

11-2009

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Shlayan, N., Venkat, R., Ginobbi, P., Singh, A. K. (2009). Energy Efficient RGBW Pixel Configuration for Light-emitting Displays. *Journal of Display Technology*, 5(11), 418-424.
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Energy Efficient RGBW Pixel Configuration for Light-Emitting Displays

Neveen Shlayan, Rama Venkat, *Senior Member, IEEE*, Paolo Ginobbi, and Ashok K. Singh

Abstract—A study on LED displays has been conducted exploring a more efficient method for color generation than the traditional method. The study is comprehensive and thoroughly performed employing various sets of experiments in order to examine the functionality of the new proposed scheme which includes a literature review, theoretical modeling based on a scientific study, experimental data measurements of a developed prototype, and statistical data based on a survey. This study resulted in very interesting outcomes that may lead to a tremendous change in the existing LED display technology.

Index Terms—Billboards, color, display, light-emitting display (LED), panel, RGB, RGBW.

I. INTRODUCTION

EVEN though the rapid development in solid state technology has resulted in major advancements in high power light-emitting display (LEDs) obtaining on average 150 lum/W [1], efficiency of full colored LED displays could be further improved by introducing a white LED to the RGB pixel with the added benefit of a better image quality. Through LEDs, There are several approaches to achieve white light. One approach is to use a blue LED with phosphors to produce white light [2], [3]. Another approach is to use RGB LEDs which are perceived as white light when set at equal relative intensities. In the second method, maintaining the desired white point within acceptable tolerances becomes a major challenge. The variation of white point results from the significant spread in lumen output and wavelength of manufactured LEDs, and the changes in LED characteristics that occur with temperature and time. Feedback schemes are required to maintain the desired white point by controlling the relative contributions of red, green, and blue to the white light [3]. This paper focuses on the first method of white light generation in which a blue LED with phosphor coating is used. The traditional method of using LED light source composed of RGB LEDs is modified to include a white LED. The white LED will be turned on to the level of the appropriate luminous flux when all three RGB are turned on in order to pro-

duce a certain color. The intensity level of the white LED will be determined based upon the minimum luminous flux of the RGB which takes into account human eye sensitivity to different wave lengths (relative intensity) [4]. A similar method has been previously implemented in different types of displays such as TFT-LCD where the white sub-pixel is used for image quality enhancement; however, it does not reduce the usage of the RGB [5]. RGBW method was also implemented in full color AMOLED displays where standard RGB LCD color filters are used. White sub-pixels in AMOLED displays do not require color filters resulting in a more efficient display maintaining the same color gamut [6]. In this research, however, the white sub-pixel is tested for LED displays in which red, green, and blue LEDs are used to produce various colors where in previous research [5], [6] color filters are used.

By introducing the white LED into the pixel, usage of the green LED will be reduced, which is the least efficient. Also, usage of red and blue LEDs will be reduced which results in a life expectancy increase of the display on an average. Moreover, less complicated feedback control schemes for RGB LEDs will be needed in order to maintain achromatic point (AP) since pure white light is used to achieve the white point resulting in more uniform white color point integration across the display with the added benefit of a less complicated control circuitry. Based on a theoretical modeling and test measurements (using a prototype) for the new suggested method (RGBW), the advantages of the new pixel configuration compared to the traditional RGB LED display technology will be demonstrated.

In Section II, issues with traditional RGB pixel are presented. Theoretical analysis of the RGBW configuration is presented in Section III. In Section IV, a brief description of the implementation is presented. Results and discussion of human perception experiments and energy measurements are in Section V. Conclusions are in Section VI.

II. ISSUES WITH THE TRADITIONAL RGB PIXEL

Although RGB configuration has the benefit of color variability, it also has some issues such as: Color instability due to temperature changes and the variability in light output of nominally identical LEDs by over a factor of two, and the wavelength variation by several nanometers due to aging differently and process variation of LEDs [3]. A study on thermal effects on RGB LED characteristics was reported in [2] showing a 10% decrease in light output for every 100°C increase in temperature for AlInGaP red LED 5% for InGaP green LED and 2% for InGaP blue LED. It is also showing that as temperature increases the LED shifts towards a longer wavelength. In [3], minimum perceptible-color-difference (MPCD) as an outcome of changes in light output of the individual LEDs due to aging or

Manuscript received December 23, 2008; revised March 31, 2009. Current version published November 18, 2009. This work was supported by the U.S. Department of Energy through contract under Grant RF-06-PRD-001 (7156APP131).

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Digital Object Identifier 10.1109/JDT.2009.2027448

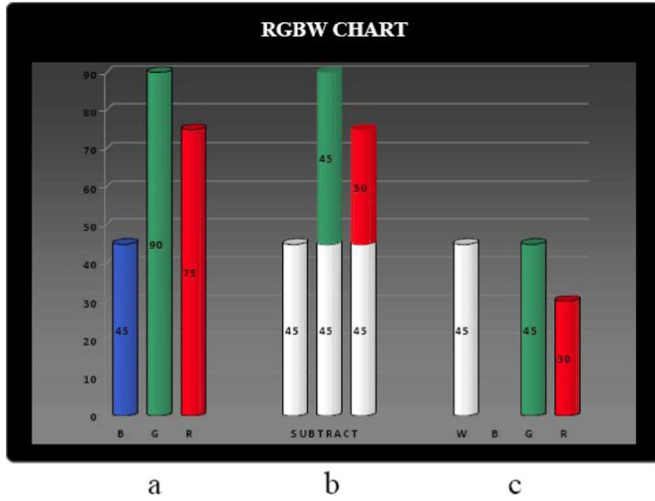


Fig. 1. RGBW chart. Y axis represents 255 different possible levels of digital color intensities that correspond to an eight bit data bus for each color. (a) Intensity levels for RGB in a pixel (b) Identified intensity of white in the pixel (c) B completely eliminated, white LED introduced and R and G reduced.

manufacturing inconsistency was studied and reported. Results show that there is a shift in the (u, v) color coordinates as a result of a change in the flux of the red, green, or blue LEDs.

III. THEORETICAL ANALYSIS OF THE NEW RGBW PIXEL

In this study, the classical pixel RGB is modified to include a white LED. In a frame, some pixels will have a certain intensity of white. In other words, certain hues can be modeled as the addition of a certain amount of white and some intensities of two of the three colors, R, G and B. For every pixel that has a certain amount of white in it, or a certain white saturation level; the maximum luminous flux of white of the color is supplied using the white LED in order to retain the saturation level required. In the process, the intensity of one of the three colors which has the lowest luminous flux will be completely eliminated and the two others will be reduced in intensity. Fig. 1 schematically demonstrates the process of conversion from RGB to RGBW through an example, where the source data in arbitrary units of luminous flux is chosen to be $R = 75$, $G = 90$, and $B = 45$. First, the three data sources are compared in order to identify the LED with the minimum intensity out of RGB, which in this case it is 45 of B. Then, the value of the minimum intensity will be deducted from all three LEDs, which makes R of the value 30, $G = 45$, and $B = 0$. Finally, this value minimum value of 45 will be supplied to the W LED. Note that in the final configuration the B is completely eliminated and a W LED is introduced with the same power of B as shown in Fig. 1 [7].

The combination of various light wavelengths in order to produce a given perceived color is not unique. The white intensity in a certain color affects its saturation [4]. In other words, a perfectly saturated color is missing the element of white; therefore, only monochromatic and dual chromatic colors can be perfectly saturated. Thus, it is concluded that by eliminating the white component, the hue will not change but its saturation level will, which could be compensated by adding a white light from any other light source such as a white LED. The human eye can not

distinguish between similar hues that are produced by different components of light wavelengths.

Given that Q is the vector representing a particular color and R , G , and B are the unit vectors representing three fixed primaries, then the vector equation

$$Q = RR + GG + BB \quad (1)$$

states that the given color is matched by a linear combination of quantities R , G , and B of the respective primaries [8]. The scalar multipliers R , G , and B are the tristimulus values of the given color with respect to the set of primaries R , G , and B . This three dimensional vector space is called the *RGB* tristimulus space.

The following analysis theoretically demonstrates that the hue from RGBW and RGB configurations will be the same. Using (1), the new color, C_{new} , after reducing the intensities of R , G and B by a scalar x , is given by

$$\begin{aligned} C_{\text{new}} &= (R - x)R + (B - x)B + (G - x)G \\ &= (RR + BB + GG) - x(R + G + B) \\ &= C - xW. \end{aligned} \quad (2)$$

Note that the rewritten (2) has two components on the right-hand side. The first term corresponds to the old color with the original intensities of the R , G and B and the second term corresponds to the amount of white intensity, which was removed from the pixel by reducing intensities of R , G and B by x . The calculations above show that the process of reducing an x amount of luminance from every RGB LED is equivalent to the process of reducing the same amount of white light. Thus C_{old} can be restored by adding x of W to C_{new} .

Considering the HSV system [5], one can also show that the hue can be maintained when comparing the traditional pixel to the new RGBW pixel set up. Using the RGB to HSV space conversion equations, the hue for given RGB values can be determined as follows [5]:

When R is maximum and G is minimum

$$H = 5 + \frac{R - B}{R - G}$$

H_{new} is obtained by subtracting the minimum value from every sub pixel

$$H_{\text{new}} = 5 + \frac{(R - G) - (B - G)}{(R - G) - (G - G)} = 5 + \frac{R - B}{R - G} = H_{\text{old}}. \quad (3)$$

This results in the same hue as the original before deducting the minimum intensity. Similarly, other RGB combinations are considered.

When R is maximum and G is not minimum

$$H = 1 - \frac{R - G}{R - B}$$

H_{new} is given by

$$H_{\text{new}} = 1 - \frac{(R - B) - (G - B)}{(R - B) - (B - B)} = 1 - \frac{R - G}{R - B} = H_{\text{old}}. \quad (4)$$

When G is maximum and B is minimum

$$H = 1 + \frac{G - R}{G - B}$$

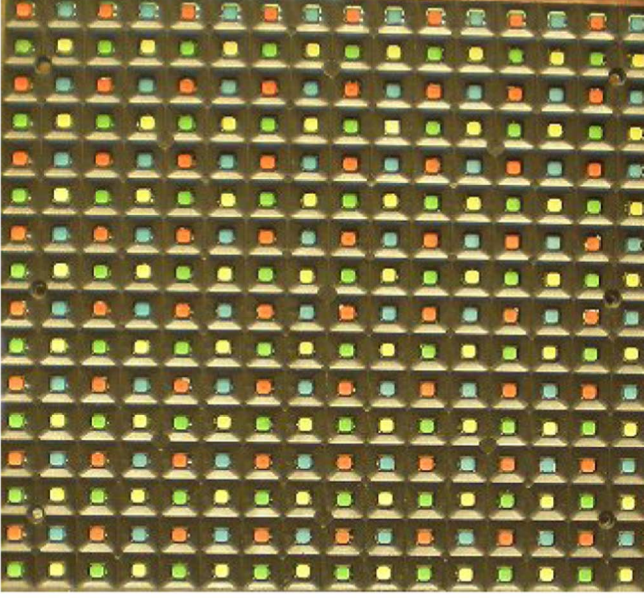


Fig. 2. A photograph of the prototype used for this research provided by TecnoVision.

H_{new} is given by

$$H_{\text{new}} = 1 + \frac{(G - B) - (R - B)}{(G - B) - (B - B)} = 1 + \frac{G - R}{G - B} = H_{\text{old}}. \quad (5)$$

When G is maximum and B is not minimum

$$H = 3 - \frac{G - B}{G - R}$$

H_{new} is given by

$$H_{\text{new}} = 3 - \frac{(G - R) - (B - R)}{(G - R) - (R - R)} = 3 - \frac{G - B}{G - R} = H_{\text{old}}. \quad (6)$$

When B is maximum

$$H = 3 + \frac{B - G}{B - \min}$$

H_{new} is given by

$$H_{\text{new}} = 3 + \frac{(B - \min) - (G - \min)}{(B - \min) - (\min - \min)} = 3 + \frac{B - G}{B - \min} = H_{\text{old}} \quad (7)$$

where H_{new} is the hue obtained from the new RGBW pixel and H_{old} is the hue obtained from the traditional RGB pixel. Equations (3)–(7) clearly show that the hues H_{new} (obtain with RGBW) and H_{old} (obtained with RGB) are the same.

IV. IMPLEMENTATION

A photograph of an 8×8 RGBW LED display prototype with square configuration manufactured by TecnoVision, Milan, Italy is shown in Fig. 2.

A schematic block diagram in Fig. 3 shows the details of the implementation scheme. There are two possible inputs, a static

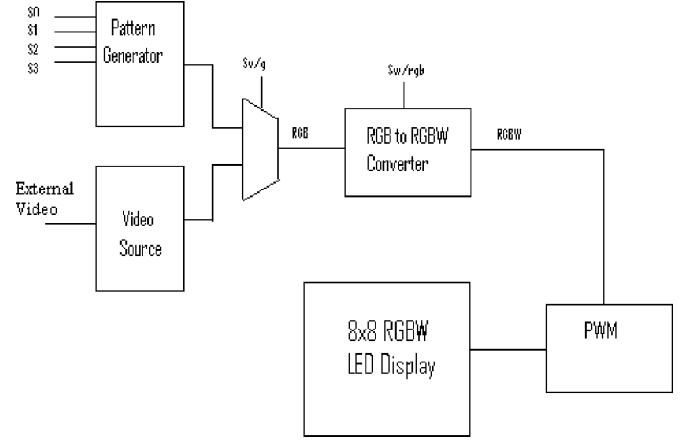


Fig. 3. Block diagram depicting the hardware/software implementation.

picture input and a live video. The S_v/g switch selects between static picture and video. S_w/rgb switch selects between RGB and RGBW configurations.

Using a field programmable gate array (FPGA) the signals are decoded and fed into the RGB-to-RGBW converter as shown in Fig. 3. Then, the RGBW input data (eight bit data bus for every color) is remapped due to the architecture of the display. Finally, the data is pulse width modulated (PWM) in order to input the RGBW data to the display. The color accuracy of the white point will be maintained by reducing the variation in white point if the LEDs are driven using PWM [9]. A 5"×5" of white plastic diffuser is used in order to properly integrate various colors emitted by the pixels in order to simulate long distance perception when viewed from a short distance.

As shown in Fig. 3, using the switches, one can choose to bypass the RGB to RGBW conversion so that the display will use the classical RGB pixel configuration instead of RGBW. Using another set of switches, the hardware provides the possibility to choose various solid colors from the pattern generator to be displayed.

V. RESULTS AND DISCUSSION

A. Human Perception Experiments

Due to significance of human perception of the display, human perception experiments were conducted following the institutional review board (IRB) protocols.

Twelve pairs of different colors were tested. The colors fall into three groups, gray scale, low saturation, and high saturation. Every subject was shown pairs of colors and asked to determine whether the colors are Identical (98% or more similarity), Almost the same (90% or more similarity), Not the same at all (less than 90%).

Three different sets of experiments were conducted. In the first set, the experimental group, each color was displayed twice once with RGB and once with RGBW; 100 test subjects were surveyed in this category. In the second set, each color was displayed twice with RGB. This set is one of the control groups and it consisted of 20 test subjects. In the third set, each color was

displayed twice with RGBW and this second control group consisted of 20 test subjects. It was expected that some test subjects may be biased by the switching action and record a change even if they do not notice a difference in color. Therefore, the purpose of the control groups 2 and 3 was to assess the reliability and consistency of the results obtained in set 1 by evaluating the severity of any psychological factors.

1) *Theory of Statistical Analysis*: Data collected in Human Perception experiments was subjected to statistical analysis based on a binomial probability model. Let $j = 1, 2, 3$ represent experimental, control 1, and control 2 groups, respectively. Let X denote the number of subjects out of N_j for experiment j ($j = 1, 2, 3$), who perceived the colors produced were 'Identical or Almost the Same'. The probability distribution of X then can be modeled by the binomial probability distribution

$$P(X = x) = N \text{ choose } x p_j^x (1 - p_j)^{N-x}, \quad x = 1, 2, \dots, N \quad (8)$$

where p_j is the proportion of subjects in the population who perceived the colors produced in two trials are 'identical or almost the same'. The population proportion, p_j , is estimated by the sample proportion as

$$\hat{p}_j = \frac{x_j}{N_j} \quad (9)$$

where x_j is the number of subjects who perceived the colors in two trials were identical, for experiment j ($j = 1, 2, 3$). 95% confidence intervals for p_j can be computed using the following approximate formula for 95% confidence:

$$p_j(95\%CI) = \hat{p}_j \pm 1.96 \times \sqrt{\frac{\hat{p}_j(1 - \hat{p}_j)}{N_j}}. \quad (10)$$

Exact confidence intervals can also be calculated using the software package MINITAB. The latter approach is used in this work. The 95% confidence interval for p_j imply that the repeated use of the formula for computing the 95% confidence interval, over similar experiments, will contain the true unknown p_j for 95% of the time.

2) *Data Analysis*: Using the collected data and (10), the estimate, p_j and the upper and lower 95% confidence intervals were calculated using MINITAB for white, gray, and dark gray. The data for "almost the same" and "Identical" were combined to obtain the estimate, p_j . Thus, values of \hat{p}_j indicate that the pair of colors appear the same. The 95% confidence intervals (U95, L95) indicate the spread or the variability of data.

It appears that white color created by RGB, as shown in Fig. 4, is perceived the same as that by RGBW only to 44%±10% of the subjects and only 34%±10% for gray. The reason for obtaining percentages below 50% stems from the fact that the white LEDs in the prototype that was used for this experiment did not have independent intensity control due to linkage of the control circuitry for red and white which means that any increase in white intensity will automatically cause an increase in the red intensity when it is not desired in order to maintain a proper relevant intensity balance of the RGB. Thus, maintaining an equivalent intensity between the two whites was a technical challenge. Since gray has low saturation, the amount of white in it is fairly high, which explains why the data is below 50%. For dark gray, how-

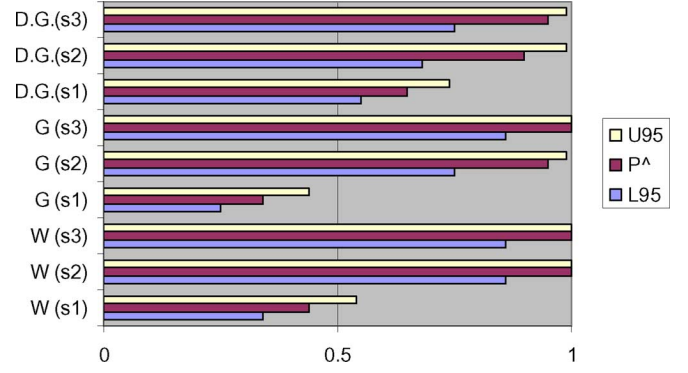


Fig. 4. Estimate, \hat{p} , with $\pm 95\%$ (U95, L95) confidence interval for white (W), gray (G), and dark gray (D.G.) for 3 group sets (s1, s2, and s3) described in Section V-A.

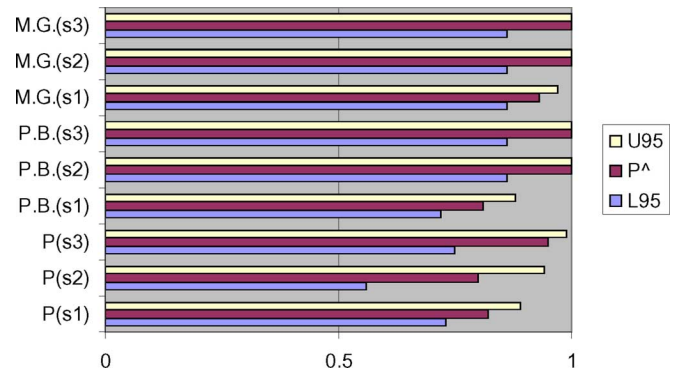


Fig. 5. Estimate, \hat{p} , with $\pm 95\%$ (U95, L95) confidence interval for purple (P), purplish blue (P.B.), and Medium Green (M.G.) for 3 group sets (s1, s2, and s3) described in Section V-A.

ever, the percentage of subjects that found the colors generated by RGB and RGBW to be the same significantly increased to be 65%+9%/−10% since the white level decreases for high saturated colors.

For similar experiments with low saturated colors, the results were dramatically different. As shown in Fig. 5, the percentages are dramatically improved compared to the gray scale. 82% (+6%/−9%) of test subjects for purple, 81% (+7%/−9%) for purplish blue, and 93% (+4%/−7%) for medium green found the difference between RGB and RGBW to be "almost the same or identical". This increase in percentage was expected since adding the right amount of white, as it illustrated in Section III, does not change the hue of the perceived color.

The results of percentages of 95% for high saturated colors, as shown in Figs. 6 and 7, are excellent. The percentages were 98% (+0%/−5%) for rose, 98% (+0%/−5%) for violet, 99% (+0%/−4%) for CYAN, 100% (+0%/−3%) for green, and 96% (+2%/−6%) for orange suggests that almost all test subjects found almost no difference between the colors when displayed using RGB or RGBW. This indicates that the two architectures (RGB and RGBW) are almost identical in color production for high saturated colors since the amount of white used in high saturated colors is minimal.

B. Energy Measurements and Calculations

Twelve different pairs of colors were tested for power consumption. The colors are divided into three groups gray scale,

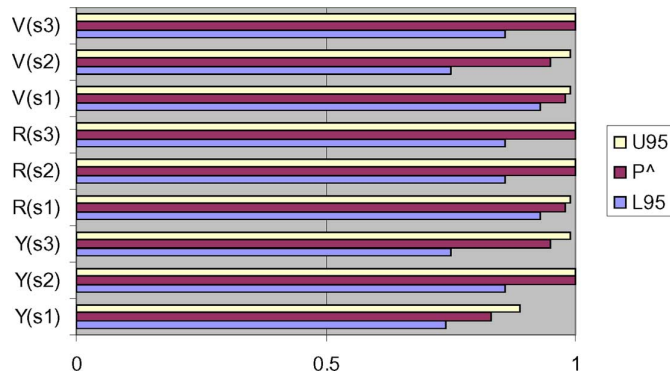


Fig. 6. Estimate, \hat{p} , with $\pm 95\%$ (U95, L95) confidence interval for yellow (Y), rose (R), and violet (V) for 3 group sets (s1, s2, and s3) described in Section V-A.

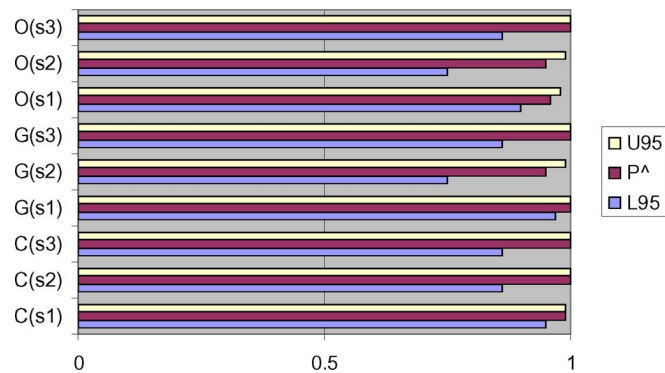


Fig. 7. Estimate, \hat{p} , with $\pm 95\%$ (U95, L95) confidence interval for cyan (C), Green (G), and Orange (O) for 3 group sets (s1, s2, and s3) described in Section V-A.

low saturation, and high saturation. For every pair, the current supplied to the 8×8 pixel display is measured twice once for RGB and once for RGBW configuration.

The currents consumed by the 8×8 pixel LED display are measured for the twelve pairs of colors using RGB and RGBW configurations. It is noted that the current values are in the range of 0.63 – 1.78 A with the highest values are for white and the lowest values for dark gray.

The power consumed by the LED display, P , is given by

$$P = V \times I \quad (11)$$

where V is the voltage supplied to the display, and I is the current through the display. The percentage of power savings as a result of using RGBW in place of RGB, $\%P_s$, is given by

$$\%P_s = \frac{(P_{\text{RGB}} - P_{\text{RGBW}})}{P_{\text{RGB}}} \times 100. \quad (12)$$

Using the collected data reported and the (11) and (12), P_{RGB} , P_{RGBW} , and $\%P_s$ were calculated for twelve different colors. % power savings ($\%P_s$) for various colors is plotted in Fig. 8 [7].

The data of $\%P_s$ for various colors presented in Fig. 8 shows power savings that ranges between 30% and 50% for gray scale and low saturated colors (purple, purplish blue, medium green, and yellow). Power savings for high saturated colors, such as rose, violet, cyan, green, and orange, is much lower than power

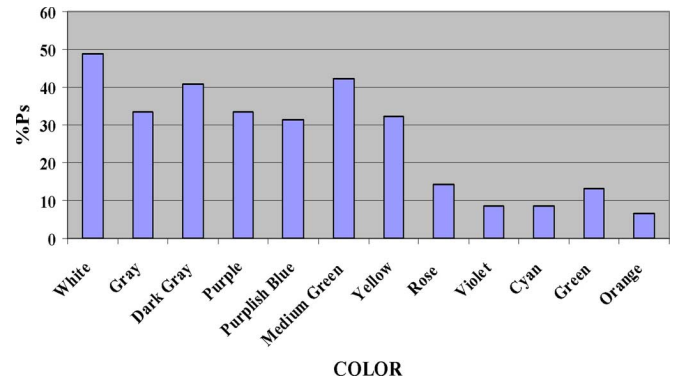


Fig. 8. The % power savings for 12 colors.

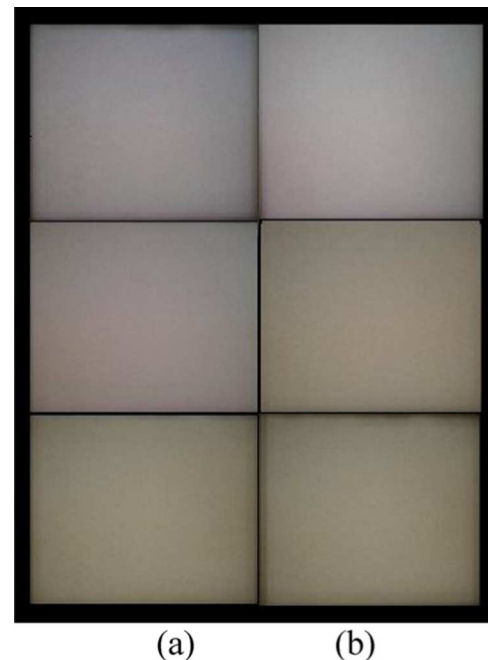


Fig. 9. Photograph of gray scale colors from (a) RGB; (b) RGBW; (i) white; (ii) gray; and (iii) dark gray.

savings for the gray scale and the low saturated colors. The low percentages for high saturated colors stems from the fact that the compensating white level of such colors is minimal. As expected, using the new RGBW pixel architecture saves power in most cases. The power saving for all the colors studied was averaged and was found to be approximately 30%.

C. Colors From Display

Photographs were taken of 12 different colors generated by RGB and RGBW and are displayed next to one another in Figs. 9–11. Photograph in (a) corresponds to RGB and that in (b) corresponds to RGBW.

For the photograph of gray scale shown in Fig. 9, it is noted that colors displayed with RGB seem to be slightly brighter than colors displayed with RGBW in other words Column (a) seems to be brighter than (b). This is due to the fact that the white generated from RGB and the white generated from RGBW are slightly different due to lack of independent control of white. This was manually fixed by using a potentiometer.

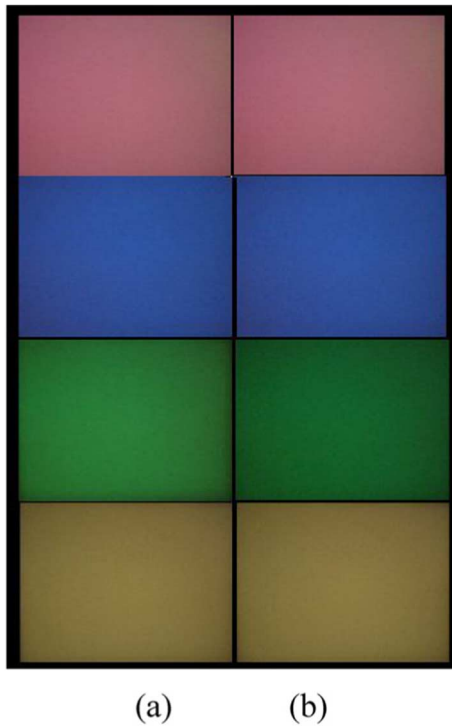


Fig. 10. Photograph of low saturated colors from (a) RGB (b) RGBW (i) purple (ii) purplish blue (iii) medium green (iv) yellow.

Photographs of Low saturated colors generated using RGB and RGBW are shown in Fig. 10. Photographs for RGB and RGBW for all colors appear to be very close; however, it is noticeable that column (a) is brighter than column (b) since the component of white is high in low saturated colors. Photographs of high saturated colors are shown in Fig. 11. Colors in these photographs are also indistinguishably similar since the white component is low for this category of colors.

VI. CONCLUSION

In this work, a new pixel configuration in LED displays, consisting of red (R), green (G), blue (B), and white (W) (RGBW) LEDs, was employed and investigated for color generation and power saving. Energy consumption and various hues of new pixels were compared to standard pixels consisting of RGB LEDs. Human perception experiments were conducted in order to study the perceptual difference between the two architectures when colors are generated using RGBW and RGB. Statistical analysis has shown that 44% of test subjects found the colors in gray scale to be the same, whereas 82% and 95% of test subject for low saturated colors and high saturated colors, respectively, found them to be identical. Theoretical analysis of the new RGBW pixel based on fundamentals of color theory has shown that using RGBW will not change the hue when it replaces RGB. Actual photographs of colors produced using RGB and RGBW configuration were shown demonstrating that the colors from the two configurations are almost indistinguishable. Power measurements for an 8×8 pixel LED display has demonstrated power savings, in all cases, using RGBW. The percentage of saved power, however, differed for various colors.

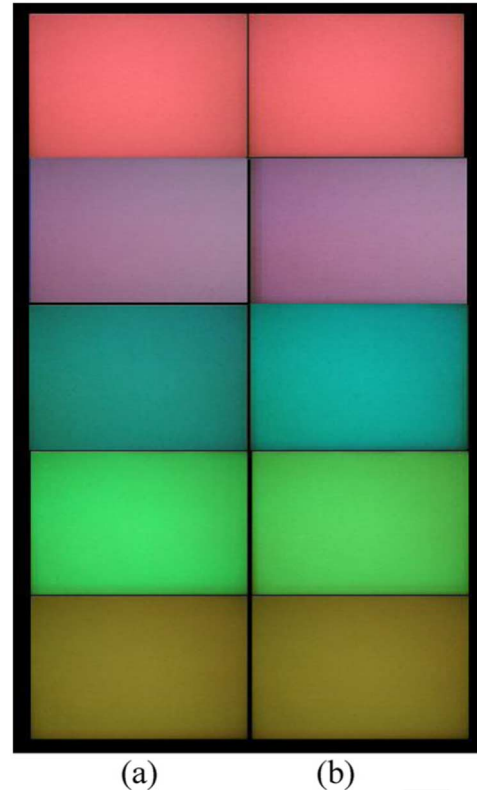


Fig. 11. A photograph of high saturated colors from (a) RGB (b) RGBW (i) rose (ii) violet (iii) cyan (iv) green (v) orange.

For instance, using RGBW as an alternative achieved up to 49% power savings for gray scale, over 30% power savings for low saturated colors, and up to 12% for high saturated colors. Average power saving for all colors studied was about 30%.

ACKNOWLEDGMENT

The authors acknowledge TecnoVision Milan, Italy, for the collaboration and for providing the LED Display prototype.

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Ms. Shlayan is the recipient of the 2006 Outstanding Senior Award from the Electrical Engineering department. She has also received the Grand Prize for the Senior Project competition from the Engineering college at UNLV.



Rama Venkat (M'89–SM'02) received the B.Tech. degree in metallurgical engineering from Indian Institute of Technology, Chennai, India, in 1983, and the M.S. degree in metallurgical engineering and the Ph.D. degree in electrical engineering from Purdue University, West Lafayette, IN, in 1985 and 1989, respectively.

He is currently a professor of Electrical and Computer Engineering Department and also the Founding Director of the state-of-the-art Science and Engineering Research Building at the University of Nevada, Las Vegas. His areas of research interests are solid state materials, sensors and devices, device physics, process and device modeling, energy efficient LED display technologies, and engineering entrepreneurship. He has published over 40 journal articles and has made numerous conference presentations.

Dr. Venkat has received several teaching awards from various organizations.



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