

IN THIS ISSUE

**CAN bus transceivers
operate from 3.3V or 5V
and withstand $\pm 60V$ faults**
13

**low power IQ modulator
for digital communications**
20

**low profile supercapacitor
power backup with input
current limiting** **25**

**boost 12V to 140V with a
single converter IC** **30**

Control Individual LEDs in Matrix Headlights with Integrated 8-Switch Flicker-Free Driver

Keith Szolusha

LEDs combine design flexibility with practical, robust circuitry, enabling automotive designers to produce striking headlight designs matched by exceptionally long life and performance. Automobile designers are increasingly incorporating LEDs in lighting because they can be arranged in distinctive eye-catching designs—helping distinguish new models from old, or high end from economy.

There is no question that automobile LED lighting has arrived, but it has not yet reached its full potential. Future models will feature more LED lights, including new shapes and colors, and more

control over the individual LEDs. Simple strings of LEDs will give way to *matrices* of LEDs that can be individually dimmed via computer control, enabling unlimited real-time pattern control and animation. The future has arrived: Linear Technology's LT[®]3965 matrix LED driver makes it easy to take the next step in automotive lighting design.

I²C CONTROL OF EIGHT POWER SWITCHES WITH A SINGLE IC

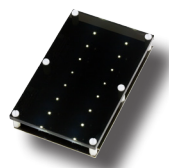
A basic LED headlight design operates with uniform LED current, and thus, uniform brightness. But this leaves much of the LEDs' potential on the table. Matrix headlights take advantage of the innate abilities of LEDs by enabling control of the brightness of individual LEDs within LED strings.

It is not difficult, in theory, to address the individual LEDs in a matrix via computer-controlled power switches, allowing individual LEDs to be turned on or off, or PWM dimmed,

(continued on page 4)



The LT3965: limitless control of automotive matrix headlights and lighting systems



When combined with a suitable constant-current LED driver, the matrix dimmer LED driver allows the individual LEDs to be computer-controlled in headlights, daytime running lights, brake and tail lights, side-bending lights, and other trim lighting.

(LT3965, continued from page 1)

to create unique patterns and functions. Each LED (or segment of LEDs) requires either its own converter or its own shunt power switch. It is possible to build a matrix driver with traditional driver/converter ICs that include a serial communications feature, but once more than two or three switches are needed for a matrix of LEDs, designing a discrete component solution becomes challenging, involving a matrix of components that exceeds the size of the LED matrix.

The LT3965 I²C 8-switch matrix LED dimmer makes it easy to control large or small LED matrices (up to 512 LEDs). Figure 1 shows the LT3965 in action on Linear's demonstration circuit DC2218.

Its highly integrated design (Figure 2) minimizes component count. The individually addressable channels of the LT3965 can be used to control LED matrices in many ways, including:

- Each LT3965 can control eight dimming channels—eight LEDs or eight clusters—within a string of LEDs.
- The eight channels can control the individual red, green, blue and white light on two RGBW LED modules for adjustable brightness or changing color of dashboard or trim lighting.
- Multiple LT3965s can be individually addressed on a single communications bus to multiply the strings in a large array.

- The LT3965 can control multiple LEDs per channel, or channels can be combined to efficiently control a single LED at higher current.

When combined with a suitable constant-current LED driver, the matrix dimmer LED driver allows the individual LEDs to be computer-controlled in headlights, daytime running lights, brake and tail lights, side-bending lights, dashboard display and other trim lighting. The LT3965's built-in automatic fault detection protects individual LEDs in case of a failure and reports failures to the microcontroller.

The 60V LT3965 includes eight integrated 330mΩ power switches, which can be connected to one or more LEDs. The power switches act as shunt devices by turning off or PWM dimming the LEDs on a particular channel. The switches create eight individually controlled brightness channels (up to 256:1 dimming ratio) and eight fault-proof segments of an LED string.

The LT3965 can handle a string current of 500mA when all eight power switches are on at the same time (all LEDs off). The switches can be connected in parallel and run at 1A through four channels of LEDs as shown later in this article. Regardless of the number of LEDs or current, the LED string must be driven by a properly designed converter that has the bandwidth to handle the fast transients of the matrix dimmer. Some reference designs are included in this article.

LT3797 BOOST-THEN-DUAL-BUCK MODE DRIVES TWO STRINGS, 16 LEDs AT 500mA WITH TWO LT3965s

The eight shunt power switches of the LT3965 control the brightness of eight channels of LEDs at 500mA. The string voltage of the 8-LED matrix dimmer system can be between 0V and 26V, depending on how many LEDs are on or off at a given time. The recommended converter topology to drive these LEDs is a 30V step-down converter with high bandwidth and little or no output capacitor. This step-down topology requires that 9V–16V automotive input is “pre-boosted” to a 30V rail from which the step-down regulators can operate.

The triple output LT3797 LED controller conveniently serves as a single-IC solution for both the “pre-boost” and step-down functions—it can be configured as a step-up voltage regulator on one channel, followed by step-down LED drivers on the other two channels. Each of two step-down LED drivers can drive a string of matrix-dimmed LEDs. This topology has a number of advantages, most notably, regardless whether the LED string voltages are above or below the battery voltage, the circuit continues to function optimally.

Figure 3 shows the schematic of the demonstration board shown in Figure 1, a boost-then-dual-buck mode LT3797 and LT3965 matrix dimming headlight system with 16 LEDs at 500mA. Each LED can be individually controlled to be on, off or PWM dimmed down to 1/256 brightness. The 350kHz switching frequency of the LT3797 is outside the AM band (good

Demonstration circuit DC2218 features a complete matrix LED dimmer system with LT3797 boost-then-dual-buck mode LED drivers and two LT3965 matrix dimmers that drive 16 LEDs at 500mA from a car battery. The board operates a matrix headlight with an attached I²C microcontroller via DC2026, the Linduino One demo circuit.

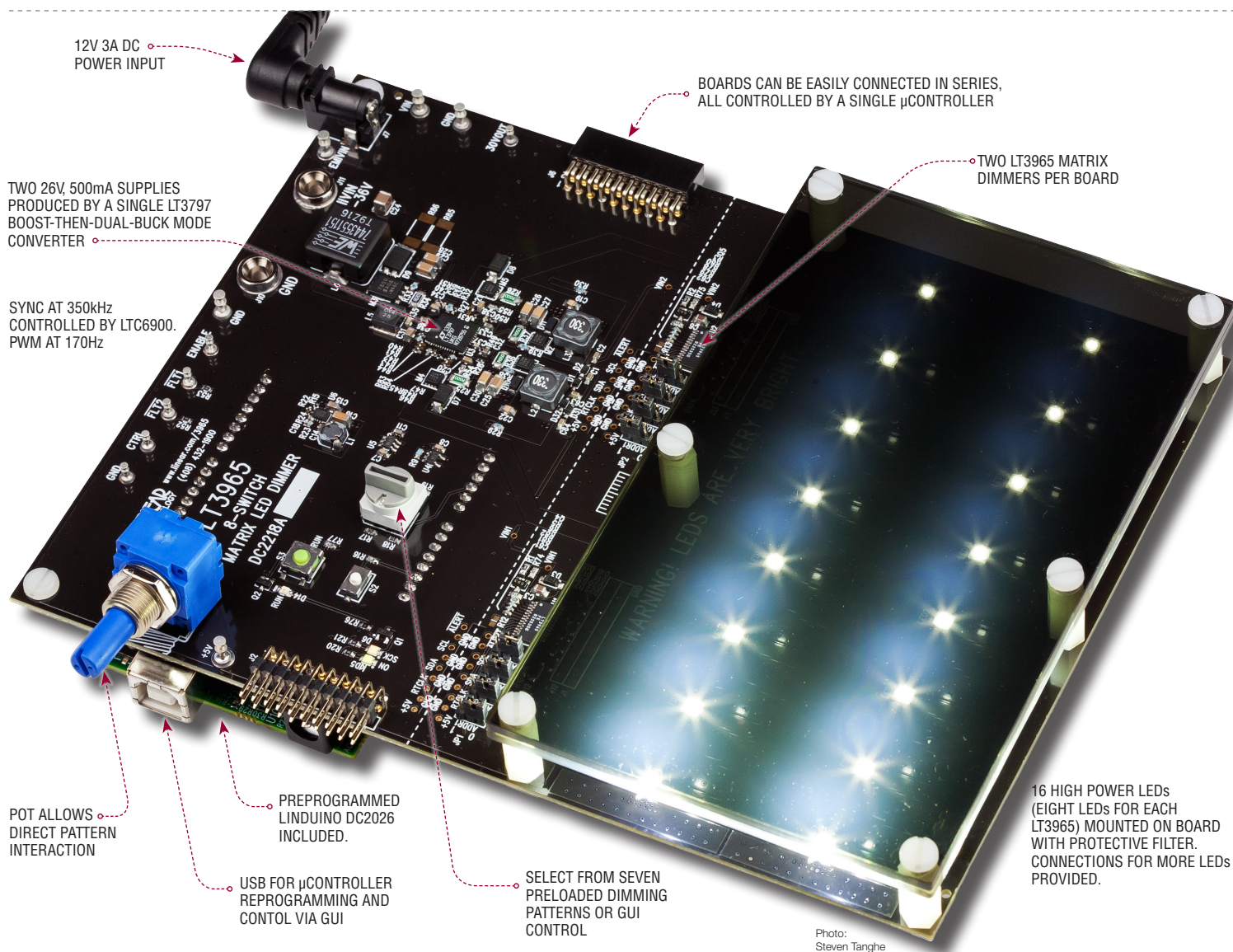
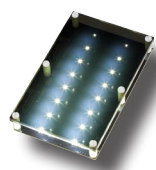


Figure 1. LT3965 LED matrix dimmer demonstration circuit DC2218 run as a Linduino™ shield (DC2026). This demonstration circuit runs headlight, turning light, tail light and trim patterns and can be evaluated with Linear's graphical user interface via a USB cable.

for EMI) and the resulting 170Hz PWM dimming frequency of the LT3965, generated from the same 350kHz clock, is above the visible range. With the system properly synchronized, the LT3797 and LT3965 matrix headlight operates flicker-free.

The LT3797 buck mode converters are optimized for extremely fast transients with little or no output capacitor and properly compensated control loops. These >30kHz bandwidth converters tolerate fast LED transients as the LEDs are turned on

and off and PWM dimmed at will. A filter capacitor placed on the LED sense resistor replaces a pole in the control system that is lost when the output capacitor is reduced or removed for the fast transient performance of the matrix dimmer.



generates different headlight patterns and interfaces with Linear Technology's graphical user interface (Figure 4).

Within the GUI shown in Figure 4, LED brightness and fault protection functions can be examined with ALL CHANNEL MODE and SINGLE CHANNEL MODE commands, as well as FAULT CHECK read and write commands to check for open and short LEDs. Flicker-free operation, fault protection and transient operation can be examined with this demonstration circuit system. DC2218 can be plugged

directly into a 12V DC source and it can be controlled by a personal computer running the GUI or reprogrammed from a simple USB connection.

1A MATRIX LED DRIVER USING PARALLEL CHANNELS

The LT3965 can be used to drive matrices of 1A LED channels. It is easy to connect the power switches of the LT3965 in parallel so that two power switches split 1A of LED current and each LT3965 controls four 1A channels. One way to use parallel power switches for higher current is to run each of the anti-phase

parallel switches for only 50% of the PWM period. By alternating and running 1A through a single NMOS power switch for half the time, the effective heating is about equal to running 500mA through the same NMOS all of the time.

Figure 5 shows a 1A matrix headlight system using eight LEDs driven by two LT3965s and another boost-then-dual-buck mode LT3797. When PWM dimming, the LT3797 uses a unique 1/8-cycle phasing of the eight switches, as shown in Figure 6. In this 1A matrix system, LT3797 channels are combined in parallel pairs, so

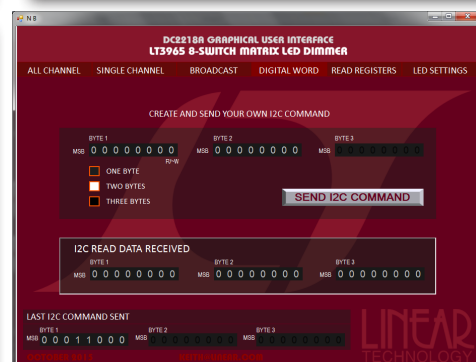
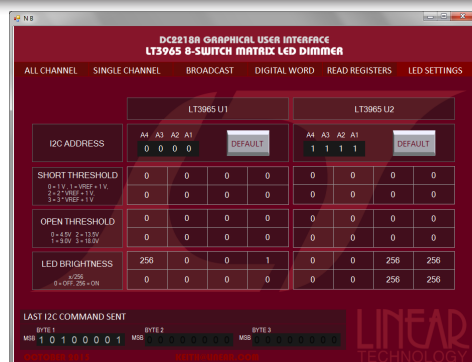
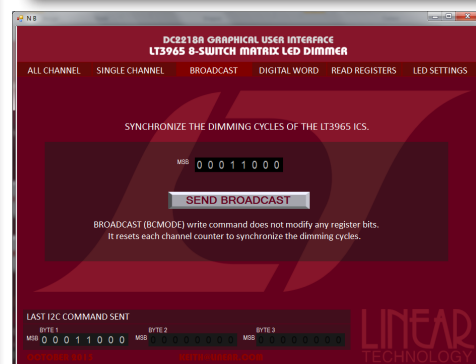
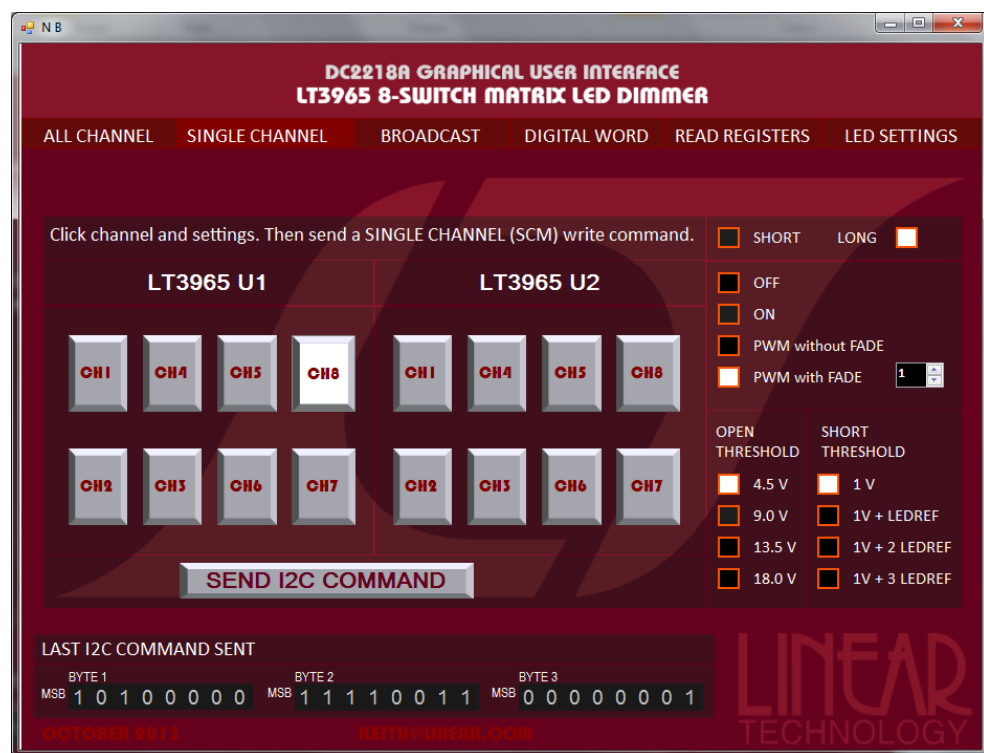
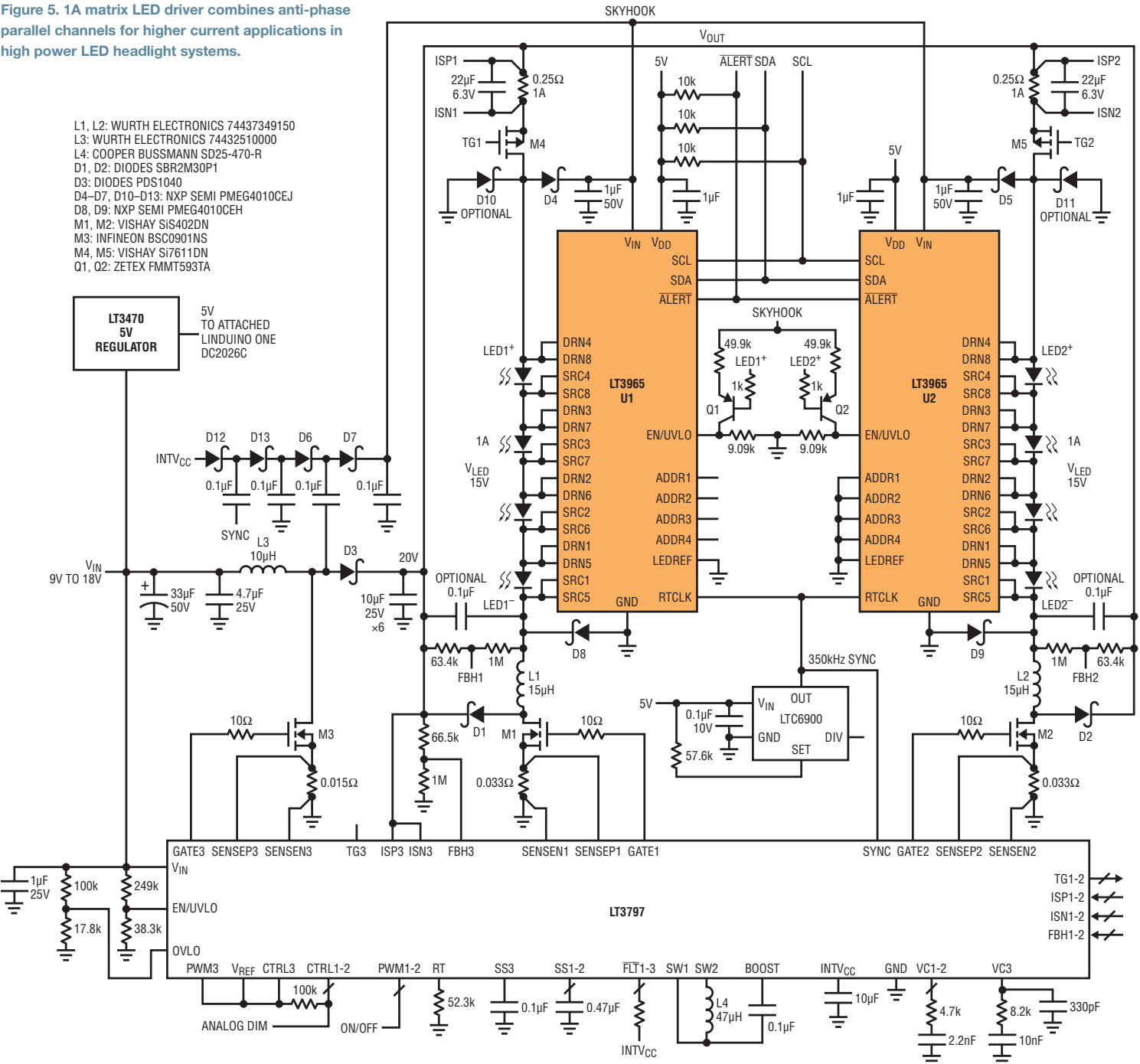
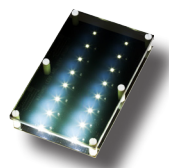


Figure 4. The PC-based interface allows designers to access control and monitoring of the LEDs driven by the LT3965.

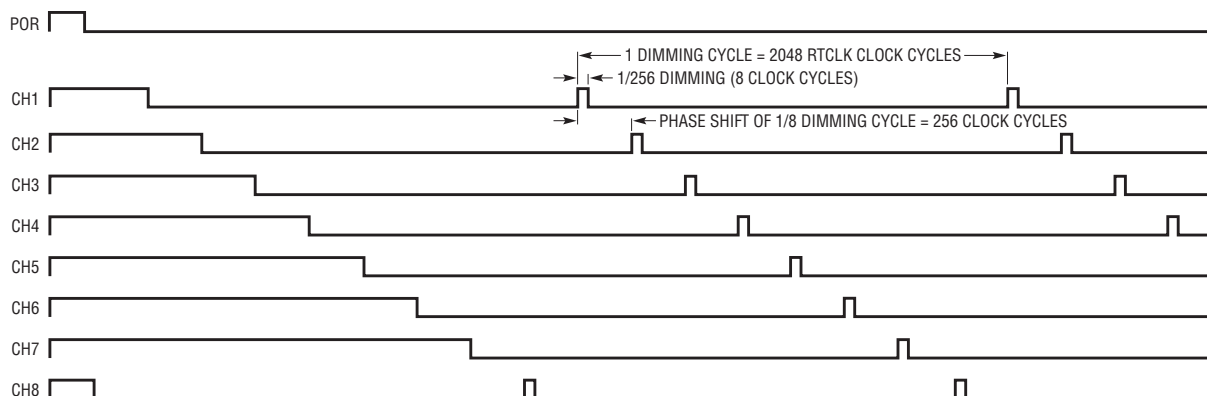
Figure 5. 1A matrix LED driver combines anti-phase parallel channels for higher current applications in high power LED headlight systems.





Turning a high number of LEDs on or off presents a significant current load step to the DC/DC converter. The converters presented here handle these transients with grace, with a small output capacitor and high bandwidth. An ACM write transitioning a high number of LEDs produces no visible flicker or significant transient on the LED current.

Figure 6. 1/8 PWM flicker-free phasing of the eight LT3965 power switches limits transients during PWM dimming brightness control.



that paired channels are anti-phase, 180° from each other; specifically pairing channels 8 and 4, 7 and 3, 6 and 2, and 5 and 1. Parallel channels alternate shunting, effectively doubling the PWM frequency, with the advantage of spreading out the shunted current and heat. For this to work properly, the maximum duty cycle for any single shunt power switch is 50%, because two anti-phase switches that are *on* 50% of the time (each shunting an LED 50% of the time) turns the LED *off* 100% of the time.

Each LT3965 controls the brightness of four 1A LEDs that are driven by two 1A buck mode LT3797 channels (from the LT3797-boosted 20V channel). This high power, robust system can be expanded to power more LEDs with more LT3965s or higher current LEDs with more channels in parallel. It is possible to drive two LEDs per channel at 1A and drive up the power of this flexible headlight system.

MORE THAN ONE LED PER CHANNEL

The LT3965 can support one to four LEDs per channel. Although it can be advantageous to individually control every single LED for fault protection or high resolution patterns, it is not always necessary. Using more than one LED per channel reduces the number of matrix dimmers in a system and is enough to accomplish the patterns or dimming required for some designs. Segments of headlights, signal lights and tail lights can have up to four LEDs with the same brightness. Emergency LED lights can have sets of three and four LEDs that blink and wave with the same pattern.

The circuit in Figure 7 demonstrates a two-LED-per-channel system—it has the same number of LEDs as the circuit in Figure 3, but uses only a single LT3965 matrix dimmer instead of two.

When an I²C command tells the LT3965 to turn on, off, or dim a channel, it affects the two LEDs that are controlled by that channel's shunt power switch. To stay within the voltage limitations of the LT3965, the 16 LEDs at 500mA still need

to be split into two series LED strings as they are in Figure 2. The same LT3797 circuit in Figure 2 can be used, but only a single LT3965 controls the brightness of the two strings. This demonstrates how each NMOS shunt power switch inside the LT3965 can be configured independently of the others, allowing an endless variety of matrix designs.

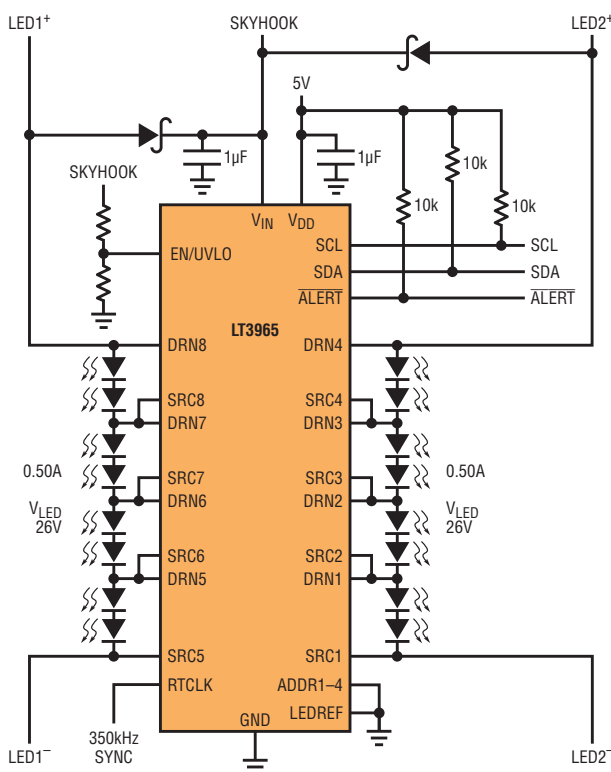
ALL CHANNEL MODE AND SINGLE CHANNEL MODE I²C COMMANDS WITH FLICKER-FREE PWM AND FADE

The I²C instruction set of the LT3965 includes 1-, 2- and 3-word commands. These commands are sent over the serial data line (SDA) alongside the master-generated clock line (SCL) at up to 400kHz speed. The master microcontroller sends all channel mode (ACM) or single channel mode (SCM) write commands to control the brightness, fade, open-circuit threshold and short-circuit threshold of the LED channels and LT3965 addresses.

Broadcast mode (BCM), ACM and SCM read commands request that the LT3965s report the content of their registers,

The LT3965 can support one to four LEDs per channel. Segments of headlights, signal lights and tail lights can have two to four LEDs with the same brightness. Emergency LED lights can have sets of three and four LEDs that blink and wave with the same pattern.

Figure 7. The flexible LT3965 can drive LED channels on independent LED strings and can drive between one and four LEDs per channel. (Complete driver circuit is similar to Figure 3, but with only one LT3956, as shown here.)



including open and short registers for fault diagnostics. The LT3965 asserts an ALERT flag when there is a new fault. The micro can respond to the fault by determining which LT3965 reported the fault, as well as the type and channel of fault. In the case that multiple LT3965 ICs are reporting faults, the LT3965s can sequence fault reporting to the master to prevent overlap errors. This makes the alert response system reliable and conclusive. A complete list of the registers and command set is given in the LT3965 data sheet.

ACM write commands instantly turn all of the eight channels of a single LT3965 address on or off with just two I²C words—the channels transition on

or off at the same time. Turning a high number of LEDs on or off presents a significant current voltage load step to the DC/DC converter. The converters presented here handle these transients with grace, with little or no output capacitor and high bandwidth.

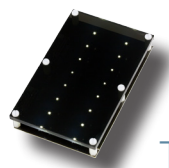
As shown in Figure 8, an ACM write transitioning a high number of LEDs produces no visible flicker or significant transient on the LED current of other channels. The high bandwidth buck mode converter built around the LT3797 is the reason for such a small and controlled transient.

Single channel mode writes produce relatively small and fast single-LED transients. SCM writes are used to set the brightness of only one channel at a time to ON, OFF, or PWM dimming with or without fade. PWM dimming values between 1/256 and 255/256 are communicated in 3-word writes while ON and OFF can be communicated in shorter, 2-word commands. A fade bit on a single SCM write command enables the LT3965 to move between two PWM dimming levels with internally determined logarithmic fade and no additional I²C traffic. The open and short thresholds of each channel can be set between one and four LEDs with SCM write commands.

SHORT AND OPEN LED FAULT PROTECTION FOR EACH CHANNEL

Short- and open-circuit protection is an inherent benefit of the matrix dimmer. Each channel's NMOS power switch can shunt out between one and four series LEDs. Traditional LED strings have protection against the entire string being open or shorted and only some ICs have output diagnostic flags to indicate these fault conditions. In contrast, the LT3965 protects against, *and rides through*, individual channel shorts and opens, keeping operational channels alive and running while recording and reporting the fault conditions.

When a fault occurs within a string, the LT3965 detects the fault and asserts its ALERT flag, indicating to the microcontroller that there is an issue to be addressed. If the fault is an open-circuit, the LT3965 automatically turns on its



Short- and open-circuit protection is an inherent benefit of the matrix dimmer. Each channel's NMOS power switch can shunt out between one and four series LEDs.

Traditional LED strings have protection against the entire string being open or shorted and only some ICs have output diagnostic flags to indicate these fault conditions. In contrast, the LT3965 protects and rides through individual channel shorts, keeping operational channels alive and running while recording and reporting the fault conditions.

corresponding NMOS power switch, bypassing the faulty LED until a full diagnosis occurs or until the fault is removed.

The LT3965 maintains registers of open and short faults for each channel and returns the data to the microcontroller during I²C fault read commands. The command set includes reads that leave the status register unchanged and those that clear the fault registers, allowing user-programmable fault diagnostics. Registers can be read in the various modes allowed for writes, SCM, ACM, BCM:

- Single channel mode (SCM) reads return the open and short register bits for a single channel. SCM reads also check the open and short threshold register, the mode control, and the 8-bit PWM dimming value for that channel.
- All channel mode (ACM) reads return the open and short register bits for all channels of a given address without clearing the bits, as well as the ACM ON and OFF bits for all eight channels.

- In more complex systems with many LT3965 matrix dimmers sharing the same bus, a broadcast mode (BCM) read first requests which, if any, LT3965 address has asserted the fault flag.
- The ACM and SCM reads can be used to check and clear faults *and* to read all of the registers for a robust I²C communications system.

UP TO 16 ADDRESSABLE LT3965s ON THE SAME BUS

Every LT3965 features four user-selectable address bits, enabling 16 unique bus addresses. Every ACM and SCM I²C command is sent to the shared communications bus, but action is only taken by the addressed LT3965. BCM commands are followed by all ICs on the bus. The 4-bit address architecture allows a single microcontroller and a single I²C 2-line communications bus to support up to $8 \times 16 = 128$ individually controllable channels. With the LT3965, for all but the most ambitious lighting displays, all individual LEDs in an automobile's

headlight, tail light and trim lights can be controlled by a single I²C communications bus and a single microcontroller. Given that each channel can be connected to up to four LEDs, one relatively easy-to-implement system can support matrix dimming for up to 512 LEDs.

CONCLUSION

The LT3965 matrix LED dimmer controls eight LED-brightness channels on a single LED string, giving lighting designers unlimited access to sophisticated and striking automotive lighting designs. The I²C communications interface allows a microprocessor to control the brightness of individual LEDs in the string. Fault protection in the I²C interface ensures LED lighting system robustness. The channels of the matrix dimmer are versatile: each channel can control multiple LEDs; channels can be combined to support higher current LEDs; or high LED-count systems can be produced with up to 16 matrix dimmer ICs on the same communications bus. Take the next step in designing automotive headlights, tail lights, front, side, dash and trim lights—the future is now. ■

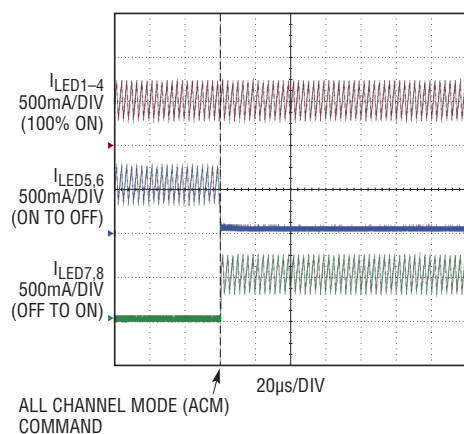


Figure 8. The LED matrix driver designs shown in this article feature minimal to no cross-channel transient effects. For instance, transitioning half the channels—here, simultaneously turning on two and turning off two—has little to no transient effect on the other four, untouched channels. The non-transitioned channels remain flicker free.