Matrix LED Dimmer Enables Accurate Color Control and Pattern Production in RGBW LEDs

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RGB LEDs are used in projector, architectural, display, stage and automotive lighting systems that require efficient, bright output. To produce predictable colors from an RGB LED, each of its component LEDs (red, green and blue) requires individual, accurate dimming control. High end systems can use an optical feedback loop to allow a microcontroller to adjust the LEDs for color accuracy. Adding a white LED to an RGB LED to produce an RGBW LED extends the hue, saturation and brightness values available in the color system. Each RGBW LED requires accurate dimming of four component LEDs. Two RGBW LEDs require eight "channels."

One way to drive and dim RGBW LEDs is to use four separate LED drivers, one for each color (R, G, B and W). In such a system, the LED current, or PWM dimming, of each individual LED or string is driven by separate drivers and control signals. In this solution, though, the number of LED drivers increases quickly with the number of RGBW LEDs. Any lighting system with a significant number of RGBW LEDs requires a substantial number of drivers and synchronization of the control signals to those drivers.

A much simpler (and more elegant) approach is to drive *all* of the LEDs with a *single driver/converter* at a fixed current, while using a matrix of shunting power MOSFETs to PWM dim the individual LEDs for brightness control. This is the analog equivalent of the transistors in an LCD display, where the number of switches is allowed to multiply while keeping the number of controllers in check. Furthermore, a single communications bus to control the dimming matrix LED makes RGBW color-mixing LED systems relatively easy to produce, while providing a wide color gamut.

The LT3965 matrix LED dimmer enables such a design, as shown in Figure 1. Each LT3965 8-switch matrix dimmer can pair with exactly two RGBW LEDs, allowing control of the individual brightness of each LED (red, green, blue and white) in PWM steps of 1/256 between zero and 100% brightness. Two-wire I²C serial commands provide both color and brightness control to all eight channels. I²C serial code to the LT3965 determines the brightness state of all eight LEDs and can check for open and short LEDs in case of a fault.

MATRIX LED COLOR MIXER WITH LT3952 BOOST-BUCK

The matrix dimmer requires a suitable LED driver to power the string of eight LEDs from a variety of inputs: standard 12V ±10%, 9V–16V (auto) or 6V–8.4V (Li-ion). One such solution is the LT3952 boost-buck[1] LED driver, which both steps-up and steps-down input-to-LED voltage, while providing low ripple input and output current. With little or no output capacitor in its floating output topology, it can react quickly to changes in LED voltage as the individual LEDs are PWM-dimmed on and off to control color and brightness (Figure 2).

The LT3952 500mA boost-buck LED driver shown in Figure 1 pairs with the LT3965 8-switch matrix LED dimmer and two RGBW 500mA LEDs. This new boost-buck topology gracefully operates over the entire range of zero-to-eight LEDs in series, with a voltage of 0V to 25V. The instantaneous series LED voltage changes, determined by which, and how many LEDs are enabled and disabled by the matrix dimmer at any given moment. The 60V OUT voltage of this converter/topology (a sum of V_{IN} and V_{LED}), and the converter duty cycle, are rated for the full input range of 6V to 20V and output range (LED series voltage) of 0V to 25V at 500mA.

This boost-buck floating output voltage topology works well with the LT3965 matrix dimmer. The matrix dimmer controls LED brightness by shunting the LEDs with parallel power MOSFETs.

The LEDs do not need to be connected to ground. As long as the V_{IN} pin of the LT3965 is connected to SKYHOOK, which is at least 7.1V above LED⁺, all of the shunt MOSFETs work properly. SKYHOOK can be created with a charge pump from the switching converter or it can be supplied with a regulated source that is at least

Figure 1. Together with the LT3952 boost-buck LED driver, the LT3965 matrix LED dimmer controls individual colors on two 500mA RGBW LEDs for serial-controlled color and patterns.

D1, D2: DIODES DFLS260
D3, D4, D5: NXP SEMI PMEG6010CEH
L1: WURTH 74437349220 22µH
L2: WURTH 74408943330 33µH
Q1, Q2: ZETEX FMMT591
M1: VISHAY Si2309DS

7.1V greater than the highest expected LED+ voltage (in this case, 20V V_{IN} max plus 25V LED max). The tiny LT8330 boost converter in a 3mm × 2mm DFN is a good choice to generate SKYHOOK.

An optional external clocking device is used to synchronize the system at 350kHz, which is suitable for automotive environments, relatively efficient and allows the use of compact components. Although this system could just as well run at 2MHz (above the AM band), 350kHz (below the AM band) enables this boost-buck converter to regulate without pulse-skipping when all LEDs are shorted by the matrix dimmer and the LED string voltage drops to 330mΩ • 500mA • 8 = 1.3V. This frequency also supports high dimming ratios without visible LED flicker.

Since each RGBW LED is designed as a single point source, the red, green, blue, and white light combine to produce color variety, with saturation, hue, and brightness control. Each LED can be set in 1/256 steps between zero (0/256) and 100% (256/256). The matrix dimmer
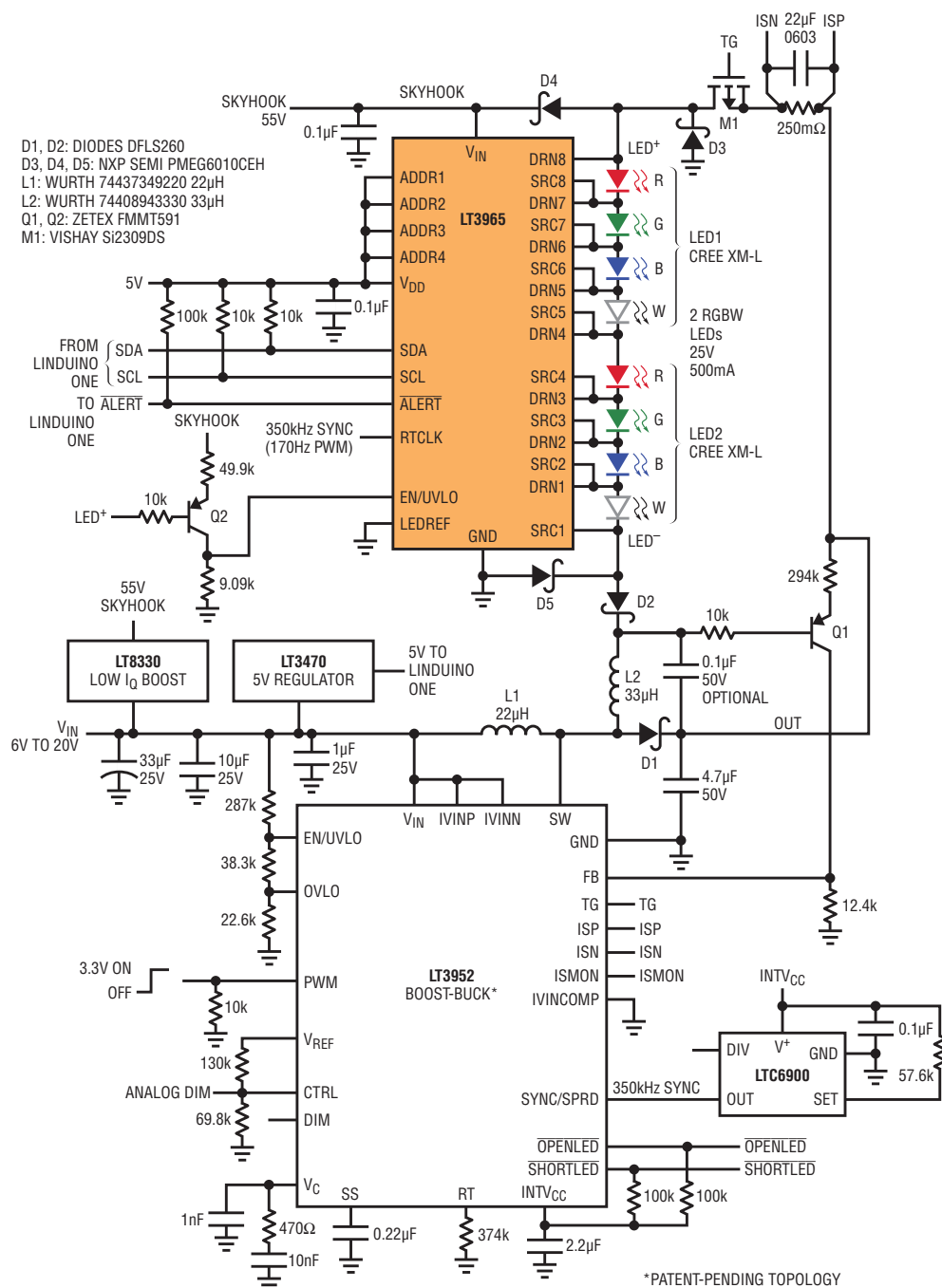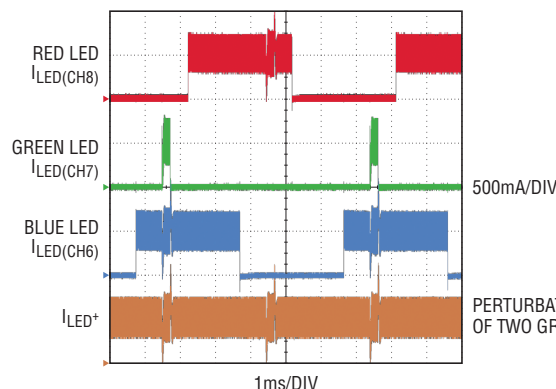
Figure 2. The RGBW 500mA LED currents are PWM dimmed and phased by the LT3965 matrix dimmer to create colors and patterns. The LT3952 boost-buck converter/LED driver easily keeps up with the rapid changes in LED voltage as individual LEDs are PWM dimmed.

RED LED $I_{LED(CH8)}$

GREEN LED $I_{LED(CH7)}$

500mA/DIV

BLUE LED $I_{LED(CH6)}$

I_{LED+}

PERTURBATIONS CAUSED BY PHASING OF TWO GREEN LEDs (ONE SHOWN)

1ms/DIV

SHOWN:
RGBW LED 1, MATRIX CH8, RED LED CURRENT, 128/256 PWM DIMMING
RGBW LED 1, MATRIX CH7, GREEN LED CURRENT, 10/256 PWM DIMMING
RGBW LED 1, MATRIX CH6, BLUE LED CURRENT, 128/256 PWM DIMMING
LED+ CURRENT

NOT SHOWN:
RGBW LED 1, MATRIX CH5, WHITE LED , 0/256 PWM DIMMING
RGBW LED 2, MATRIX CH4 RED LED, 128/256 PWM DIMMING
RGBW LED 2, MATRIX CH3 GREEN LED, 10/256 PWM DIMMING
RGBW LED 2, MATRIX CH2 BLUE LED, 128/256 PWM DIMMING
RGBW LED 2, MATRIX CH1 WHITE LED, 0/256 PWM DIMMING

An alternative to PWM dimming is to simply reduce the drive current for each LED, but accuracy suffers in this method, allowing only 10-to-1 dimming ratios, and incurring color drift in the LEDs themselves. A matrix approach using PWM dimming outperforms drive-current schemes in color accuracy.

can change PWM dimming levels with or without an internal fade function using a single channel serial command.

ACCURATE 0–256 RGBW COLOR AND BRIGHTNESS CONTROL

RGBW LEDs can produce accurate color and brightness with PWM dimming of the individual component red, green, blue and white LEDs. Individual PWM brightness control can support 256-to-1 or higher

dimming ratios. An alternative to PWM dimming is to simply reduce the drive current for each LED, but accuracy suffers in this method, allowing only 10-to-1 dimming ratios, and incurring color drift in the LEDs themselves. A matrix dimming approach using PWM dimming outperforms drive-current schemes in accuracy of color and brightness.

The bandwidth and transient response of the LED driver (the source of the 500mA LED current) affects the color accuracy. With over 10kHz crossover frequency and little or no output capacitor, the compact boost-buck converter reacts quickly to changes in the number of driven LEDs as the matrix dimmer turns its switches on and off.

To illustrate how important this is to accuracy, red, green and blue LEDs are run separately at different PWM duty cycles and measured for light output with an RGB optical sensor. The results in Figure 3 show uniform slopes of each color from 4/256 to 256/256, with a slight change in slope below that. Of course, red, green and blue LEDs are not perfect in their color, so some color from other bands sneaks out even when only one is driven. Overall, this is a highly accurate system.

Accuracy can be improved down to 1/256 using a very high bandwidth (>40kHz) buck converter version of the LT3952 LED driver, but that involves either the expense of adding another step-up converter to create a regulated, greater than 30V output voltage, or having an input voltage source above 30V. Unless a high level of accuracy at low light is necessary, there is little reason to forgo the boost-buck's versatility, simplicity and compact size by adding an extra converter.

The matrix dimmed RGBW LED color mixer system described here achieves a broad color gamut, as shown in Figure 4. Adding additional colors, such as amber, can expand the gamut. RGBWA LEDs
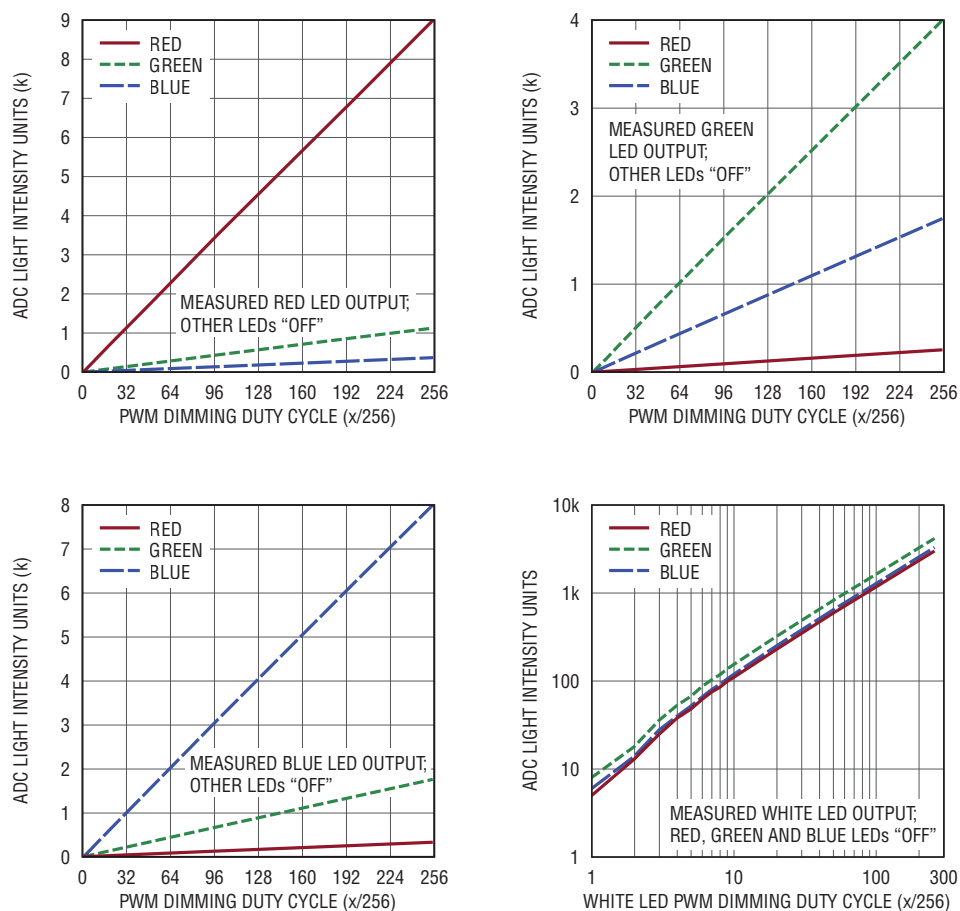
Figure 3. Red, green, blue, and white brightness control versus 0–256 (out of 256) PWM dimming duty cycle controlled by the matrix LED dimmer when paired with the LT3952 boost-buck LED driver in Figure 1.

Figure 4. RGB LEDs feature a wide color gamut. Adding white is one way to simplify the algorithmic mixing of specific colors. In some mixing schemes, white is used to change the saturation, while red, green and blue set the hue.

VISIBLE COLOR GAMUT

RGB COLOR GAMUT
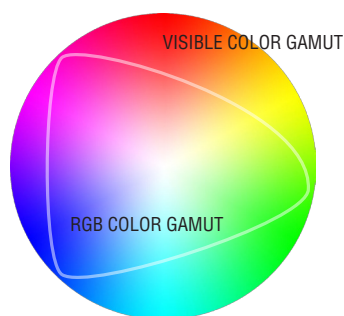
(with an amber LED component) can produce deep yellows and oranges that RGBW LEDs cannot. These LEDs can also be driven with the matrix dimmer, but the eight channels of the matrix dimmer match well to two RGBW LEDs.

The 256-level dimming scheme of the LT3965 easily translates to typical RGB paint programs and common color-mixing algorithms. For instance, if you open a standard PC paint program, you will see that colors are mixed using a 256-value RGB system as shown in Figure 5.

For example, the LED current waveforms in Figure 2 produce purple light from an RGBW matrix LED system controlled by a basic PC-based paint program. Because the design described in this article produces accurate current drive and PWM control, RGBW LEDs can be predictably color-calibrated by adjusting the duty cycles of the component LEDs, easily accounting for inherent variations in LED brightness.

## START-UP SEQUENCE WITH LEDs ON OR OFF

The LT3965 matrix dimmer system can be set to start with all of the LEDs on or off. Starting up with all of the LEDs off allows them to fade on softly or to start at a programmed color and brightness, such as green-blue at 10% brightness. If all of the LEDs start with full 500mA current before the serial communications begin telling the dimmer what to do, then full bright "white" light may be observed before serial communications start.

Figure 5. Colors can be chosen using a standard PC-based color picker. The 0–256 values used by the matrix dimmer can be related to the 0–255 values used in typical RGB systems. For instance, RGB(128,10,128) produces a purple hue. As can be seen in the photograph below, the matrix dimmer can produce predictable colors with a real RGBW LED, simplifying the work of a lighting designer.
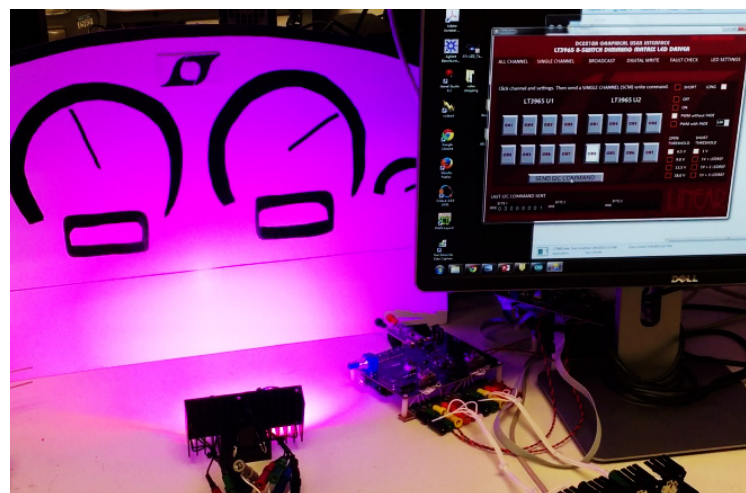
Choose a color.
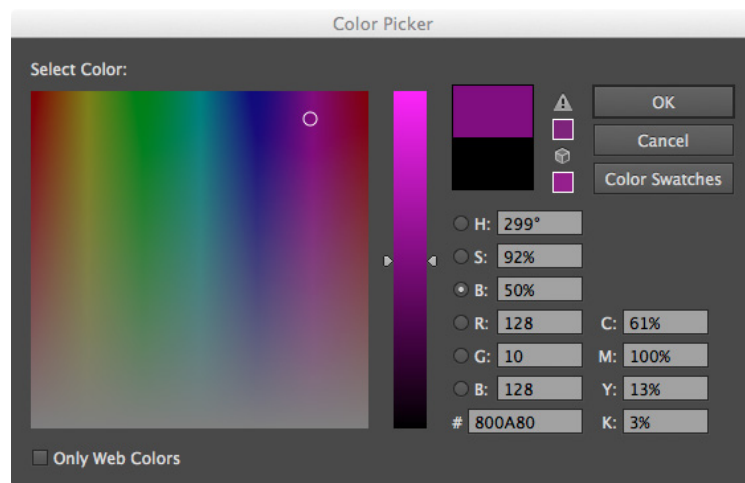
The RGB values correspond to the LT3965 LED matrix dimming ratios.
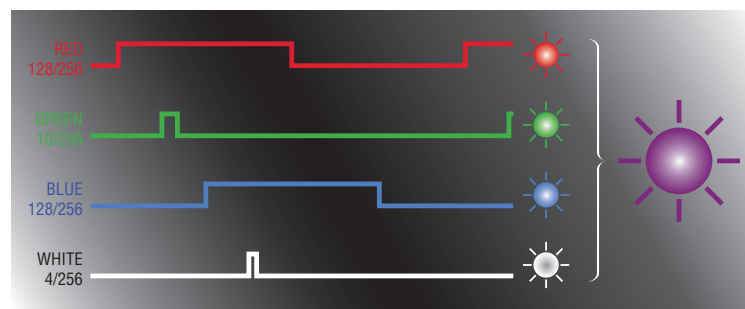
Use your PC to set the dimming values, and see the results.

Each LT3965 8-switch matrix dimmer can pair with exactly two RGBW LEDs, allowing control of the individual brightness of each LED (red, green, blue and white) in PWM steps of 1/256 between zero and 100% brightness. A versatile 500mA LED driver, such as an LT3952-based boost-buck,[1] can be used to drive the LEDs.

With either start-up method, the LT3965 should be powered up before it receives I²C serial communications, or the initial communications may be lost when it performs a power-on reset (POR). The POR occurs when the EN/UVLO pin crosses above the 1.2V threshold. Since this voltage is based on SKYHOOK being at least 7.1V above LED⁺, this can occur at any time after a high SKYHOOK voltage is applied, such as 55V from a small boost regulator, or it can happen after a charge-pumped voltage from the LT3952 switch node is high enough to create SKYHOOK. In the case of a charge-pumped SKYHOOK, the LED current may be present before the charge-pumped SKYHOOK, so the LEDs light up before the LT3965 switches can turn the LEDs off. This is a simple solution for a designer who would like the LEDs to turn on full brightness to start.

To start the LEDs off, SKYHOOK must be present at a high voltage before the LT3952 is turned on. As shown in Figure 6, if the PWM pin is held low during start-up, the LT3952 will not start up until it is commanded to do so by an external source, such as the master microcontroller. The microcontroller can send I²C setup commands to the LT3965 once SKYHOOK is present and set up its switches to the LED OFF position before current is flowing to them. Then, after setup, the LT3952 PWM can be asserted and the current begins to flow through shorted LT3965 switches, with the LEDs off. After this, a fade start can occur, or the LT3965 dimmer can jump to a particular color or brightness.

Figure 6.   Start the matrix LED dimmer color mixer with all of the LEDs off using this sequence.
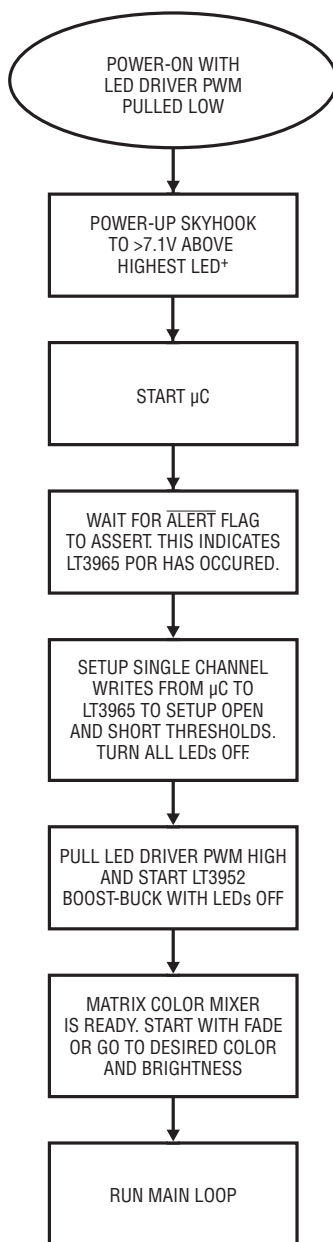
Upon a reset, the PWM of the LT3952 must be pulled low again to turn it off and restart in the LEDs off position. In the case of Figure 1, a simple micropower boost such as an LT8330 can supply 55V from the 6V–20V input. The microcontroller receives a signal that LT3965 is powered up and ready to receive serial communications by asserting the ALERT flag. Before any of the switches are shorted out, zero current through the LEDs shows up as zero voltage across the switches—interpreted as, and reported as, a short-circuit fault. Only after the LT3965 is powered up by SKYHOOK, is the flag asserted.

CONCLUSION

The LT3965 matrix LED dimmer can be paired with the LT3952 boost-buck converter to form an accurate-color RGBW LED color mixer system. It can be used to drive two RGBW LEDs at 500mA with 350kHz switching frequency from a 6V to 20V input. This versatile system can be powered with automotive batteries, 12V power or Li-ion batteries.

High color accuracy results from the fast transient response of the patent-pending boost-buck LED driver topology and predictable dimming control via the 256:1, I²C-controlled matrix system. It can be set up to start up with all of the LEDs off and can fade to start or jump to a particular color. Although not required, optical feedback (via microcontroller) can be added to improve color accuracy. ■

NOTES
1 patent-pending topology