

How to Select a RGB LED Driver

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ABSTRACT

This application report describes what key considerations for the user when selecting RGB LED drivers in design. Some basic concepts for RGB LED drivers are also introduced.

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1 Introduction

A single LED can emit monochromatic light in red, green, or blue. These three primary color LEDs together can generate many different colors by adjusting their brightness. By combining multiple LEDs and programming their drivers, vivid and beautiful effects and animations can be performed. Applications in (but not limited to) the industrial, automotive, and personal electronics can achieve dramatic visual effects and better human-machine interfaces by using RGB LEDs.

To select the right driver for the design, the user has several key considerations to decide on:

- What is the LED type, common anode, or common cathode?
- What is the power supply type, line power, or battery power?
- Which dimming method: PWM or analog dimming?
- Is there a special requirement for the communication interface?
- Which topology plan to drive LEDs: direct driving or time-multiplexing driving?
- Is a programmable lighting engine desired?

Some advanced aspects of color mixing are also introduced:

- What are the common indexes to evaluate the optical performance of RGB LEDs?
- How is the color temperature of RGB LEDs controlled?

2 LED Connection Types

A 'common anode' means that the anode connections of RGB LEDs are tied together, as shown in [Figure 1](#). A 'common cathode' means that the cathode connections of LEDs are tied together, as shown in [Figure 2](#). For common anode RGB LEDs, a current-sink LED driver must be used. For common cathode RGB LEDs, a current source LED driver is necessary. In general, common anode LEDs are more popular, as NFET can sink more current than PFET can source in the same area, so a smaller size driver for common anode LEDs can be used for the same current supply. But common cathode LEDs have capability to save more power since they can accurately control the power supply for each LED. Note that common cathode LEDs cannot directly replace common anode LEDs and vice versa, as it connects the LEDs in reverse and causes light emission to not take place.

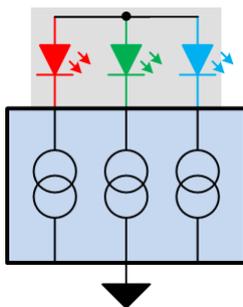


Figure 1. Common Anode LEDs and Current Sink Pair

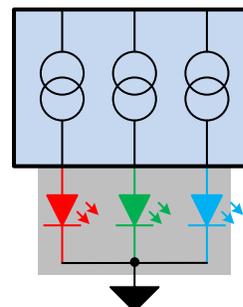


Figure 2. Common Cathode and Current Source Pair

3 LED Power Supply

3.1 Line Supply and Battery Supply

When the power supply comes from DC/DC, USB, or adapter, it is usually called a line power supply. In this case, LED drivers can be connected to the power supply directly, since the supply voltage is larger than V_{LED} . When it comes from battery power, which may be lithium ion batteries or AA batteries, supply voltage is not sufficient enough to power the RGB LEDs. Boost circuitry inside the driver is necessary to achieve the required V_{LED} . Usually, there are two structures to boost the supply voltage: DC-DC or charge pump.

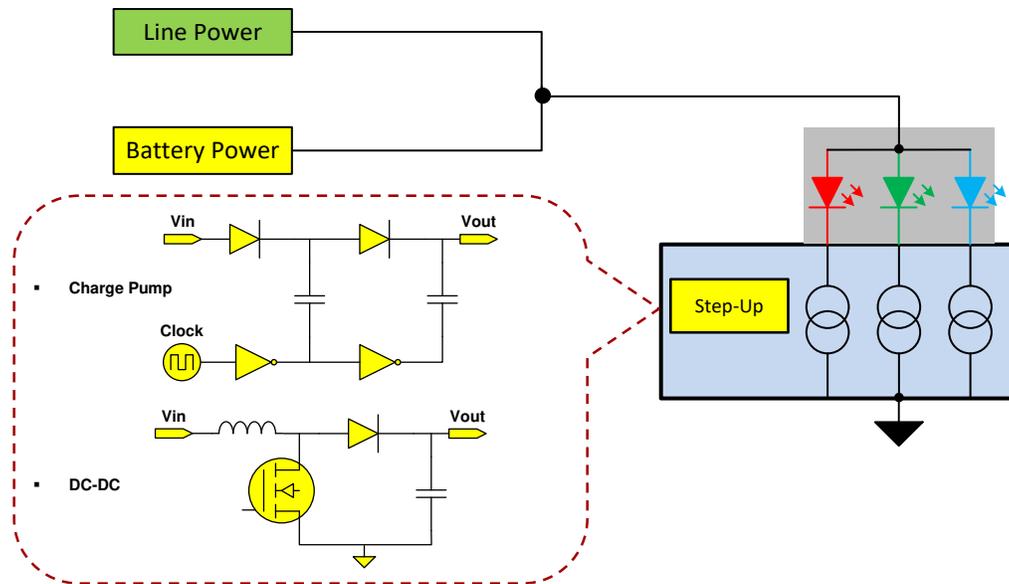


Figure 3. Power Supply Demonstration

3.2 V_{LED} Definition

When it comes to LED driver design, power consideration is important. A common anode LED connection, for example, is shown in Equation 1. The voltage drop on the LED is called LED forward voltage, and the voltage drop on the device channel is called channel output voltage. The LED power supply equals the LED forward voltage plus channel output voltage, as shown in Figure 4.

$$V_{LED} = V_F + V_{OUT} \tag{1}$$

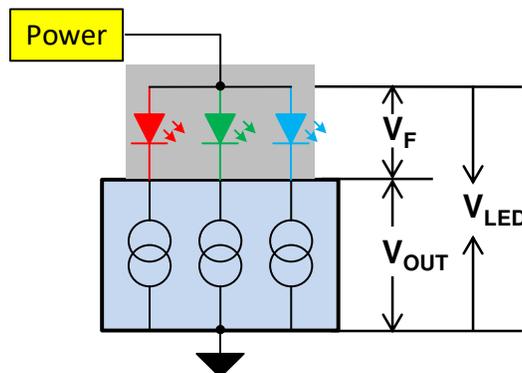


Figure 4. VLED Definition

3.3 The LED Forward Voltage and Headroom Voltage

Forward voltage is positive voltage applied across the anode of the LED to the cathode of the LED. The LED forward voltage is not the same among differently colored LEDs. As shown in Figure 6, the forward voltage of the red LED is smaller than the green and blue, while they are all smaller than white LEDs. The forward voltage also varies across the LED current and bias.

Headroom voltage, which is also called knee voltage, is marked V_{knee} , as shown in Figure 6. If the supply voltage is too small, then the channel output voltage is smaller than the knee voltage, and the current is not able to sink the desired amount. On the contrary, if the supply voltage is too large, the channel output voltage becomes too large and causes too much power consumption.

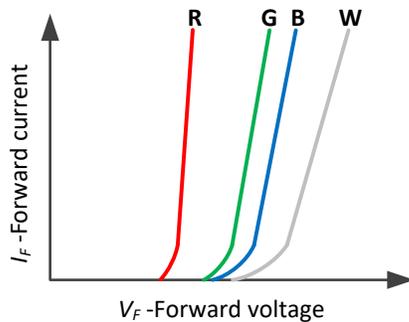


Figure 5. Forward Voltage

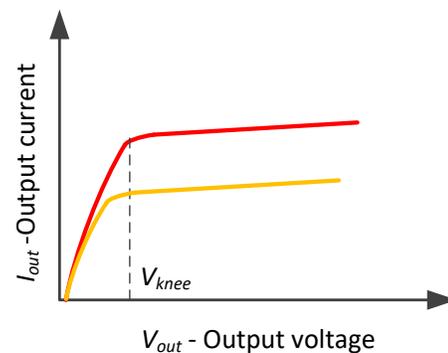


Figure 6. Headroom Voltage

4 Dimming Method

4.1 PWM Dimming and Analog Dimming

PWM dimming and analog dimming are the common dimming methods. Analog dimming adjusts the LED current to change the brightness, while PWM dimming changes the current duty cycle to realize dimming control and keeps LED current constant.

Analog dimming allows simple and easy color calibration. If the user wants to achieve an expected white balance with a certain color temperature, it is easy to make it through RGB LED current adjustment. However, the resolution is limited and usually less than eight bits.

PWM dimming makes it easy to achieve higher resolution up to 16 bits. Since the current is constant when the LED turns on, the color temperature keeps consistent. However, high-frequency PWM pulses cause potential switching noise, like audio noise or flickering, when taking a picture of the LEDs.

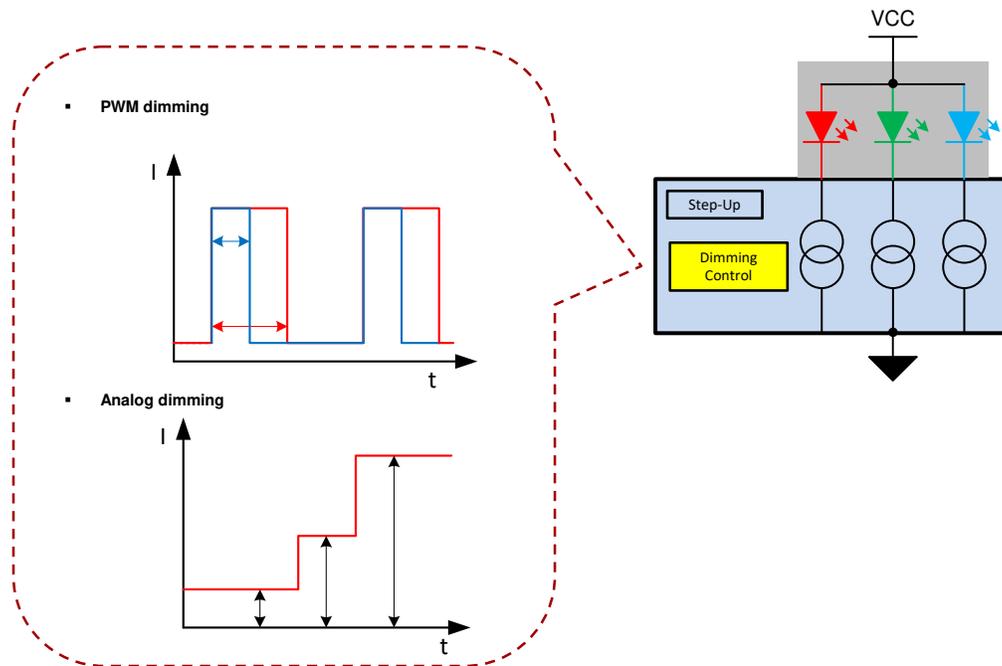


Figure 7. Dimming Method Demonstration

4.2 Color Mix

Figure 8 shows a RGB color model used for RGB LED color mixing based on tri-color theory. The variation of the proportion for RGB colors can result in different colors. Dimming control is easy to visualize since designers always need to adjust the brightness of the LEDs to achieve some effects like breathing, water drop, and so on. If each RGB has an eight-bit value, it can achieve 16.8 million colors. Higher RGB bit values can extend the total color resolution. Usually, the CIE 1931 color space model is used for RGB color mixing, as shown in Figure 9. A detailed introduction of the CIE 1931 model is demonstrated in Section 8.

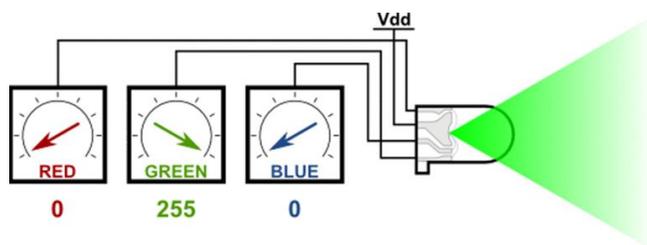


Figure 8. RGB Color Mixing Model

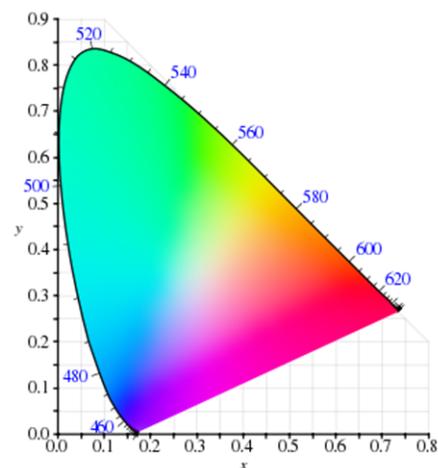


Figure 9. CIE 1931 Color Space Model

4.3 Exponential Dimming

Human perception of brightness is not linear with luminance of the LEDs and is more sensitive at low luminance, which is approximated to a logarithmic curve. So if the linear dimming control method is used, the final perceived brightness is not linear in human perception. That is why exponential dimming is used. The perceived brightness is linear with the actual LED luminance, which is fuller into the human eye.

Figure 10 shows the dimming curve of linear and exponential methods. Usually, both linear and exponential dimming are provided for RGB LED drivers. The user can choose the one that best fits the system.

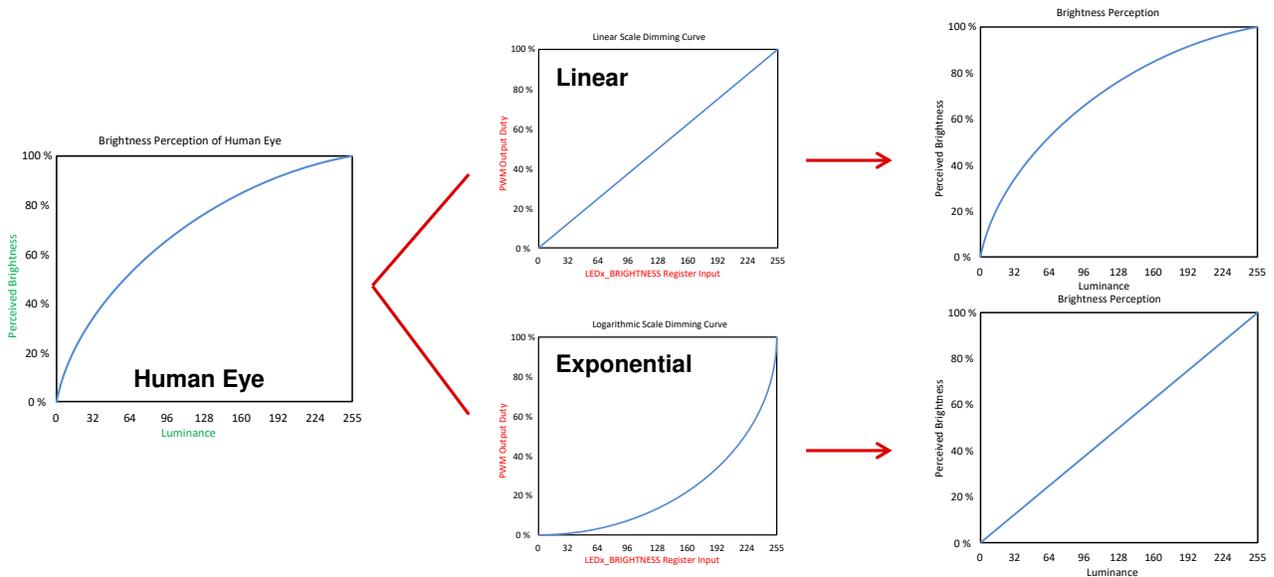


Figure 10. Linear Versus Exponential Dimming Curve

5 Communication Interface

5.1 Protocol Type

To achieve vivid lighting patterns, high-speed communication interfaces between the host micro-controller and LED drivers are very important. There are three common interfaces for selection: I²C, SPI, and single-wire.

I²C is the most popular interface for RGB LED drivers. I²C only has two wires that can jump up to 1 MHz in speed, which makes it a good fit for most applications (including smart speakers and gaming keyboards). If a high-refresh rate or high-volume data is required, serial interface with high communication speed is a good choice. SPI is typically used in industrial applications, such as LED displays. There are also some off-board applications, like architectural illumination, that use LED stripes. A specifically designed single-wire interface might be the right fit for a reliable protocol with minimal wires.

There are also some other restrictions. For example, if LED drivers are needed in cascading to drive large amount of LEDs, the SPI interface is better to use. Sometimes, when small-flex PCBs that require fewer wires are used, a single-wire interface is more suitable.

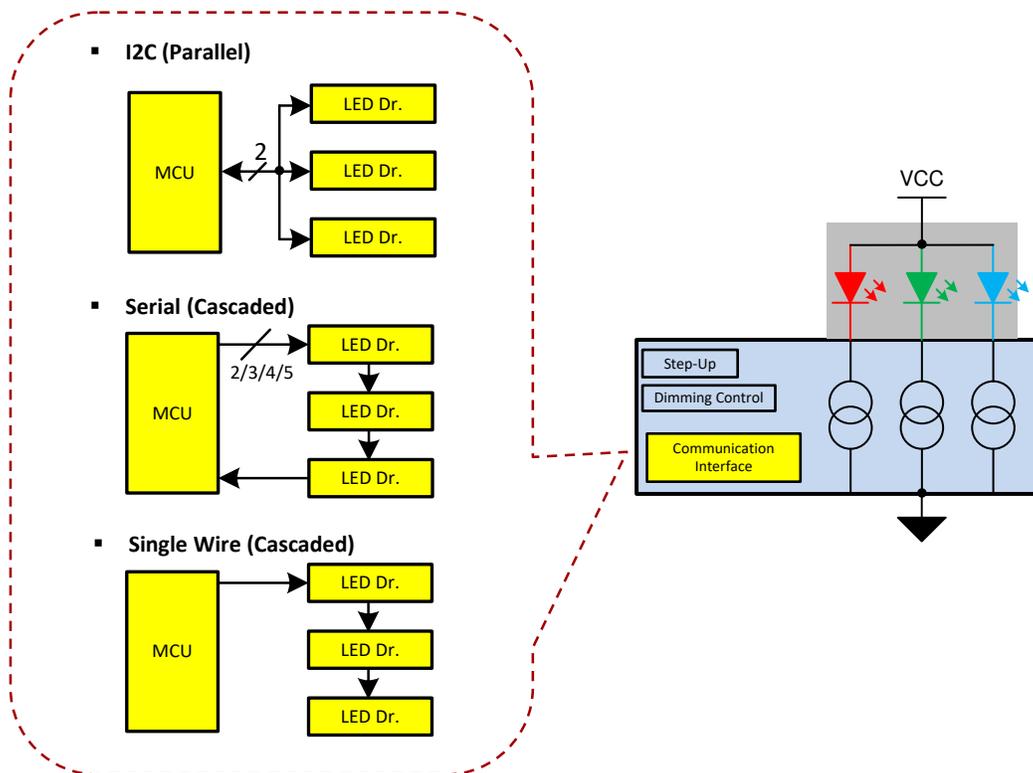


Figure 11. Communication Interface Demonstration

5.2 I²C

I²C uses two wires to control LED drivers, and the data transfer rate is lower than 1 MHz. It can support multiple drivers together in parallel. As the block diagram [Figure 12](#) shows, two LED drivers are driven by a controller through the I²C interface in parallel. It requests at least two wires: SDA and SCL. SDA transmits data, while SCL is used for clock. Different addresses are used to distinguish different drivers.

There are three types of I²C interfaces, according to their maximum SDA frequency. The standard one supports up to 100 kHz, and fast mode I²C supports up to 400 kHz. The fast plus mode I²C can support the fastest frequency, up to 1 MHz.

There are two ways to drive multiple LED drivers. One is using different I²C addresses for each driver and controlling them one by one. For example, address 1 was used to control the first driver, then address 2 for the second one, and so on.

The broadcast address can also be used to control all of the drivers together. For example, if the user wants to control all drivers in the same behavior, a broadcast address ensures all the drivers respond together.

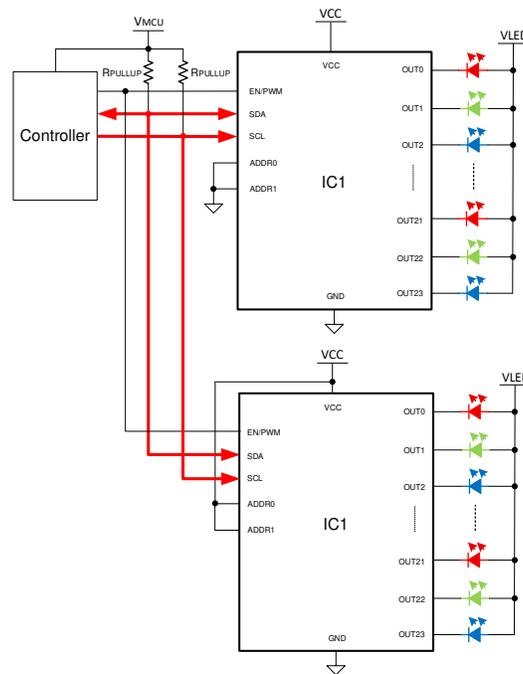


Figure 12. Structure of I²C

5.3 SPI

The data transfer rate of SPI is much higher than I²C, which is up to 35 MHz, so that SPI is suitable for applications that require high-speed data transfer rates. In this scenario, the user can use multiple LED drivers in a cascade to drive all LEDs or LED arrays. Since the data transfer rate is high, large quantities of LED drivers can be used together. Serial interfaces are also suitable to drive time-multiplexing matrix displays.

For example, Figure 13 shows an interface with four wires. SIN is used for data input and SCLK is used in comparison with SIN to shift the data into the driver. LAT is used for latching the data into the internal registers of the driver. GCLK is a clock reference for output PWM signals. For drivers with an internal oscillator, GCLK is not necessary.

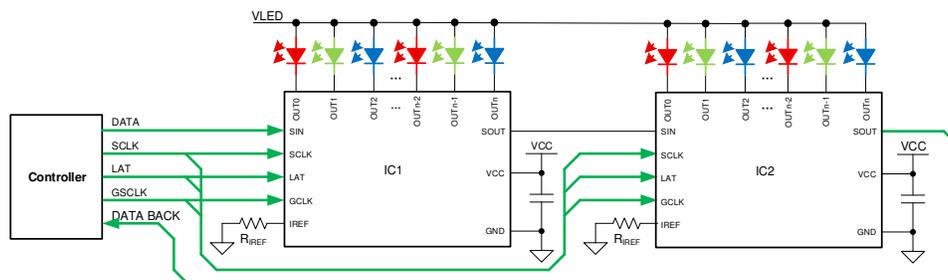


Figure 13. Structure of SPI

5.4 Single Wire

Single-wire interfaces target applications that require multiple LED drivers in cascading, and long signals wires that need to avoid data losses. The maximum data transfer rate for a single-wire interface is 3 MHz. Just as the name implies, single-wire interfaces use one wire to communicate with the host. Drivers have SDI for data input and SDO for output to the next driver, so there are not long signal wires from the controller. To make sure there are no data losses, an internal buffer is necessary. This makes it possible to connect unlimited devices in a series. A single-wire interface can also reduce wire costs and communication failure, making it a great option for applications using a long LED stripe.

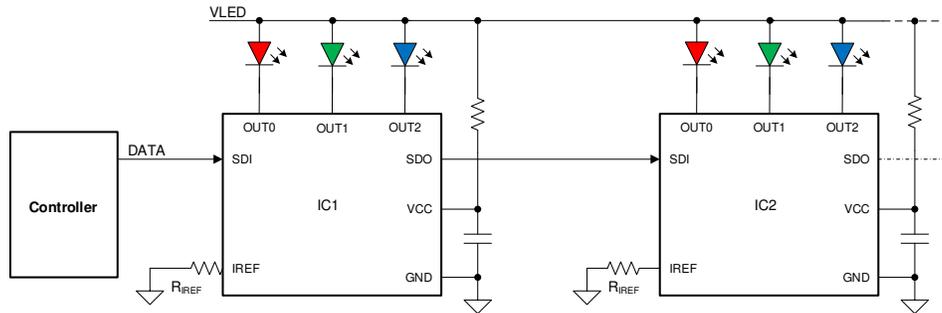


Figure 14. Structure of Single Wire

6 Driver Topology

Direct drive and time-multiplexing drive are two driver topologies for a different count of LEDs. When the LED channel count is less than 100, it is recommended to go with the direct driving method that makes for easy connection and simple control. If the LED channel count is above 100, the time-multiplexing driving method must be considered. It can reduce the device count dramatically with additional Y external FETs and some decode ICs, which can drive X times Y channels in total.

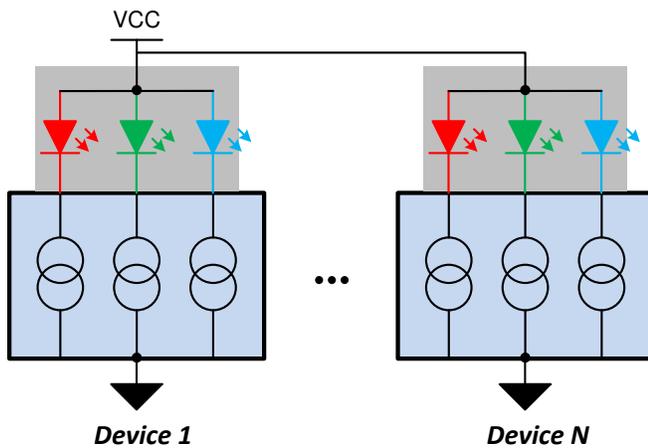


Figure 15. Direct Driving Method

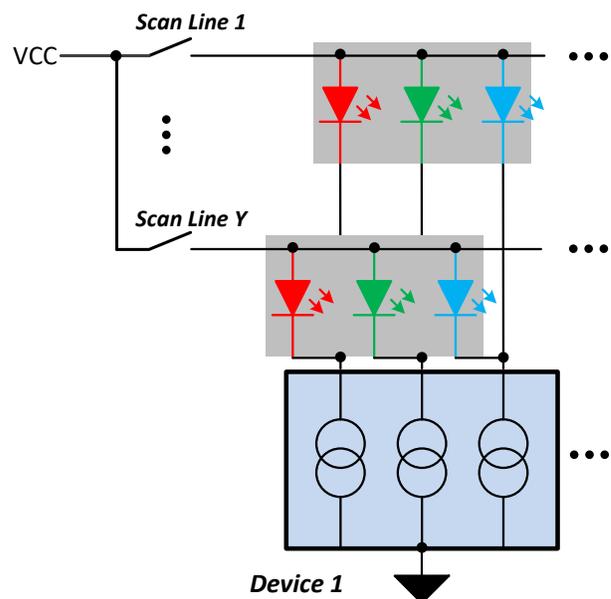


Figure 16. Time-Multiplexing Driving Method

The work sequence of the time-multiplexing LED matrix is introduced as follows: First, signal the first-line switch to turn on this line FET. Then, turn the current sinks in all channels on; the LEDs connected to this line lights up. After turning the channels off, the LEDs of this line also turn off. Next, shut down the first-line FET. Signaling the second-line switch, which turns on the next line FET, then turns on all lines and follows the same sequence. This begins the next period display.

This is not a flawless structure, and it brings a lot of issues. The common issues of the display mainly consist of:

- Dimming and first scan line
- Color shift and low grayscale
- Upper side and downside ghost
- Caterpillar by open LED
- Non-uniformity and low grayscale
- Coupling issues

Fortunately, TI has the technology that can solve these problems and achieve great LED display performance.

7 Autonomous Control

In order to improve the user experience in smart home or other human-machine interaction applications, advanced LED animation effects, like breathing and color changing, are used. However, a common issue is that the MCU becomes overloaded by trying to handle the fancy but complex lighting patterns. To optimize this, TI has a portfolio of RGB LED drivers that provide a unique programmable lighting engine function, which allows the LED driver to operate autonomously without MCU control.

Figure 17 shows an RGB LED driver diagram with a programmable lighting engine. Besides a digital interface and a multi-channel output stage, this LED driver also includes a programmable memory and a command-based pattern generator. This allows for all lighting patterns to be coded as commands, which are stored in the program memory inside the LED driver. When the animation effect starts, the pattern generator compiles the commands and controls the output stage automatically.

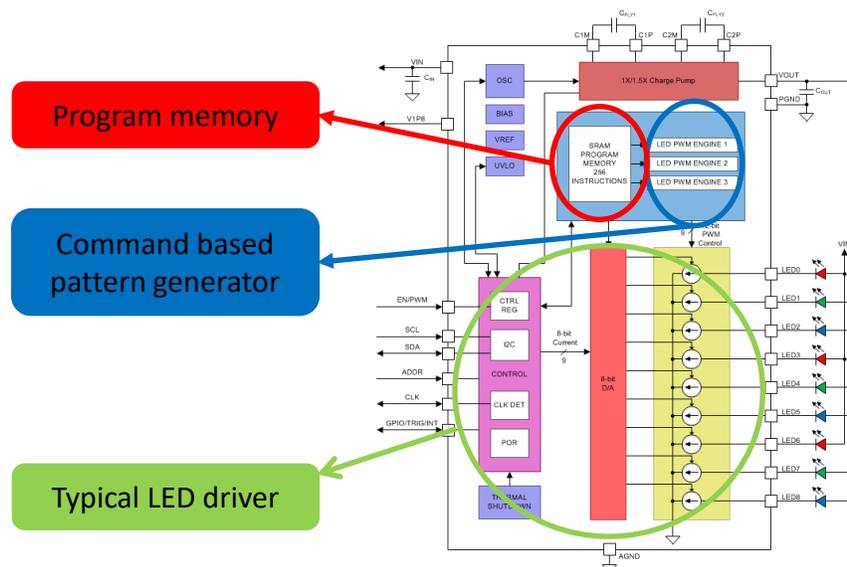


Figure 17. Function Diagram

When playing the animation patterns without a programmable lighting engine, a MCU takes full ownership of controlling the lighting patterns. It causes the MCU to complete the remaining operation and drains system power. With the use of a programmable lighting engine, it becomes a one-time job for the MCU to load the commands into the LED driver. After loading, the LED driver works as a commander to deliver the programmed lighting patterns autonomously while the MCU is sleeping. The lighting engine can be offloaded from the MCU and system-level standby power can be reduced.

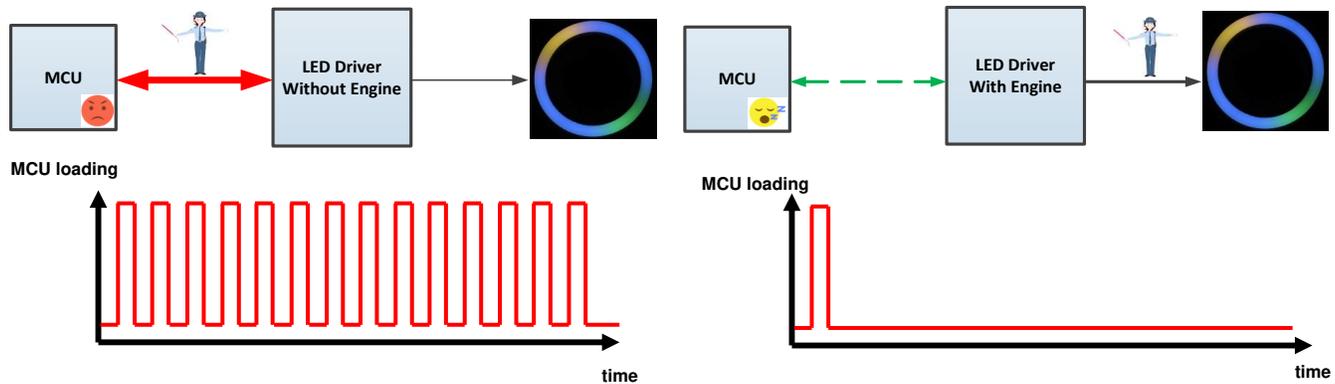


Figure 18. Without Programmable Engine

Figure 19. With Programmable Engine

8 Optical Performance Index

8.1 Introduction to CIE1931 Color Space

As shown in [Figure 20](#), the color matching functions of the CIE are the numerical description of the chromatic response of the observer. They can be thought of as the spectral sensitivity curves of three linear light detectors yielding the CIE tristimulus values X, Y, and Z. The tristimulus values X, Y, and Z can be computed from spectral data with [Equation 2](#), where $S(\lambda)$ represents the relative energy distribution of spectrum of light source. $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ represent color matching functions; λ is the wavelength of the equivalent monochromatic light.

$$\begin{aligned}
 X &= k \int_{380}^{780} S(\lambda) \bar{x}(\lambda) d\lambda \\
 Y &= k \int_{380}^{780} S(\lambda) \bar{y}(\lambda) d\lambda \\
 Z &= k \int_{380}^{780} S(\lambda) \bar{z}(\lambda) d\lambda \\
 k &= \frac{100}{\int_{380}^{780} S(\lambda) \bar{y}(\lambda) d\lambda}
 \end{aligned}
 \tag{2}$$

The tristimulus value Y is defined as luminance, since $\bar{y}(\lambda)$ is roughly analogous to the spectral sensitivity of human cone cells of middle wavelength types. The chromaticity coordinates x and y of the CIE 1931 color space can be derived from three tristimulus values X, Y, and Z with [Equation 3](#).

$$\begin{aligned}
 x &= \frac{X}{X + Y + Z} \\
 y &= \frac{Y}{X + Y + Z} \\
 z &= \frac{Z}{X + Y + Z} = 1 - x - y
 \end{aligned}
 \tag{3}$$

As shown in [Figure 21](#), the derived color space specified by x, y, and Y is known as the CIE xyY color space. It is widely used to specify colors in practice. The tristimulus values X and Z can be calculated back from the chromaticity values x, y, and the Y tristimulus value.

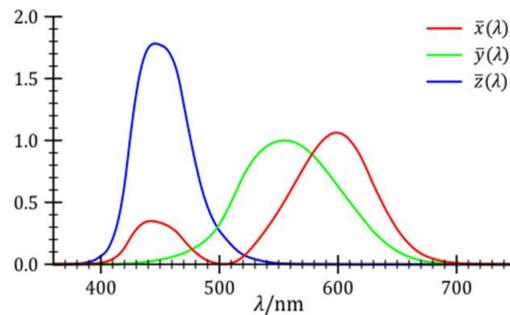


Figure 20. The CIE XYZ Standard Observer Color Matching Functions

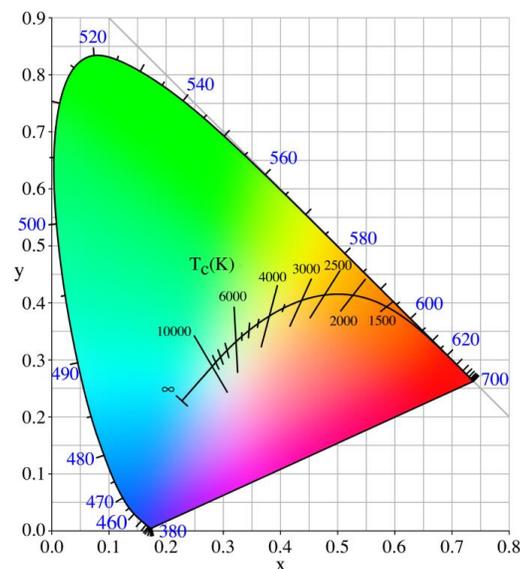


Figure 21. The CIE 1931 xyY Space Chromaticity Diagram

8.2 Color Temperature

The concept of color temperature is widely used in areas of lighting and photography. The color temperature of a visible light source is the temperature of an ideal black-body radiator that radiates light of a color comparable to that of the visible light source. It must be pointed out that the color temperature is only meaningful for light in a range going from red to orange to yellow to white to blueish white, which actually corresponds somewhat closely to the Planckian radiator.

8.3 Correlated Color Temperature

For light source spectra that are not Planckian, the attribute of color temperature is no longer applicable. The concept of correlated color temperature (CCT) was developed to map such sources, as well as possibly the one-dimensional scale of color temperature. The CCT is defined as the temperature of the Planckian radiator whose perceived color most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions.

8.4 Color Tolerance Adjustment

According to the definition of CCT, it can be concluded that multiple chromaticity coordinates can be mapped to a specific CCT. In other words, different colors can have the same CCT value. The line corresponding to equal CCT is shown in [Figure 21](#). In order to describe the color accurately by using CCT, the concept of color tolerance adjustment is usually used in different standards, which defines the difference between the spectrum emitted by the light source and the standard spectrum.

9 Correlated Color Temperature Control

Let (x_i, y_i) denote the CIE 1931 chromaticity coordinates and Φ_i denote the luminous flux of the light emitted by the i_{th} LEDs. The color coordinates (x, y) of light synthesized by N LEDs can be calculated with [Equation 4](#).

$$x = \frac{\sum_{i=1}^N \frac{x_i}{y_i} \phi_i}{\sum_{i=1}^N \frac{1}{y_i} \phi_i} = \frac{\sum_{i=1}^N \frac{x_i}{y_i} \frac{\phi_i}{\phi_N}}{\sum_{i=1}^N \frac{1}{y_i} \frac{\phi_i}{\phi_N}}, \quad y = \frac{\sum_{i=1}^N \phi_i}{\sum_{i=1}^N \frac{1}{y_i} \phi_i} = \frac{\sum_{i=1}^N \frac{\phi_i}{\phi_N}}{\sum_{i=1}^N \frac{1}{y_i} \frac{\phi_i}{\phi_N}} \quad (4)$$

For RGB LEDs ($i = R, G, B$), the corresponding equations can be derived as [Equation 5](#).

$$x = \frac{\frac{x_R \phi_R}{y_R \phi_B} + \frac{x_G \phi_G}{y_G \phi_B} + \frac{x_B \phi_B}{y_B \phi_B}}{\frac{1}{y_R \phi_B} + \frac{1}{y_G \phi_B} + \frac{1}{y_B \phi_B}}, \quad y = \frac{\frac{\phi_R}{\phi_B} + \frac{\phi_G}{\phi_B} + \frac{\phi_B}{\phi_B}}{\frac{1}{y_R \phi_B} + \frac{1}{y_G \phi_B} + \frac{1}{y_B \phi_B}} \quad (5)$$

The CCT of the synthesized light is as [Equation 6](#).

$$CCT = 449A^3 + 3525A^2 + 6823.3A + 5520.33$$

$$A = \frac{x - 0.3320}{0.1858 - y} \quad (6)$$

Since variations of the $(x_i, y_i, i=R, G, B)$ are relatively small, the CCT synthesized by RGB LEDs can be expressed as a function of the flux ratios Φ_i / Φ_B , as shown in [Equation 7](#).

$$CCT = \xi\left(\frac{\phi_R}{\phi_B}, \frac{\phi_G}{\phi_B}, \frac{\phi_B}{\phi_B}\right) \quad (7)$$

Hence, the color temperature can be controlled by adjusting the proportions of luminous flux of RGB LEDs according to [Equation 7](#).

Besides, the luminous flux of light synthesized by RGB LEDs can be calculated by [Equation 8](#) if PWM dimming is adopted, where Φ_{RN} , Φ_{GN} , and Φ_{BN} represent the nominal luminous flux of R, G, and B LEDs at rated current, and D_R , D_G , and D_B represent the duty cycles of each R, G, and B channels.

$$\begin{aligned}\phi &= \phi_R + \phi_G + \phi_B \\ &= D_R \phi_{RN} + D_G \phi_{GN} + D_B \phi_{BN}\end{aligned}$$

(8)

The concrete chromaticity coordinates can be derived from the expected CCT value, and the desired color tolerance adjustment required by different standard according to [Equation 6](#). For a given color (x, y) and the desired luminous flux Φ , the duty cycles can be solved exactly to achieve accurate color temperature control of RGB LEDs according to [Equation 5](#) and [Equation 8](#).

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