Color Mixing Accuracy with EZ-Color™ High-Brightness LED Controllers

AN33640

Author: Ben Kropf
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Associated Part Family: CYxCxxxxx
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Software Version: PSoC Designer™ 4.4 or PSoC Express™ 3.0
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Application Note Abstract

This application note describes some of the factors that affect the color mixing accuracy of high brightness LED systems. You can use Cypress EZ-Color™ High-Brightness LED controllers to control LEDs to create accurate mixed colors.

Introduction

LEDs are becoming increasingly popular in intelligent lighting applications. Many of these applications require highly accurate mixed colors. Achieving this accuracy is difficult because of the varying characteristics of LEDs. A common intelligent lighting application is color mixing, where multiple LED colors are individually dimmed to produce desired mixed colors. Cypress's EZ-Color High-Brightness LED controllers are optimized for achieving high color accuracy in these systems.

EZ-Color High-Brightness LED controllers are not limited to RGB systems. Many combinations of LED colors can be mixed intelligently. For instance, two white LEDs along with an amber LED could form a WWA system that creates many different shades of warm white color.

LED manufacturers sort LEDs into bins, based upon the LEDs' measured flux, color, and forward voltage (V_F) characteristics. This application note discusses how EZ-Color parts are used to correct the large characteristic variances of high power LEDs.

High Power LED Bins

The high power 1W LED manufacturing process makes it necessary to sort LEDs into bins. There are typically three characteristics that are binned.

- Luminous Flux (the amount of light output)
- Chromaticity/Color (the exact color of the light output)
- Forward Voltage (V_F)

Every LED that is ordered should have a set of three bin codes that specify the three characteristics mentioned. This set of bin codes are not likely known until the LEDs are received.

Luminous flux is the amount of light the LED outputs at a rated current and temperature. It is typically measured in lumens (lm). Figure 1 shows an example of how bin codes are associated with flux characteristics.

Figure 1. Flux Bin Codes

Bin Code	Minimum Photometric Flux (lm)	Maximum Photometric Flux (lm)
J	6.3	8.2
K	8.2	10.7
L	10.7	13.9
M	13.9	18.1
N	18.1	23.5
P	23.5	30.6
Q	30.6	39.8
R	39.8	51.7
S	51.7	67.2
T	67.2	87.4
U	87.4	113.6
V	113.6	147.7
W	147.7	192.0
X	192.0	249.6

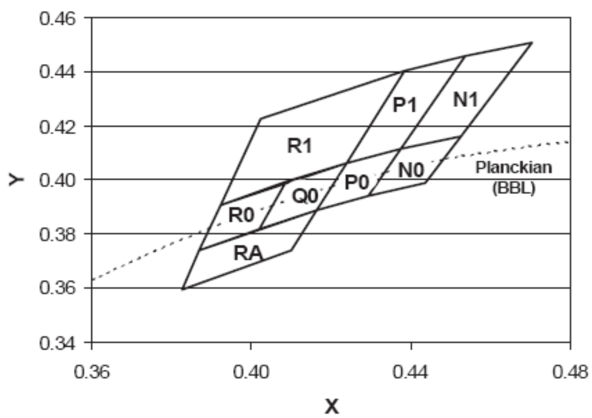
For non-white LEDs, chromaticity is typically specified by the dominant wavelength, measured in nanometers (nm), of the LED light output.

The following figure shows an example of how bin codes are associated with wavelengths. For white LEDs, the chromaticity is typically binned as regions of the CIE 1931 color space. Figure 3 on page 2 shows an example of this method of binning for white LEDs.

Figure 2. Color Bin Codes for non-white LEDs

Bin Code	Minimum Dominant Wavelength (nm)	Maximum Dominant Wavelength (nm)
2	613.5	620.5
4	620.5	631.0
5	631.0	645.0

Figure 3. Color Bin Codes for White LEDs



Because LEDs are binned, some design difficulties occur. LEDs from a particular bin cannot typically be ordered without paying a premium. With reference to Figure 2 on page 2, it is usually impossible to order LEDs from color bin 2. Instead, the LED is ordered and the received packaging specifies that the LED is from color bin 2, 4, or 5. Therefore, the LEDs' color and flux characteristics are not known until the LEDs are actually received. Moreover, if many LEDs are ordered, it is likely that LEDs from multiple bins are received, rather than LEDs from a single bin.

Figure 4 and Figure 5 show how the color mixing gamut of a three-LED system can change for different color bin codes. The LEDs in both systems have the same part numbers, yet the LED color bins are different for the two systems.

Figure 4. Gamut using one set of LED Color Bins

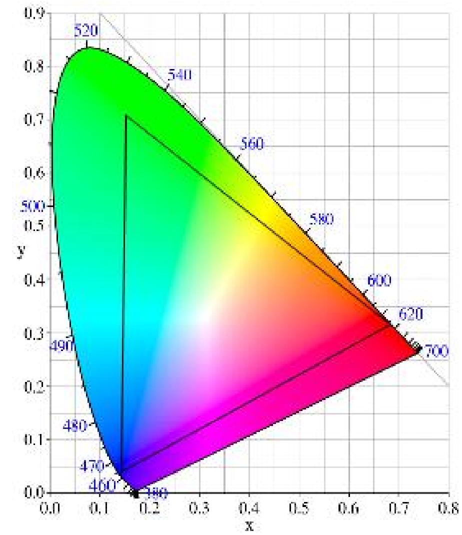
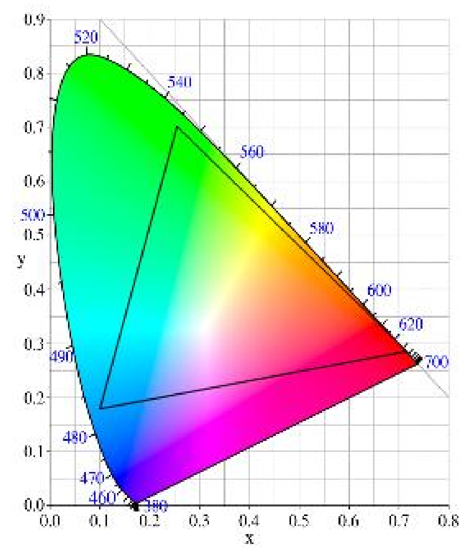


Figure 5. Different Gamut using a second set of LED Color Bins



For high accuracy applications, LED bins have large characteristic variances. With reference to Figure 1 on page 1, the M flux bin has a lumen range from 13.9 lm to 18.1 lm. This is a variability of ±13.1% from the bin midpoint of 16 lm. This variability is a problem in high accuracy color mixing designs.

Color Accuracy

A standard way of specifying color accuracy is with a ∆u'v' value. The CIE 1976 color space (seen in Figure 6) has (u',v') coordinates. This color space is useful because its distances are proportional to the human perception of color. There are standard transformations to convert between (u',v') and (x,y) coordinates (see Figure 7 on page 4). These transformations are shown in Equations 1, 2, 3, and 4.

$$u' = \frac{4x}{-2x + 12y + 3} \qquad \text{Equation 1}$$

$$v' = \frac{9y}{-2x + 12y + 3} \qquad \text{Equation 2}$$

$$x = \frac{27u'}{18u' - 48v' + 36} \qquad \text{Equation 3}$$

$$y = \frac{12v'}{18u' - 48v' + 36} \qquad \text{Equation 4}$$

To determine the color accuracy of a system a target (u',v') coordinate is specified. Alternatively, an (x,y) target coordinate could be specified, but it must be converted to a (u',v') coordinate. After the target color is specified and created, the (u',v') coordinate of the actual output color is measured. The ∆u'v' value is determined from Equations 5, 6, and 7.

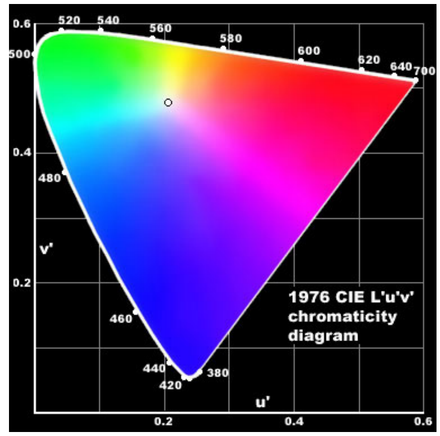
$$\Delta u' = u'_{target} - u'_{actual} \qquad \text{Equation 5}$$

$$\Delta v' = v'_{target} - v'_{actual} \qquad \text{Equation 6}$$

$$\Delta u'v' = \sqrt{\Delta u'^2 + \Delta v'^2} \qquad \text{Equation 7}$$

A ∆u'v' of 0.004 or less is theoretically so accurate that a human cannot differentiate between the specified target color and the actual output color. In other words, the color is so accurate that the color looks perfect to humans. A ∆u'v' of 0.008 or less is a good target accuracy for color mixing applications. However, a suitable ∆u'v' requirement must be determined for each individual application.

Figure 6. CIE 1976 Color Space



Color Mixing

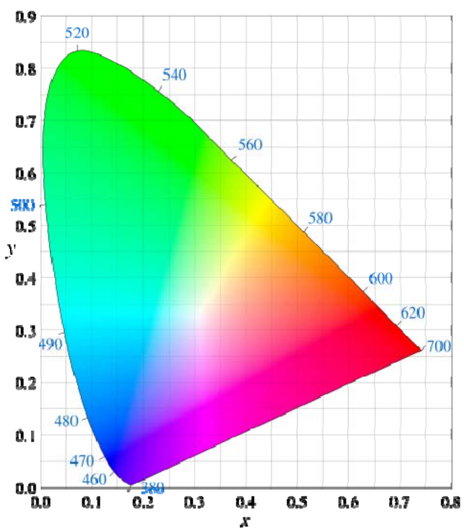
The color mixing system discussed in this application note uses a CY8CLED16 EZ-Color™ controller with LM3402 dimmable constant current drivers. Three Luxeon® K2 LEDs are used (one red, one green, and one blue). Although these are the three LED colors used in this system, similar results could be achieved with any other combination of three LED colors. The red, green, and blue colors are chosen because an RGB system is readily available. PrISM™ dimming signals with 8-bit resolution are used to dim the LEDs. Two firmware projects are used for the EZ-Color™ controller. The first project was generated using the PSoC Express 3.0 graphical embedded design software. The second project was developed using the PSoC Designer code editor software. For more information about the hardware of this system see application note AN15733. For more information about the firmware of this system see application note AN16035. This color mixing system can be evaluated with the CY3261A-RGB Evaluation Kit.

For the EZ-Color™ controller to solve for the correct dimming values that create the specified mixed color, there are certain LED characteristic values that must be programmed into the part. The controller must know the (x,y) coordinates of every color to mix in the system. It must also know the flux of each color in the system when the LEDs are fully on. Determining what to use for these values is discussed in the following sections.

Option 1: Using No Bin Values

It is possible to design a system without taking any LED bin values into account. To do this, the average flux and color values would be used from the LED part data sheets.

Figure 7. CIE 1931 Color Space



Red, green, and blue LEDs are discussed only because they are present in the CY3261A-RGB Kit. Any other three colors LEDs could potentially be used. The assumption is made that there is one LED for each of these colors in the system. The respective K2 part numbers (350 mA versions) chosen for these LEDs are LXK2-PD12-Q00, LXK2-PM12-R00, and LXK2-PB12-K00. The three appending digits of each part number specifies the flux bin of the LEDs ordered (refer to Figure 1 on page 1). The respective typical flux values for these LEDs are 35 lm, 45 lm, and 9.5 lm. The flux values are determined only with information from the K2 data sheet. In this case, LEDs from a particular flux bin can be ordered, but neither the color nor V_F bins can be specified. Therefore, a typical color of 530 nm is used from the K2 data sheet. This wavelength is approximated to have an (x,y) coordinate of (0.1873, 0.7196). Figure 7 shows the CIE 1931 color space where this (x,y) coordinate can be plotted to see the shade of color. By using this approach the values in Table 1 are used for all three LEDs.

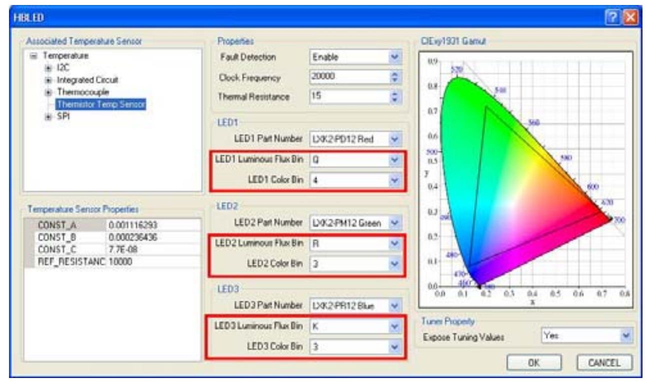
Table 1. LED Characteristics from Data sheet Only

LED	λ (nm)	X	Y	Flux (lm)
Red	627	0.7030	0.2963	35
Green	530	0.1873	0.7196	45
Blue	470	0.1319	0.0680	9.5

Note The wavelength values in Table 1 are obtained from the data sheet. They are converted to (x,y) coordinates by using assumed color purity values. This conversion process is not discussed in this application note.

The LED characteristics are stored in the EZ-Color controller of the system. This is accomplished in PSoC Express by modifying the properties of the color mixing output driver. Figure 8 shows the six dropdown menus that are used to select the bin codes of the three LEDs in the system. This approach does not use bin codes. However, bin code selection properties are used that correspond to the values shown in Table 1. These properties are highlighted in Figure 8.

Figure 8. Color Mixing Output Driver Properties



The board is used to create six target mixed colors. The target (x,y) coordinates and the Δu'v' values are seen in Table 2. It must be noted that the results presented throughout the rest of this application note are obtained when using the firmware generated with PSoC Express. The results when using the firmware developed with PSoC Designer are very similar in all cases. The Δu'v' average in Table 2 is much greater than 0.008, showing that this system is not effective at creating accurate mixed colors. There are only few color mixing applications where this color accuracy is acceptable.

Table 2. Color Accuracy Results when not using LED Bin Codes

Target Color	x	y	Δu' v'	< 0.008?
Neutral White	0.3330	0.3330	0.050744	No
Warm White	0.3823	0.3838	0.038182	No
Cold White	0.2499	0.2548	0.066766	No
Cyan	0.2084	0.3978	0.053903	No
Yellow	0.4192	0.4950	0.030617	No
Magenta	0.4456	0.1944	0.057597	No
		Avg.	0.049635	

Option 2: Using Bin Values

The second design method examined is the use of LED data obtained from the bin code values of the LEDs in the system. As stated earlier, the bin codes are generally known after receiving the LEDs. Also, it is unlikely that LEDs of the same bin are used for each unit of the entire production run. Because of this, each unit must have the controller's flash reprogrammed with the correct LED data.

The LEDs on the boards used in measuring the color accuracy of this method has the bin codes shown in Table 3. Table 4 shows the LED data that is determined based upon these bin codes. This information is found in the "Luxeon® Product Binning and Labeling" document from Lumileds.

Table 3. Bin Codes of K2 LEDs in System

LED	Flux Bin	Color Bin
Red	Q	4
Green	R	5
Blue	K	1

Table 4. LED Data obtained from Bin Codes

LED	λ (nm)	x	Y	Flux (lm)
Red	625.75	0.7011	0.2982	35.2
Green	542.5	0.2559	0.7010	45.75
Blue	462.5	0.1434	0.0396	8.7

The values in Table 4 are stored in the EZ-Color™ controller. This time the bin codes from Table 3 are entered in the property menus of the window seen in Figure 8 on page 4. The board is again used to create approximately the same six target mixed colors. The target (x,y) coordinates and the Δu'v' values are seen in Table 5.

Table 5. Color Accuracy Results when using LED Bin Codes

Target Color	x	y	Δu' v'	< 0.008?
Neutral White	0.3330	0.3330	0.017242	No
Warm White	0.3823	0.3838	0.021675	No
Cold White	0.2499	0.2548	0.008769	No
Cyan	0.1986	0.3432	0.006002	Yes
Yellow	0.4456	0.5193	0.024066	No
Magenta	0.4093	0.1701	0.022353	No
		Avg.	0.01668463	

The average Δu'v' when using bin code values is much better than when not using bin codes. A Δu'v' of 0.01668 is still not very accurate, but it is accurate enough for some color mixing applications. Figure 6 on page 3 shows which colors can tolerate larger Δu'v' values and still look like the correct color. The larger the region of color is, the larger the Δu'v' error can be. Figure 6 on page 3 shows that mixed colors like white and yellow cannot tolerate very large errors.

Option 3: Using Measured LED Data

It is clear from the data presented in the previous section that even using bin code values in firmware is not accurate enough for some color mixing applications. LCD TV backlighting applications often require very low Δu'v' errors. This complicates the design process even more. Each unit must now be calibrated by measuring the characteristics of the LEDs of each unit. Then the unit must be reprogrammed with the LED data values that are unique to that unit only.

Table 6. Measured LED data

LED	X	Y	Flux (lm)
Red	0.7037	0.2955	32.9
Green	0.2470	0.7126	37.7
Blue	0.1407	0.0441	8.9

The flux of the green LED in Table 6 is lower than it should be given its flux bin code of R. This is because the flux of the green LED was initially measured after the LED had been on for approximately 2 s. This is enough time for the junction temperature of the LED to heat up which causes the flux output to decrease. When measured later, the LED had a flux of about 42 lm. Therefore, it is clear that even the data in Table 6 is not completely accurate.

The values in Table 6 are again stored in the flash of the EZ-Color™ controller. This process is more complex than selecting bin codes in the properties window in Figure 8 on page 4. So instead of storing the values in the flash of the EZ-Color™ controller, the underlying C code generated by PSoC Express must be slightly modified. After any PSoC Express design is built, a PSoC Designer project is generated in the same folder as the PSoC Express project. This PSoC Designer project must be opened and modified. There is a source file in the project called *driverdecl.c*. Code 1 shows part of the code in this file.

Code 1. Driver Property Declarations

```
const CMX_TRILUMILED_ParameterBlock
pse_[DRIVER_NAME] = {


. . .

   329,
   377,
   89,

. . .

   7037,
   2470,
   1407,

   2955,
   7126,
   441,


. . .
}
```

`CMX_TRILUMILED_ParameterBlock` is a structure definition made in *CMX_TRILUMILED.h*. It is informative to examine this structure definition to learn what all the structure members are, since this is not clear in *driverdecl.c*. In Code 1 on page 5, `pse_[DRIVER_NAME]` is the particular instance of the structure type and contains the name of the driver that is specified in the PSoC Express project. Because the structure declaration is preceded by `const`, the structure is stored in flash. The tenth through twelfth members of the structure are the flux values of the LEDs. These are shown as `329, 377, and 89` in Code 1 on page 5. The sixteenth through twenty-first members of the structure are the three (x,y) coordinates of the three LEDs. They are shown in Code 1 as `7037`, `2470`, `1407`, etc. The first three are the x values of the LEDs. The second three values are the y values of the LEDs. The values in Code 1 are changed to match those in Table 6 on page 5. After the six values are changed, the PSoC Designer project can be compiled and the EZ-Color™ device is programmed with the firmware. After this process is completed, the LED characteristic values used by the firmware are very close to the actual characteristics of the LEDs.

Table 7. Color Accuracy Results when using Measured LED Data

Target Color	x	y	∆u' v'	< 0.008?
Neutral White	0.3330	0.3330	0.005770	Yes
Warm White	0.3823	0.3838	0.006633	Yes
Cold White	0.2499	0.2548	0.004226	Yes
Cyan	0.1986	0.3462	0.002784	Yes
Yellow	0.4390	0.5223	0.006662	Yes
Magenta	0.4192	0.1823	0.002414	Yes
		Avg.	0.00474828	

When using the method described in this section, the average ∆u’v’ error in Table 7 is good. Each test color has an error less than 0.008. Using the actual measured LED data allows accurate color mixing that is not possible when relying on bin code values only.

Summary

The accuracy of a color mixing system is highly dependent on the accuracy of the LED characteristic data that is used in the color mixing firmware. To design an accurate color mixing system, the LED bin codes should be used in the firmware. EZ-Color controllers along with PSoC Express make the process of compensating for LED binning a trivial process. If very accurate color mixing is required, some form of LED measurement and calibration may be required.

About the Author

Name: Ben Kropf

Title: Applications Engineer

Background: Graduated with a B.S. degree in Electrical Engineering from Seattle Pacific University. Professional experience includes mixed-signal embedded system design, firmware design, and high brightness LED applications.

Contact: Email: btk@cypress.com

Cypress Semiconductor
198 Champion Court
San Jose, CA 95134-1709
Phone: 408-943-2600
Fax: 408-943-4730
http://www.cypress.com/