Perfecting the Color Reproduction of RGBW OLED

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Abstract

Displays that employ RGBW primaries have demonstrated greater power efficiency than similar displays with only RGB primaries. Unfortunately, RGBW systems with spatial light modulators, such as LCD flat panels and DMD projectors, have typically traded color accuracy for improvements in power efficiency. This paper presents a color-processing algorithm for emissive RGBW OLED displays that preserves colorimetric accuracy while still reaping the efficiency benefits of RGBW. RGBW extensions of additive RGB color models are discussed, along with a methodology for deterministically choosing RGBW solutions. A flexible image-processing path is illustrated that may be optimized for power efficiency, uniformity, and color gamut.

Introduction

Additive displays have long depended on RGB primaries to synthesize color mixtures. Recently, displays of a variety of technologies using RGBW primaries have emerged, promising improved efficiency through higher luminance and/or lower power consumption. Color reproduction in these displays often suffers as a result of the desire to boost efficiency, but this tradeoff is not always necessary, depending on the display technology and color-processing algorithm applied. "Perfect" color reproduction is always a matter of perspective. Here, it is asserted that in a display system, perfection means accurate reproduction of the color specification encoded in the signal it receives.

Many displays, such as LCD and DMD, rely on spatial light modulators to attenuate a backlight, projector bulb, or other always-on, full-field light source. In these displays, efficiency is determined by how much of the light generated by the always-on light source is transmitted to the viewer, leading to drive schemes that maximize the use of all four RGBW primaries to synthesize the display white point. Algorithms for driving displays with spatial light modulators typically add an amount of luminance from the W primary that is correlated with the amount of input RGB. These algorithms result in color reproduction error, displaying at least some colors less saturated and/or lower in luminance as compared to the color reproduction of an otherwise similar RGB display. More sophisticated algorithms mitigate the color reproduction error by modifying the corresponding RGB intensities where possible; however, this approach cannot both repair the effect for all colors and maintain the efficiency improvement. Lee et al. describe such an algorithm for a TFT-LCD RGBW display, in which white is added to colors in different amounts to make the color error less objectionable [1].

Emissive displays, such as OLED displays, utilize an array of light-emitting subpixels, meaning that the efficiency of the display is dependent on the efficiencies of the subpixels in use. A filtered white RGBW (W-RGBW) OLED uses an independently controlled white emitter at each subpixel site with color filters for each of the RGB subpixels and no filter for the W subpixel. Because they are unfiltered, a W-RGBW OLED display's W subpixels are much more efficient that its RGB subpixels, so efficient drive schemes utilize the W primary as much as possible and the RGB primaries as little as possible. It has been shown that a W-RGBW OLED panel requires half the power, on average, of an otherwise similar W-RGB OLED panel, without color error [2]. The present paper outlines an algorithm for accomplishing this combination of power savings and color accuracy.

Additive Model of RGBW

The light output of many color display systems can be modeled using a combination of a set of nonlinear characteristic curves and a linear primary matrix. The familiar primary, or phosphor, matrix is used to describe the linear addition of color in the display by computing the XYZ tristimulus values that a given linear RGB intensity input triad will produce. This is simply a linear combination, as in Eq. 1.

$$\mathbf{P}_{3x3}\begin{bmatrix}R\\G\\B\end{bmatrix}=\begin{bmatrix}X\\Y\\Z\end{bmatrix} \tag{1}$$

The columns of the 3×3 primary matrix $\mathbf{P}_{3\times3}$ are typically filled with the XYZ tristimulus values of each primary, scaled such that input linear RGB intensities (1, 1, 1) result in the tristimulus values of the desired display white point. This implicitly defines the maximum luminance, or unit intensity, for each primary.

The primary matrix relationship provides an essential feature through inversion, allowing the prediction of the necessary RGB triad to provide a desired XYZ tristimulus output. For a display with stable primary chromaticities and without any crosstalk or loading effects, the model works very well, and any XYZ tristimulus specification within the RGB gamut is reproduced accurately. XYZ specifications outside the RGB gamut result in RGB intensity values outside the interval [0, 1], which still are useful for modeling but are not physically realizable in the display.

A four primary system can be modeled similarly: the output is the linear combination of four primaries' contributions instead of three. Likewise, the 3×3 primary matrix may easily be extended to a 3×4 matrix, as in Eq. 2. The 3×4 primary matrix $\mathbf{P}_{3\times4}$ is formed from the 3×3 RGB matrix appended with a fourth column holding the tristimulus values of the W primary, such that an input linear RGBW intensity quad results in an XYZ triad. In this arrangement, two questions are immediately apparent: how to invert the non-square matrix $\mathbf{P}_{3\times4}$, and how to normalize its fourth column.

$$\mathbf{P}_{3x4}\begin{bmatrix}R\\G\\B\\W\end{bmatrix}=\begin{bmatrix}X\\Y\\Z\end{bmatrix} \tag{2}$$

Normalization for a 3×3 primary matrix is well understood: using Eq. 1, unit intensity in all three RGB primaries results in the XYZ tristimulus values of the display white point. Proper normalization for the additional W column in $\mathbf{P}_{3\times4}$ is less obvious and depends on how the display will be used. This discussion will progress focusing on what is best for W-RGBW OLED displays, which might not be what is best for displays using spatial light modulators. Some reasons for this distinction will be discussed later.

Unfortunately, the 3×4 RGBW primary matrix is not invertible, with the practical implication that given desired XYZ tristimulus values, there is not a unique RGBW solution; rather, there are many that will give equivalent results. A goal of this paper is to outline a method for choosing intelligently and deterministically from the possible solutions.

White Equivalence

Important to the use of a W primary in an additive display is the concept of white equivalence. Metamerism is the phenomenon whereby two spectrally dissimilar stimuli integrate to the same XYZ tristimulus values, implying that a viewer with normal color vision would see them as the same color, assuming similar viewing conditions. A W-equivalent RGB intensity triad is a combination of RGB intensities that produces a metamer of some amount of W primary intensity. The normalized W-equivalent RGB intensity triad, W_{rgb}, is scaled such that the maximum of the RGB intensities is unity. This works for any color; as long as the chromaticities of the W primary are within the RGB gamut, all three W_{rgb} intensities are positive.

This normalization can be used to define the unit intensity of the W primary, and thus the scaling of the fourth column of the 3×4 RGBW primary matrix. This ensures that color resulting from the peak intensity of the W primary can be equivalently, i.e., metamerically, reproduced using only the RGB primaries. Note that a convenient case arises when the chromaticities of the W primary are the same as those of the desired display white point; in this case, the W_{rgb} values are (1, 1, 1).

White Replacement

Because in a W-RGBW OLED display, the W subpixels are much more efficient than are any of the RGB subpixels, an effective concept is that of white replacement. W intensity is equivalent to a combination of R, G, and B intensities, thus the W subpixel can be used in place of a combination of R, G, and B subpixels. Conceptually, this means removing the neutral luminance from an RGB triad of subpixels and transferring it to the W subpixel for an equivalent result.

A bounding example of this is to compute for each image pixel the min(R, G, B), which may be thought of generally as neutral luminance, subtract it from each of the R, G, and B values, and assign it to W. This is termed 100% white replacement, as all possible neutral luminance has been transferred from the RGB to the W subpixel. Similarly, some fraction, termed the white mixing ratio (WMR), of the neutral luminance may be transferred. Equations 3 and 4 show the transfer from RGB to W, resulting in R', G', B', and W. Use of varying WMR values offers a range of solutions while maintaining a metameric match to the original color. They range from WMR = 0, corresponding to a strictly RGB solution that does not utilize W, to WMR = 100%, corresponding to the transfer of as much neutral luminance as possible to the W subpixel. When the W subpixel is more efficient than the RGB subpixels, a WMR of 100% achieves the highest possible display efficiency.

$$W = WMR \cdot \min\left(\begin{bmatrix} R \\ G \\ B \end{bmatrix}\right) \tag{3}$$

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} R \\ G \\ B \end{bmatrix} - W \tag{4}$$

Some similarity might be seen between this algorithm and CMYK printing with undercolor removal (UCR) or gray component replacement (GCR), in which dark colors are formed using black ink to replace large amounts of CMY ink. In printing, this is done for cost, to avoid physical problems with ink quantity, and/or to prevent color errors that arise when forming neutrals from CMY combinations. Significantly, white replacement in an additive RGBW display can be justified entirely by efficiency and need not change the color reproduction at all.

White replacement using WMR between 0 and 100%, assuming that the chromaticities of the W primary are the same as those of the display white point (the combination of unit intensities of the RGB primaries), results in equivalent color reproduction. Of course, if the W-equivalent RGB values are not equal, the W primary is not the same color as the white synthesized from the original three primaries, and the color subtracted from RGB will not be equivalent to the color produced by W. In this case, further compensation must be made.

When W Is Not Quite White

In a display, "white" is generally defined by the display white point, which might be set manually to meet a specification in a colorimetric space such as xyY, or which might be the physical result of a light source with light modulators and/or color filters. In a display that utilizes a broadband source and color filters, it is generally most efficient to choose a white point equivalent to the broadband color. This is true of both filtered-white OLED displays and backlit or projection spatial light modulation displays. However, regardless of the display technology, the inherent broadband color might not be the same as the desired display white point. When this is true, the basic white replacement algorithm will introduce color error; for example, a W primary that is yellowish compared to the display white point will introduce a yellow bias to the extent that it is used to replace RGB intensity that is equivalent to the white point.

The solution is to account for the color of the W primary when transferring luminance from the RGB subpixels to the W subpixel, using the concept of W equivalence introduced earlier. The three W-equivalent RGB intensity, W_{rgb}, values are used to scale the RGB input before the minimum is computed, as in Eq. 5.

$$\begin{bmatrix} W_r & 0 & 0 \\ 0 & W_g & 0 \\ 0 & 0 & W_b \end{bmatrix}^{-1} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} R_n \\ G_n \\ B_n \end{bmatrix} \quad (5)$$

The result of this scaling is to transform the RGB intensity values, which are by definition normalized such that an equal-RGB triad produces a color having the chromaticity coordinates of the display white point, to W-normalized RGB, or $R_nG_nB_n$, in which an equal-$R_nG_nB_n$ triad produces a color having the same chromaticity coordinates as the W primary. In the $R_nG_nB_n$ space, the minimum is computed and the WMR fraction of the minimum is subtracted, resulting in $R_n'G_n'B_n'$ values as in Eqs. 3 and 4. Subsequently, a renormalization is performed to return to the white point-normalized RGB space, as in Eq. 6. Earlier this process was conceptually described as a transfer of "neutral" luminance, an intentionally ambiguous descriptor; truly, it is a transfer of luminance of the color of the W primary, and this is made explicit through the normalization process.

$$\begin{bmatrix} W_r & 0 & 0 \\ 0 & W_g & 0 \\ 0 & 0 & W_b \end{bmatrix} \begin{bmatrix} R_n' \\ G_n' \\ B_n' \end{bmatrix} = \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \quad (6)$$

Again, note the convenient case in which the W primary shares the chromaticities of the display white point. In this case, W_{rgb} is (1, 1, 1) and both of the above transformations become identity matrices. Using a W primary close to the display white point, the transforms are likely to be close to identity, providing a small but important correction.

When W Is Not White at All (RGBX)

The normalization and W-equivalency concepts above are also applicable to systems with a fourth primary that is not near white, in general termed RGBX, where the X can be cyan, yellow, or another color. As long as the X is still within the RGB gamut, the method works without modification. If the X is outside the RGB gamut, one required modification is a change to the definition of W-equivalent RGB intensity. It is useful to define instead the X-equivalent RGB intensity, X_{rgb}, whose values are now scaled such that $\max(|X_{rgb}|)$ is unity. Taking the absolute value is necessary because mathematically reproducing the XYZ tristimulus values of an out-of-gamut X primary requires a negative amount of intensity from at least one of the RGB primaries. A second modification comes in the computation of the $\min(R_n, G_n, B_n)$ value. The negative value or values in X_{rgb} should be used in the normalization step, making some of the normalized $R_nG_nB_n$ intensity values negative. However, these negative values must be excluded when computing the minimum $R_nG_nB_n$ value. Thus, the minimum of the non-negative $R_nG_nB_n$ values should be computed.

Another simple extension can be made to handle more than four primaries. The replacement algorithm can be applied multiple times in series, minimizing power draw by successively transferring luminance to more efficient primaries. Each replacement step transforms three intensities to four; therefore, in subsequent steps when more than three are present, the largest three values should be used. The result is a multi-step transfer of luminance from the least to the most efficient primaries.

Algorithm Summary

The general white replacement algorithm is shown in the form of a flow chart in Fig. 1, leading from linear RGB intensity to linear RGBW intensity. In this flow chart, the *min* function computes *x* from the normalized RGB values, (R_n, G_n, B_n), specifically taking the minimum of the non-negative values, thus delaying the clipping of out-of-gamut colors. The min *x* times the WMR becomes the W intensity value as well as the value subtracted from the normalized RGB values. Thus, the WMR parameter controls the amount of luminance transferred from the RGB subpixels to the W subpixel.

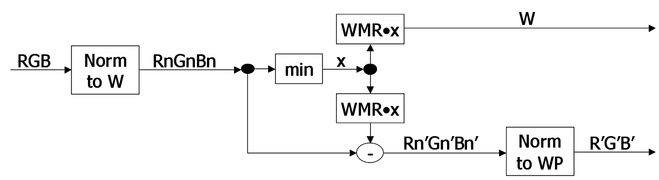

Figure 1. *Flow diagram for RGB to RGBW via white replacement*

Significantly, the linear RGB intensity values must be linear and in the device-dependent RGB primary space of the display itself. For example, an sRGB-encoded signal must be linearized with the proper gamma decoding transform, then rotated from the ITU-R Rec. 709 RGB primaries to the display RGB primaries before proceeding with this algorithm. Likewise, if the display characteristic is nonlinear, the resulting RGBW intensity values must be transformed according to this nonlinearity for proper display.

Conclusion

A flexible algorithm for maximizing the efficiency of emissive W-RGBW OLED displays while preserving colorimetric accuracy has been presented. It is useful regardless of the color of the fourth primary and in cases with more than four primaries, working on the principle of white replacement. Using this principle, luminance is transferred from less efficient subpixels to more efficient subpixels without changing the display's color reproduction.

It is perhaps debatable whether "perfect" color reproduction for a display system is defined by colorimetric accuracy. If it is assumed that the incoming color signal is indeed device-independent and rendered as desired by elements upstream in the image-processing chain, then it is easy to argue that reproducing the color faithfully as encoded is correct. A display designer may decide to "enhance" an incoming image through color modification, among other things, and the usefulness of such improvement is outside the scope of this discussion. It is assumed, however, that lowered saturation and/or luminance of colors through the use of a high-efficiency primary is not an improvement, and that accurate color is a preferred result.

An important distinction can be made between algorithms that use white to augment luminance and the one discussed here that uses white to efficiently replace neutral luminance. Algorithms in the former category trade away color accuracy, in at least some colors, for higher efficiency. The white replacement algorithm preserves color reproduction and does not modify the white point luminance, yet it provides greater efficiency by favoring the subpixel with the highest efficiency. Interestingly, specific display technologies clearly steer the choice of which style of algorithm is to be employed.

Emissive displays such as W-RGBW OLEDs draw power proportionally to their light output. This makes them well suited to take advantage of white replacement because the efficiency of the light output of the individual subpixels is important. Utilizing a higher-efficiency W subpixel in lieu of lower-efficiency RGB subpixels results in lower power consumption. Also, OLEDs can be driven to very high luminance levels, so there is little need to use W to augment luminance.

Displays employing spatial light modulators and an always-on light source, such as backlit LCDs and DMD projectors, draw a constant amount of power regardless of the modulated light output. Because of this, white replacement does not provide a benefit; in fact, it can provide a net loss. The use of additional primaries typically reduces the relative spatial aperture ratio or temporal fraction provided for each color, and restricting the use of the RGB results in lost light and power.

The efficiency benefit realized in a W-RGBW OLED display system depends heavily on how often the W subpixel is utilized in place of RGB. This means that the nature of the content displayed has a large effect. In pictorial applications, neutral and near-neutral colors are extremely frequent, providing a large benefit: in fact, about 2 times the efficiency on average using a set of typical consumer digital camera images [2]. Other applications and content might provide different levels of W primary utilization, and likewise different efficiency benefits.

Designing an RGBW display system requires co-optimizing a large set of parameters, including the WMR parameter offered by the present algorithm, the physical pixel layout, including aperture ratio, and the chromaticities of the primaries themselves. Details on the effects of these variables on image quality, display lifetime, and power consumption are provided in [3].

References

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