the MSP430G2553 device has been written to test the design. The program mainly consists of an emulated bidirectional 16-bit SPI as required by the TLC5928 device. All signals are generated using GPIOs to maintain maximum flexibility in pin assignment, timing, and portability. See the following Figure 15 for the software flow diagram.

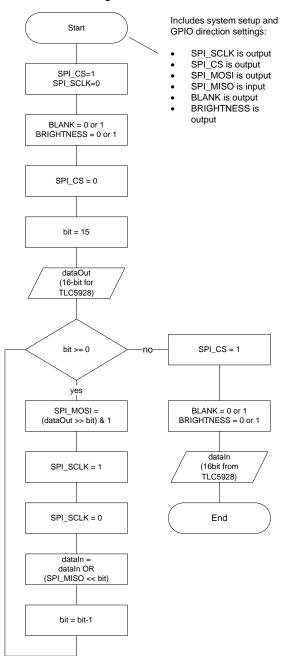


Figure 15. Software Flow (Test Program)

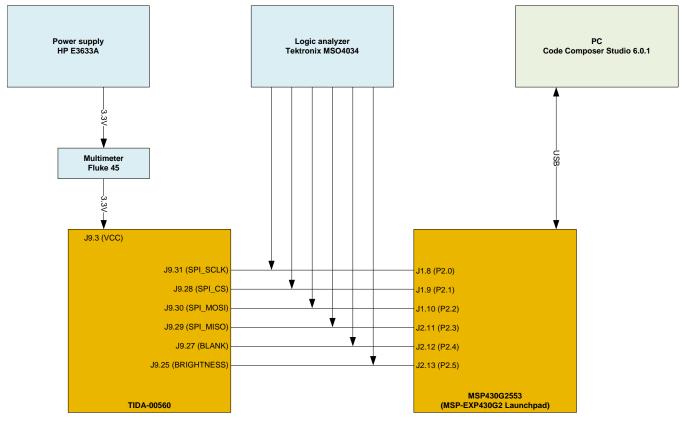


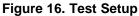
Test Setup

www.ti.com

# 7 Test Setup

Figure 16 shows the test setup.







# 8 Test Data

# 8.1 Normal Operation

Figure 17 shows a standard data feed from the host to the TLC5928 device. This 16-bit standard SPI is supported by most processors. Data bits are sampled and driven at the SCLK rising edge. SCLK idles low if no transfer is performed. The data feed supports data rates up to 35 MHz.

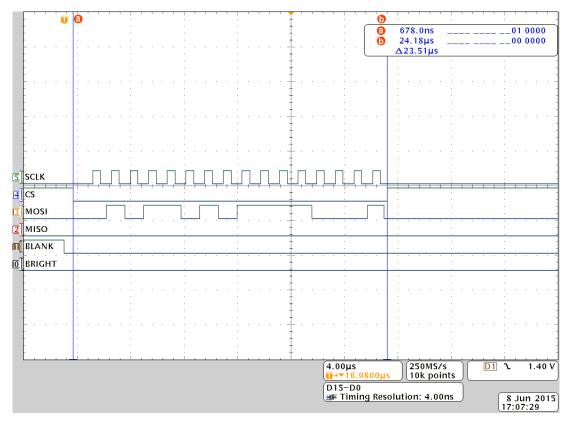


Figure 17. Normal Operation

# 8.2 LED Open and LED Short to GND

This section explains the *LED open* and *LED short to GND* features. To understand how these conditions were simulated, please refer to Section 5.1.4. Table 3 shows the setup of the test (the connection of the LEDs and whether the LED is driven). The LEDs D9 through D16 not mentioned in Table 3 are turned on.

Table 3.	Fault	Simulation—Conditions
----------	-------	-----------------------

DIODE	J1 JUMPER	CURRENT SINK	SIMULATED FAULT	RESULT	COMMENT
D1	J1A.1–J1B.1	On	None	No error	Normal operation
D2	J1A.2–J1B.2	On	None	No error	Normal operation
D3	J1A.3–J1B.3	Off	None	No error	Current sink off
D4	No jumper	Off	Open	No error	Current sink off
D5	J1B.5–J1C.5	Off	Short	No error	Current sink off
D6	J1A.6–J1B.6	On	None	No error	Normal operation
D7	No jumper	On	Open	Fault	Open detected
D8	J1B.7–J1C.7	On	Short	Fault	Short detected



Test Data

www.ti.com

As the TLC5928 data sheet describes, a fault is reported only if the following conditions are met: the current sink is enabled, BLANK is low, and a fault event is detected.

Figure 18 shows the jumper settings that Table 3 describes with the LEDs D3, D4, D5, D7, and D8 turned off.

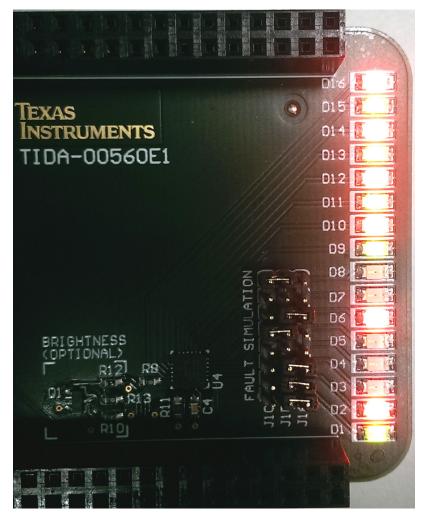


Figure 18. Fault Simulation Evidence

The MISO line reports the condition of each LED through the MOSI line while new data are clocked into TLC5928. Figure 19 describes a fault case using four consecutive transfers; Table 4 describes each transfer in detail.

		· · · · · · · · · · · · · · · · · · ·	· · · · · · · ·			· · · · · · · · · · · · · · · · · · ·			
3 2	MOSI MISO BLANK	· · · · ·						· · · · ·	
Q		· · · · · · · · · · · · · · · · · · ·	· · · · · · · · · · · · · · · · · · ·	· · · · · · · · · · · · · · · · · · ·		- - - - - - -			
		· · · · · · ·	· · · · · · ·		10	.0μs ▼47.6400μs	100MS/s 10k point		λ 1.65 V
					D1	✓47.6400µs 5-D0 Timing Resol			0 Jun 2015

Figure 19. Fault Simulation—Data Transfer

As previously mentioned, the SCLK rising edge drives new data and latches data at the same time. With the last rising SCLK edge of a given transfer, that last status bit (from D1) latches in. After that last status bit is latched in, the TLC5928 device inserts the new value of D16 (latched-in with the first rising SCLK edge of the current transfer) to the MOSI line. This theory is proven by the fact that in transfer 1 this pulse is not present except on all consecutive transfers, where D16 is set high. This behavior has no impact to the host readings because the data changes after the last rising SCLK edge only.

TRANSFER	MOSI	MISO	FAULT SENSING							
1	LEDs off	No fault reported	No fault							
2	D1–D2 on	No fault	No fault (LED data from MOSI updated at rising CS)							
2	D6–D16 on	reported	No radit (LED data non webs) updated at hising 60)							
3	D1–D2 on	No fault	LED faults datasted (faults latebod at rising CS)							
3	D6–D16 on	reported	LED faults detected (faults latched at rising CS)							
4	D1–D2 on	Fault	LED faults detected (latched faults transmitted)							
4	D6–D16 on	reported								

Table 4. Fault Simulation—Data Transfer



Test Data

Figure 20 shows a zoomed-in view of SCLK cycles 8, 9, and 10 of the 4th transfer to show the dependency of the SCLK and MISO edges. The user can observe that the TLC5928 changes to the next data bit value as soon as the hold time is elapsed after the SCLK rising edge, in that an error is reported on the 9th and 10th SCLK cycle. This series of events corresponds to TLC5928 pins OUT7 and OUT6, which are assigned to LEDs D8 and D7. According to Table 3 and Figure 18, the user can expect these pins to report a fault.

1 1 1 1		8		+			0	
- 		· · · · · · · · ·				84.41µs 87.21µs ∆2.795µs		_00 1000 _00 1100
- - - - -	· · · · · · ·	· · · · · · · · · ·						· · · · · · · ·
	· · · · · ·	· · · · · · · · ·	· · · · · · · · · · · · · · · · · · ·		· · · · · · · ·			
SCLK	· · · ·		· · · · · · · · · · · · · · · · · · ·					
[CS								
MOSI MISO						· · · · · · · ·	<u> </u>	
BLANK		· · · · · · ·	· · · · · · · · · · · · · · · · · · ·			· · · · · · · · · · · · · · · · · · ·	· · · · ·	
- 	· · · · ·	· · · · · · · ·	· · · · · · · · · · · · · · · · · · ·			· · · · · · · · · · · · · · · · · · ·		
• •• • • • •			· · · · · · · · · · · · · · · · · · ·			· · · · · · · · · · · · · · · · · · ·		· · · · · ·
L	<u></u>	<u>L. :</u>		D15	<mark>*85.7280µs</mark> 	2.50GS/s 10k points		λ 1.65
				L MF	Fiming Resol	ution: 2.00ns		0 Jun 201 1:45:40

Figure 20. Fault Simulation (Zoomed-In SCLK Cycles 8th–10th)

# 8.3 Brightness

The user can control the brightness of the LEDs in three ways:

- Globally PWM the constant forward current
- Globally adjusting the constant forward current
- Individually toggling the constant forward current of certain LEDs on or off



# 8.3.1 Globally PWM the Constant Forward Current

By asserting the BLANK pin (high) of the TLC5928 device, the user can turn off all of the LEDs simultaneously without involving the serial port (to preserve the latched data). When the BLANK = low, all LEDs are controlled by the supplied data over the serial interface and the set forward current. The user can directly control the brightness of the LEDs by the high-to-low ratio by applying a PWM signal (see Figure 21).

					1	,		1		;	1	;	;			1	,	;			<b>Y</b>	,		,	1	;					,			1							,		٦
	t i			U	1						÷					÷					Ť				1									1									1
	E.							- 1								÷					Ţ													÷									
	ŀ.																				÷																						
										1				1					1	1	-			1					1								1						
	Ľ –				÷.			1			1					1					1				1									1									
	ŀ.																				+																						
	ŀ.										•										÷																		•				-
											÷										1				1									1			•						
	Ŀ.																				4																						
	ŀ.																				÷																						-
	Ľ.,				1			1			1					1					1				1					:				1									
	F.																				1																						
	ŀ.				÷						•					÷					÷																		•				-
	t i				1			1			÷					÷					Ť				1									1									1
	[																				_																						
	ŀ.				·																÷																						-
$\nabla$	t.					 			 							1					1				1									1									1
5	SC	ĽK					ЦŲ														+																						-
		·····		1		 			 					i		-	i		i		+		 	<b>i</b>	-	1	·		-j	-	i-			-		i	···]				i		-
14	CS				1											1					1				2									1					•				1
									_												+																						-
13	IN	osi									-1										+				1									1									-
പ്	M	ISO									Ē										1																						
						 			 		 <u> </u>				_				_		+	_	 					_			-										_		-
ГÌ	ΪBL	AN	К					1			1	Π			Π	1			Π		İ	Π			[			Π						1							Π		
												١Ļ			١Ļ				١Ļ		-				Ļ			ĻĽ			ļĻ				Ļ.,			- <u> </u>			١Ļ		
0	( BF	RIGI	HΤ		÷						•					÷					+				•																		-
-	ţ.					 															1		 																				-
	ŀ.																				÷																						-
	h.,																				-			1					1	•													
	E.							- 1			÷					÷.					Ţ													÷.									
	ŀ.				÷											÷					÷													÷									-
	ŀ.										•										÷									•									•				-
								- 1								÷					4													1									
	ŀ.																				÷																						-
	t -				1			1			1					1					t				1									1									-
					i				<u> </u>		i					i					T		-		i.					<u> </u>				i		<u> </u>							_
																							1	0.	0μs 742	5				16	10	DΜ	S/s oin	;		ĺ	D	4	r		1.6	65 V	1]
																								<b> </b> →`	42	. 8	80	0µ	S	Л	10	k p	oin	its									
																							Ē	)15	i– D	0							0.01		5								Ĩ
																								k	Tin	۱İn	۹I	Res	sol	utio	on:	10	0.01	ns				G	0	lur	1 2	015	5
																							~												_			li	2.1	07.	42	015	1

Figure 21. Brightness Control With Blank



## 8.3.2 Globally Adjusting the Constant Forward Current

Another option to control the brightness is to globally control the forward current of the LEDs. This global control is achievable by connecting a resistor from the TLC5928 pin 20 (IREF) to GND. The value of the resistor sets the current. This TIDA-00560 TI design supports a dynamic change of this resistor value by switching a second resistor in parallel, which in effect, supports two levels of brightness. See Section 5.1.3 for more information.

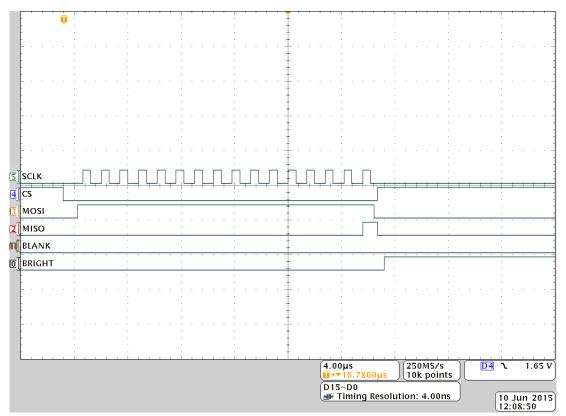


Figure 22. Brightness Control By Changing Forward Current

# 8.3.3 Individually Toggle Constant Forward Current of Certain LEDs On or Off

This TIDA-00560 TI design uses red- and green-colored LEDs. These colors are also widely used in PLC I/O modules. By nature, brightness with the same forward current differs so much that it is noticeable by the human eye. As an example, with  $I_F = 5$  mA, the Wurth Electronic green LED supplies 10 mcd while the red LED supplies 50 mcd. To compensate for that mcd disparity, the user can set SPI data transfers to trigger with a fixed frequency that turns red LEDs on or off while constantly keeping the green LEDs on.



## 8.3.4 Current Consumption

The quiescent current for the board (all LEDs off) is expected to be fairly low. According to the data sheet, the TLC5928 device consumes typically 1 mA when the BLANK = high and  $R_{IREF} = 27 \text{ k}\Omega$ . The measured value with  $R_{IREF} = 25.5 \text{ k}\Omega$  is 0.535 mA. This measured value is a fairly good value given the fact that this number includes the (static) current of the BeagleBone Cape circuitry (EEPROM, logic).

Table 5 shows the current consumption of the entire board with all of the LEDs on with 2 mA or 5 mA for a different  $V_{cc}$ .

V <sub>cc</sub> [V]	I <sub>LED</sub> [mA]	I <sub>cc</sub> [mA]	$\Delta I_{cc}$ [5 mA, 2 mA]
3 V	2 mA	31.69	-
3.3 V	2 mA	31.89	-
5 V	2 mA	33.12	-
5.5 V	2 mA	35.71	-
3 V	5 mA	78.37	46.68
3.3 V	5 mA	79.9	48.01
5 V	5 mA	81.67	48.55
5.5 V	5 mA	82.19	46.48

#### **Table 5. Current Consumption**

The expected current delta between 2 mA and 5 mA for the same  $V_{\mbox{\tiny CC}}$  is:

 $I_{DELTA CALC} = 16 \times 5 \text{ mA} - 16 \times 2 \text{ mA} = 48 \text{ mA}$ 

(4)

The measured current delta for the four different  $V_{cc}$  is in the range of 46.48 mA to 48.55 mA, which is in the expected range.

The current measurement for a single LED (here D1 through OUT0) has been performed for 2 mA and 5 mA. Table 6 shows the results of these current measurements.

Table 0. Current measurement Dr	Table	6.	Current	Measurement	D1
---------------------------------	-------	----	---------	-------------	----

R <sub>IREF</sub> [kΩ]	I <sub>LED_EXPECTED</sub> [mA]	I <sub>LED_MEAS</sub> [mA]	e [%]
25.5	1.976	1.938	1.9
10.16	4.959	4.924	0.7

According to the data sheet, the error tends to get larger at lower currents (maximum 1.5% for 2 mA). With the reference resistor value tolerance of 1%, the results are all in the range of expectation.

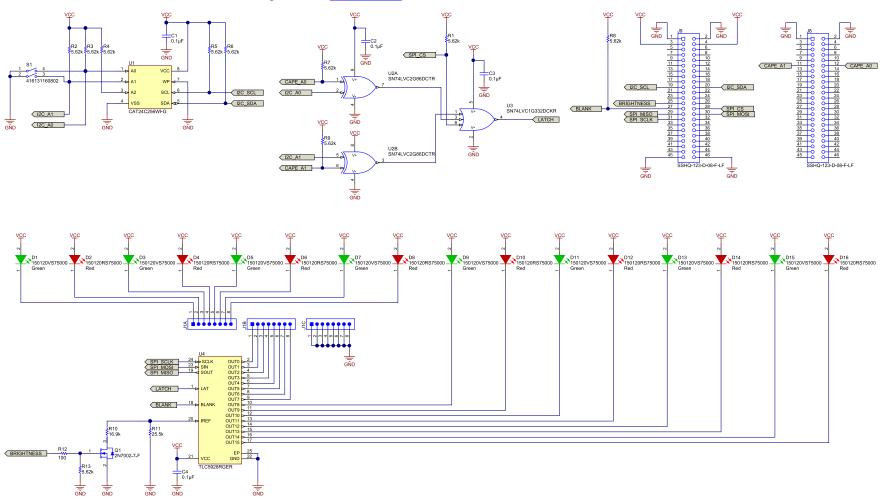


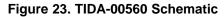
#### Design Files

# 9 Design Files

# 9.1 Schematics

To download the schematic, see the design files at TIDA-00560.







# 9.2 Bill of Materials

To download the bill of materials (BOM), see the design files at <u>TIDA-00560</u>.

# 9.3 PCB Layout Recommendations

# 9.3.1 Layer Plots

To download the layout prints, see the design files at TIDA-00560.

# 9.4 Altium Project

To download the Altium project files, see the design files at TIDA-00560.

# 9.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00560.

# 9.6 Assembly Drawings

To download the assembly drawings, see the design files at <u>TIDA-00560</u>.

# 10 Software Files

To download the software files, see the design files at TIDA-00560.

# 11 References

- 1. Texas Instruments, *16-Channel, Constant-Current LED Driver with LED Open Detection*, TLC5948 Data Sheet (<u>SBVS120</u>)
- 2. Texas Instruments, MIXED SIGNAL MICROCONTROLLER, MSP430G2553 Data Sheet (SLAS735)
- Texas Instruments, PCF8574 Remote 8-Bit I/O Expander for I<sup>2</sup>C Bus, PCF8574 Data Sheet (<u>SCPS068</u>)
- Texas Instruments, 8-BIT SHIFT REGISTERS WITH 3-STATE OUTPUT REGISTERS, SN74HC595 Data Sheet (<u>SCLS041</u>)
- 5. Texas Instruments, HDC1000 Low Power, High Accuracy Digital Humidity Sensor with Temperature Sensor, HDC1000 Data Sheet (SNAS643)
- 6. Texas Instruments, AM335x Sitara<sup>™</sup> Processors, AM3359 Data Sheet (SPRS717)
- GitHub.com, BeagleBone Black System Reference Manual Revision B, BeagleBone Black System Reference Manual .pdf (<u>http://bit.ly/1LQWUEI</u>)

# 12 About the Author

**LARS LOTZENBURGER** is a Systems Engineer at Texas Instruments where he is responsible for developing reference design solutions for the industrial segment. Lars brings to this role his extensive experience in analog/digital circuit development, PCB design, and embedded programming. Lars earned his Diploma in Electrical Engineering from the University of Applied Science in Mittweida, Saxony, Germany.

#### **IMPORTANT NOTICE FOR TI REFERENCE DESIGNS**

Texas Instruments Incorporated ("TI") reference designs are solely intended to assist designers ("Buyers") who are developing systems that incorporate TI semiconductor products (also referred to herein as "components"). Buyer understands and agrees that Buyer remains responsible for using its independent analysis, evaluation and judgment in designing Buyer's systems and products.

TI reference designs have been created using standard laboratory conditions and engineering practices. **TI has not conducted any testing other than that specifically described in the published documentation for a particular reference design.** TI may make corrections, enhancements, improvements and other changes to its reference designs.

Buyers are authorized to use TI reference designs with the TI component(s) identified in each particular reference design and to modify the reference design in the development of their end products. HOWEVER, NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY THIRD PARTY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT, IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI REFERENCE DESIGNS ARE PROVIDED "AS IS". TI MAKES NO WARRANTIES OR REPRESENTATIONS WITH REGARD TO THE REFERENCE DESIGNS OR USE OF THE REFERENCE DESIGNS, EXPRESS, IMPLIED OR STATUTORY, INCLUDING ACCURACY OR COMPLETENESS. TI DISCLAIMS ANY WARRANTY OF TITLE AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, QUIET ENJOYMENT, QUIET POSSESSION, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS WITH REGARD TO TI REFERENCE DESIGNS OR USE THEREOF. TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY BUYERS AGAINST ANY THIRD PARTY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON A COMBINATION OF COMPONENTS PROVIDED IN A TI REFERENCE DESIGN. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, SPECIAL, INCIDENTAL, CONSEQUENTIAL OR INDIRECT DAMAGES, HOWEVER CAUSED, ON ANY THEORY OF LIABILITY AND WHETHER OR NOT TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES, ARISING IN ANY WAY OUT OF TI REFERENCE DESIGNS OR BUYER'S USE OF TI REFERENCE DESIGNS.

TI reserves the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques for TI components are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

Reproduction of significant portions of TI information in TI data books, data sheets or reference designs is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards that anticipate dangerous failures, monitor failures and their consequences, lessen the likelihood of dangerous failures and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in Buyer's safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed an agreement specifically governing such use.

Only those TI components that TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components that have **not** been so designated is solely at Buyer's risk, and Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265 Copyright © 2015, Texas Instruments Incorporated