Dynamic Voltage Scaling of OLED Displays * †

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ABSTRACT

Unlike liquid crystal display (LCD) panels that require high-intensity backlight, organic LED (OLED) display panels naturally consume low power and provide high image quality thanks to their self-illuminating characteristic. In spite of this fact, the OLED display panel is still the dominant power consumer in battery-operated devices. As a result, there have been many attempts to reduce the OLED power consumption. Since power consumption of any pixel of the OLED display depends on the color that it displays, previous power saving methods change the pixel color subject to a tolerance level on the color distortion specified by the users. In practice, the OLED power saving techniques cannot be used on common user applications such as photo viewers and movie players.

This paper introduces the first OLED power saving technique that does not result in a significant degradation in the color and luminance values of the displayed image. The proposed technique is based on dynamic (driving) voltage scaling (DVS) of the OLED panel. Although the proposed DVS technique may degrade luminance of the panel, the panel luminance can be restored with appropriate image compensation. Consequently, power is saved on the OLED display panel with only minor changes in the color and luminance of the image. This technique is similar to dynamic backlight scaling of LCDs, but is based on the unique characteristics of the OLED drivers. The proposed method saves wasted power in the driver transistor and the internal resistance with an amplitude modulation driver, and in the internal resistance with a pulse width modulation driver, respectively. Experimental results show that the proposed OLED DVS with image compensation technique saves up to 52.5% of the OLED power while keeping the same human-perceived image quality for the Lena image.

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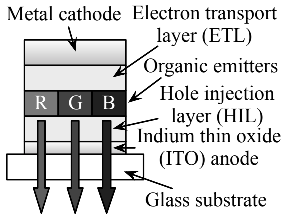
1. INTRODUCTION

Display systems account for a significant portion of the total power consumption in battery-powered electronics despite the advances in low-power display device technologies. As of today, liquid crystal display (LCD) panels are widely used in portable as well as desktop systems. The LCD panels do not illuminate themselves and require a high intensity backlight which generally consumes a significant amount of power due to low transmittance of the LCD panels [1, 2]. On the other hand, an organic light emitting diode (OLED) is a self-illuminating device using organic light emission material. Therefore, OLEDs provide high brightness, high luminance, fast response, wide viewing angle, and thin and lightweight form factors compared with conventional LCD panels [3]. One of the major disadvantages of OLED panels was their relatively short lifetime. However, fortunately, the OLED lifetimes have already became long enough to allow commercial offerings by major display manufacturerers.

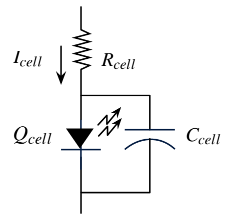
There are several system-level low-power techniques dealing with displays. Table 1 summarizes representative low-power display techniques. The first two categories of techniques essentially disable the display functionality of the entire panel or part of the panel whereas the last two categories of techniques apply a transformation to the image being displayed. Techniques in the first category control the display according to the behavior of the user [4, 5]. These techniques are applicable to any types of display with an interactive application where the user does not always pay attention to the display. The third category of techniques are dedicated to LCD and OLED displays [6, 7]. They attempt partial display turnoff. Some LCD panels have a zoned backlighting system, which can be partially turned off or dimmed. One such technique selectively turns off or dims the backlights that do not illuminate any displayed object of interest to the user [6]. Background dimming techniques set the background colors to a dark color, which results in lower power consumption in OLED panels [7]. The fourth category of techniques are also dedicated to LCD and OLED displays. They attempt content (color) change of the displayed image exploiting the power consumption difference by the pixel colors [8, 9, 10]. LCD panels exhibit around

Table 1: Classification of display power saving techniques.

Techniques	Features	Applications	Applicable displays
Usage-based control [4, 5]	Not functional during low-power mode	Interactive applications	CRT, LCD and OLED
Partial display turn off [6, 7]	Disable objects no in interest	Mixed active/idle objects	Some LCDs and OLED
Color remapping [8, 9, 10]	Altered look and feel	GUI	LCD and OLED
Backlight scaling [1, 2, 12, 13, 14]	Minor color distortion	No restrictions	LCD



(a) OLED device struture.



(b) Equivalent circuit model.

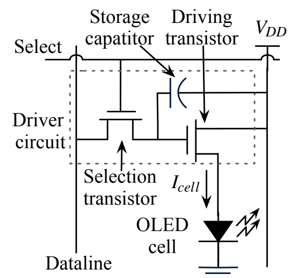
Figure 1: Device structure of OLED (a) and equivalent circuit model (b).

10% power consumption difference due to change in the colors being displayed [11]. In addition, pixel color remapping provides more headroom for backlight dimming and, in turn, higher power saving [8]. Color remapping also has an big impact on the OLED panel power consumption [9]. Unfortunately, color remapping is not always feasible. It is applicable only to the graphics user interface (GUI) and applications not dealing with natural images, photos, or video. Techniques in the last category reduce the backlight luminance and adjust colors to enhance the brightness and/or contrast of the image to compensate the image quality degradation [1, 2, 12, 13, 14]. These backlight scaling technique does not incur noticeable image degradation, nor does it result in a large color change. Unfortunately, it is not applicable to self-illuminating display devices such as the OLED panels.

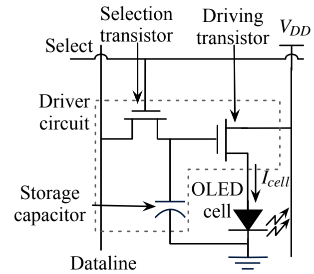
There exist no OLED display power saving technique that i) induces only minimal color change to accommodate display of natural images, and ii) is applicable to only the displayed object that is of interest to the users. This is because of the nature of the OLED panel. The power consumption of an OLED panel is dependent on each pixel color value and, in therefore, existing OLED power management techniques are not capable of altering power consumption of the OLED panel, without changing the pixel color values.

In this paper, we introduce the first OLED power saving technique that overcomes the above limitations. We call the technique OLED dynamic voltage scaling (DVS). The proposed technique exploits the unique characteristics of the OLED driver circuits. The OLED panel requires a controllable supply current driver circuit for each OLED pixel. Generally, the supply voltage of an OLED driver circuit is set to the maximum value to support the full luminance of a pixel. However, the supply voltage of pixels with less luminance does not need to be the maximum, and thus it has some margin for supply voltage reduction. We define a headroom as the difference between the actual supply voltage and the required voltage to illuminate the pixel with a given luminance. If we decrease the supply voltage, the luminance of pixels will decrease. Fortunately, if the scaled voltage is within the headroom of the pixel, we can restore it by increasing the brightness of the image data.

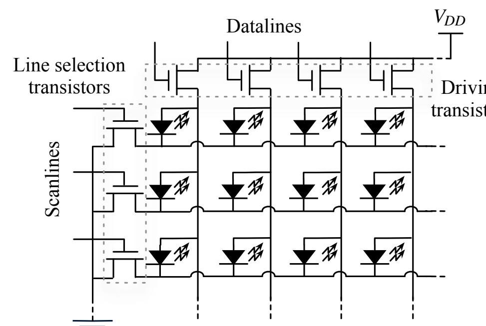
Contributions of this paper can be summarized as follows: i) we introduce the concept of DVS for the OLED displays; ii) we analyze the power model of OLED displays and generate the DVS model based on accurate measurement and characterization of OLED displays; iii) we propose an image compensation algorithm and demonstrate its power saving effectiveness on real images.



(a) DVS-applicable amplitude modulation AMOLED driver.



(b) non-DVS-applicable amplitude modulation AMOLED driver.



(c) Driver matrix circuit for PMOLED driver.

Figure 2: Driver circuit topologies of (a) DVS-applicable driver, (b) non-DVS-applicable driver for AMOLED display and (c) PMOLED driver matrix circuit.

2. ORGANIC LED DISPLAY

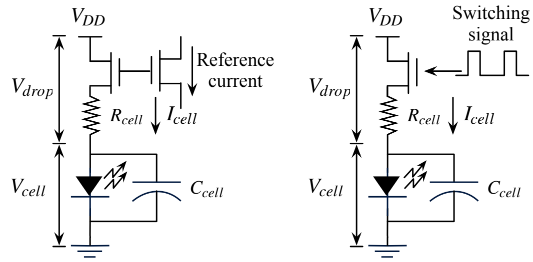
2.1 OLED Cell Structures

Figure 1(a) shows the typical structure of the OLED cell [3]. The OLED device has a large area, but the thickness of the organic layers between the electrodes is only 100–200 nm. As a result, OLED cells have a large internal capacitance. The internal capacitance is not constant, but depends on the voltage and switching frequency. The value of C_{cell} is typically 200–400 pF/mm^2. OLED cells have a resistive component for each layer that lies between anode and cathode. The dominant resistive component is caused by the transparent Indium-Thin-Oxide (ITO) layer. Hence, the parasitic resistor is in series with the internal capacitance. The value of the parasitic resistor is strongly dependent on the design of the ITO electrode (anode). A typical value of the cell resistance is 15Ω/sq[1]. We calculate the R_{cell} with the cell area and sheet resistance. A simple equivalent circuit obtained with the physical parameters is depicted in Figure 1(b). It consist of the parasitic resistor R_{cell}, internal capacitance C_{cell}, and a diode Q_{cell}.

2.2 OLED Driver Architectures

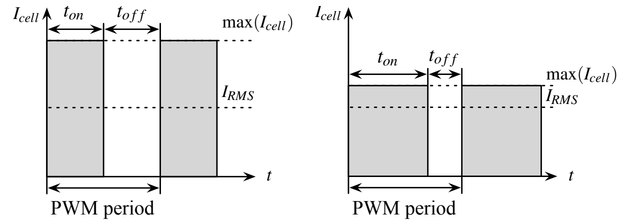
There are several ways to classify the OLED driver architectures. Like LCD panels, we can make an OLED panel with a passive matrix (PMOLED) or an active matrix (AMOLED). PMOLED panels have a relatively simpler structure and thus a low cost. How-

[1] Ω/sq denotes the sheet resistance.



(a) AM driver. (b) PWM driver.

Figure 3: Behavioral concept of (a) AM driver and (b) PWM driver for the OLED display.



(a) OLED cell current with the maximum supply voltage. (b) OLED cell current with the scaled supply voltage.

Figure 4: OLED cell current with (a) the maximum supply voltage and (b) scaled supply voltage.

ever, the practical maximum size is limited, typically up to 3". In contrast, a thin film transistor (TFT) controls every pixel of AMOLED panels similar to TFT LCD panels. Thus, AMOLED panels can be implemented with large size, but more complicated and expensive.

The OLED cell current, I_{cell}, determines its luminance. The cell current is basically controllable by adjusting the cell voltage, V_{cell}. However, because the parasitic resistance is not stable, we commonly use a constant current driver. We can easily make a constant current source with a current mirror. We call an OLED driver using a current mirror-based current steering circuit an amplitude modulation (AM) driver. AMOLED panels are typically controlled by an AM driver circuit. There is a current source transistor whose gate voltage is maintained by a storage capacitor in the AM AMOLED driver. The storage capacitor is tied to either V_{DD} (Figure 2(a)) or GND (Figure 2(b)). The AM driver scheme ensures a higher reliability and efficiency of the OLED cells. However, the current steering circuit consumes large area, which results in higher cost.

On the other hand, PMOLED panels have a row-column structure driver circuit as shown in Figure 2(c). There is no storage capacitor in the PMOLED driver circuit. The cell current can be a pulsed current. We can easily achieve a pulse width modulation (PWM) of the cell current in the PMOLED panels. The luminance of an OLED cell is actually dependent on the average value of I_{cell}. The PWM cell current steering is inexpensive and provides precise luminance control. However, it is known to be less power efficient in high luminance region [3]. Unfortunately, the PWM driver in AMOLED panels is expensive. Some AMOLED drivers use both PWM and AM at the expense of even higher cost to tackle both display quality and power consumption.

There is an important requirement for the driver structure to apply DVS to an OLED panel, which is described in Section 3. Basically, V_{DD} change should not alter I_{cell} to make the DVS of an OLED panel feasible. In other words, V_{DD} change should not incur V_{GS} change. The relationship between V_{DD} and V_{GS} is dependent on the storage capacitor position. DVS changes the cell current and thus prohibits the DVS if the storage capacitor is hooked up to V_{DD} as shown in Figure 2(a). Thus, the DVS can be applied to AMOLED panels with a driver structure that in Figure 2(b) and PMOLED panels.

3. OLED DVS

3.1 Supply Voltage Scaling of OLED Drivers

The concept of DVS of an OLED panel is to reduce power loss due to V_{drop} by scaling down V_{DD} (Figure 3). As mentioned in Section 2.2, there is no change in I_{cell} in the AM driver as far as the driving transistor remains in the saturation mode (Figure 3(a)). Of course, the driving transistor goes into the triode mode if I_{cell} is large enough. The cell luminance decreases as we scale down V_{DD} in this case, which can cause image distortion. DVS acts a bit differently in a PWM driver (Figure 3(b)). Scaling V_{DD} down directly affects I_{cell}. So we need to restore the luminance of image. We apply an appropriate image data modification (image compensation) to restore the luminance with a PWM driver in Section 4. Unfortunately, the image compensation cannot always restore the original luminance. If the original I_{cell} is large, the maximum possible I_{cell} under a reduced V_{DD} cannot be the same as the original I_{cell} even when the PWM duty ratio is set to 100%. Thus, luminance distortion for some very bright pixels becomes unavoidable for both the AM and PWM drivers. We sacrifice a small display quality by allowing a certain amount of color distortion of the image but save significant amount of power consumption.

The power loss of OLED cell is given by $P_{loss} = I_{cell}V_{drop}$. Typical OLED driver has 50% to more than 100% headroom between V_{DD} and V_{cell} to ensure contrast and reliable luminance control of the OLED cell for AM drivers. A large enough headroom is generally beneficial for display quality, but, at the same time, it results in a large V_{drop} which gives rise to power inefficiency. PWM drivers also maintain a large headroom to guarantee accurate current control, and hence high image quality.

The proposed OLED DVS is thus can be applicable to both PMOLED and AMOLED panels where the storage capacitor is connected to GND. The forward bias voltage of the diode, V_f and R_{cell} determine the maximum valus of I_{cell}

$$\max(I_{cell}) = (V_{DD} - V_f)/R_{cell}. \tag{1}$$

The luminance of the OLED is approximately proportional to the root mean square (RMS) value of I_{cell}, I_{RMS}, which is calculated as

$$I_{RMS} = \max(I_{cell})\sqrt{\frac{t_{on}}{t_{on}+t_{off}}}, \tag{2}$$

where t_{on} and t_{off} are the switch turn on and off durations in a PWM period, respectively. The power loss of an OLED cell during a PWM period is calculated by

$$P_{loss} = {I_{RMS}}^2 R_{cell}. \tag{3}$$

The analysis of OLED DVS with an AM driver is simpler. Note that I_{cell} does not change over time unless the color is changed. The power loss of an AM driver OLED cell is given by

$$P_{loss} = I_{cell}(V_{DD} - V_f). \tag{4}$$

As a result, from (3) and (4), we can reduce the power consumption in an OLED cell while preserving the luminance by using a reduced V_{DD}.

3.2 OLED Display Characterization

We measure the relationship between the power consumption and luminance/chromaticity of an OLED panel while changing

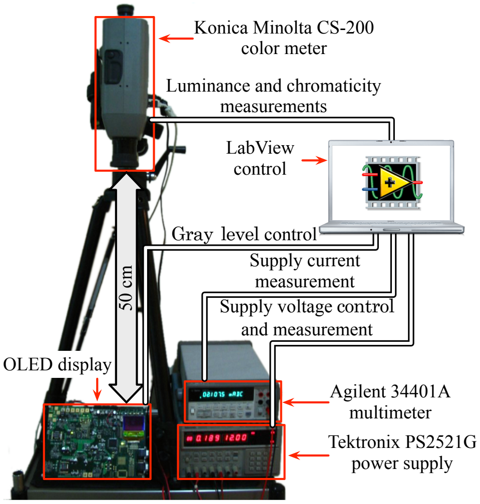


Figure 5: Experimental setup for the OLED panel characterization.

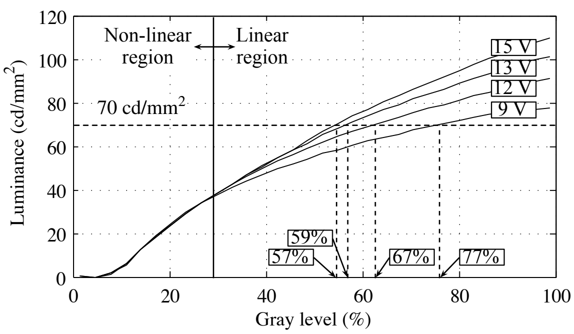


Figure 6: Measured luminance by V_{DD} and gray level.

V_{DD} and pixel colors. We setup the measurement environment as shown in Figure 5. The target OLED panel is UG-2076GDEAF02 from Univision Technology [15] with a 2.2" display area, a 220×176 resolution and a PMOLED structure with a PWM driver. We change V_{DD} with a programmable power supply and measure the current with an Agilent 24401A multimeter. We use a Konica Minolta CS-200 color meter to measure the luminance and chromaticity of the OLED panel. The experiment is automated by a National Instruments LabView. We perform the entire measurement process in a darkroom to block ambient light.

We visualize a part of characterization data in Figure 6 as an illustrative purpose. This demonstrates that the OLED display can achieve the same luminance by adjusting the color value (gray level here) even under different V_{DD} levels. In other words, we can restore the color value with a reduced V_{DD}, which proves the key premise of DVS for OLEDs. As we can see in Figure 6, the OLED panel generates a 70 cd/mm^2 luminance with a 15 V, a 13 V, a 11 V, and a 9 V V_{DD} by setting the gray level to 57%, 59%, 64%, and 77%, respectively. It turns out that the luminance is not affected by V_{DD} when the gray level is below a certain level such as non-linear region in Figure 6. Therefore, only in the linear region of Figure 6, we can compensate the voltage scaling-induced luminance reduction by modifying image data. We will perform the image compensation in Section 4 only for the linear region.

From (1) and (2), I_{cell} is proportional to V_{DD} and PWM duty ratio such that $d = t_{on}/(t_{on}+t_{off})$, i.e,

$$I_{cell}(d, V_{DD}) = p_1 V_{DD} d + p_2 d + p_3, \tag{5}$$

where p_1, p_2, and p_3 are characteristic coefficients. With the help of actual measurements, we characterize I_{cell} for an OLED panel in the form of (5).

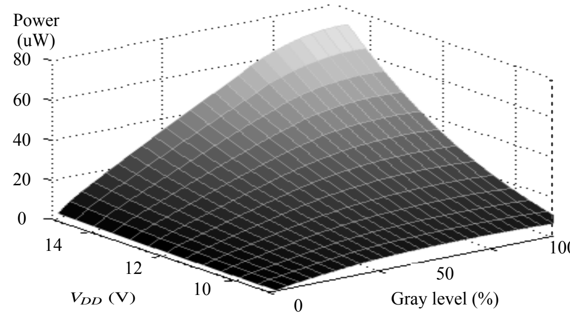


Figure 7: Measured power consumption by V_{DD} and gray level

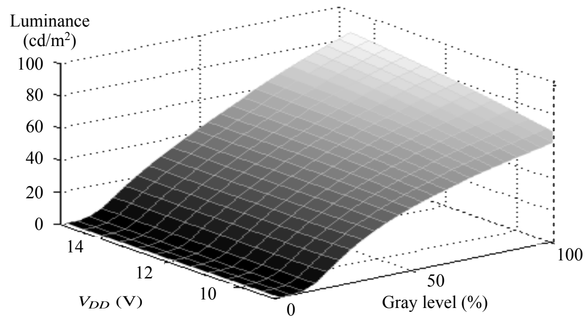


Figure 8: Measured luminance by V_{DD} and gray level.

Figures 7 and 8 demonstrate the target OLED panel power consumption and luminance according to the gray level of pixels and the supply voltage. We set the same gray level to all pixels in the panel. We repeat the same experiment for red, green and blue colors and fill various entries of Table 2.

3.3 Color Characterization for OLED DVS

We use human perception-aware color space to evaluate the image distortion. Typical RGB and CMYK spaces reflect the output of physical devices rather than human visual perception. CIE Lab color space is designed to approximate human-perceived vision. It is derived from the CIE 1931 XYZ color space, which reflects the spectral distribution of colors, and can be computed via simple formulas from the XYZ space. Due to its perceptual uniformity, its L component closely matches the human perception of brightness. The Euclidean distance in the Lab color space is widely used as a metric to measure the human perceived color difference [16].

The XYZ measurement result shows that X, Y, and Z values of RGB pixels are highly correlated (almost linearly proportional) with the cell current or almost constant regardless of the cell current. We build a transformation function using regression analysis which is given by

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} a_X \\ a_Y \\ a_Z \end{bmatrix} I_{cell} + \begin{bmatrix} b_X \\ b_Y \\ b_Z \end{bmatrix}, \tag{6}$$

Table 2: Extracted parameters for the power estimation and image difference evaluation (I_{cell} is in μA).

	R		G		B	
I_{cell} estimation	p_1	6.648e-2	p_1	6.701e-2	p_1	6.734e-2
	p_2	-4.951e-1	p_2	-4.944e-1	p_2	-4.798e-1
	p_3	4.957e0	p_3	4.992e0	p_3	4.790e0
Image difference evaluation	a_X	3.573e5	a_X	1.035e5	a_X	4.903e4
	b_X	-4.554e-1	b_X	-2.764e-1	b_X	-3.230e-1
	a_Y	1.793e5	a_Y	2.556e5	a_Y	6.139e4
	b_Y	-2.282e-1	b_Y	-7.086e-1	b_Y	-3.020e-1
	a_Z	0.000e0	a_Z	2.263e4	a_Z	2.384e5
	b_Z	7.100e-3	b_Z	-6.030e-2	b_Z	-1.937e1

Algorithm 1: Algorithm for OLED DVS.

Input: Image $I = (R,G,B)$ and image distortion tolerance t_{image}.
Output: Transformed image I'

1. Set the supply voltage at the maximum supply voltage V_{max}.
2. Decrease a supply voltage step ΔV_{DD} from the previous supply voltage.
3. Calculate the power reduction by (5).
4. Calculate the average image distortion $\bar{\varepsilon}$ caused by supply voltage scaling by (8).
5. Calculate minimum grayscale step increment for R, G, and B by (5)–(8) to increase enough amount of I_{cell} to satisfy the image distortion tolerance constraint ($\bar{\varepsilon} \leq t_{image}$).
6. Calculate the power of the modified image and scaled voltage by (5).
7. If the voltage scaling induced power reduction is less or equal to the required power to satisfy the the image distortion tolerance constraint, then stop the DVS.
8. Otherwise, repeat 2–7.

where coefficients a_X, a_Y, a_Z, b_X, b_Y, and b_Z are obtained by performing the regression analysis on the measurement results, and are summarized in Table 2.

4. IMAGE COMPENSATION

4.1 OLED Panels with An AM Driver

The transistor in an AM driver is originally designed to operate in the saturation mode. Operation in the saturation mode ensures the same I_{cell} regardless of changes in the V_{DD} level. The proposed OLED DVS lowers V_{DD} in such a way that the transistor is no longer guaranteed to operate in the saturation mode. More precisely, if the color value is small enough, the reduced V_{DD} does not change the transistor's operation mode. On the other hand, if the color value is large, reduced V_{DD} can change the transistor's operation mode to the triode mode, which means that the original cell luminance is not preserved. In this paper, with AM driver, we do not attempt to combat the color distortion by changing the cell luminance. Instead we limit the number of distorted pixels by imposing a lower bound on the minimum value of V_{DD}.

4.2 OLED Panels with A PWM Driver

From (1), the reduced V_{DD} decreases the luminance of every OLED cell. At the same time, we can restore the luminance by increasing the PWM duty ratio, t_{on} in (2). As described in Section 3.2, bright images have pixels with a high gray level that are affected by V_{DD} decrease, and so image compensation is required. In contrast, dark images are not affected as much as the bright images by V_{DD} decrease, and so image compensation is seldom required for dark images. We convert an original image $I = (R,G,B)$ in RGB space image to an XYZ space image such that $I_{xyz} = (X,Y,Z)$ by (5) and (6). We again transform I_{xyz} into a Lab color space image such that $I_{lab} = (L^*, a^*, b^*)$ by using the following transform functions [17]:

$$\begin{aligned} L^* &= 116 \cdot (Y/Y_w)^{\frac{1}{3}} - 16 \\ a^* &= 500 \cdot ((X/X_w)^{\frac{1}{3}} - (Y/Y_w)^{\frac{1}{3}}) \\ b^* &= 200 \cdot ((Y/Y_w)^{\frac{1}{3}} - (Z/Z_w)^{\frac{1}{3}}), \end{aligned} \tag{7}$$

where L^*, a^* and b^* are matrices representing brightness, red-green content, and yellow-blue content in the Lab color space, respectively. Values of X_w, Y_w, and Z_w are the color coordinate values of the reference white in the color space.

We describe the human-perceived image difference with the Euclidean distance in the Lab color space. The Euclidean distance between two different colors $c_1 = (L_1^*, a_1^*, b_1^*)$, $c_2 = (L_2^*, a_2^*, b_2^*)$ in the Lab color space is calculated by

$$\varepsilon = (L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2. \tag{8}$$

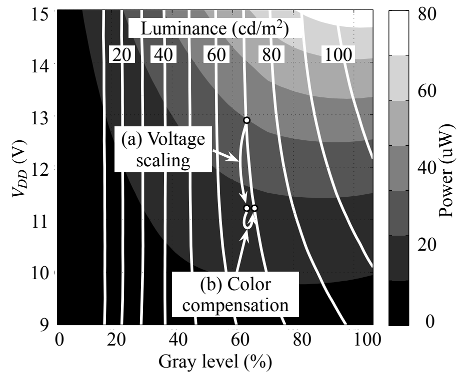


Figure 9: Power and luminance measurement with a different supply voltage and image data.

The Lab color space considers two colors to be perceptually identical when the Euclidean difference between the two color is less than a certain threshold. The threshold is generally determined by the human vision characteristics and environmental conditions, but it can also be determined by the user. As a result, we formulate an optimization problem to find a transformed image $I' = (R', G', B')$ and V_{DD} that maximize the power saving subject to a threshold for distinguishing two colors. The threshold, t_{image}, can be thought of as the maximum allowable average Euclidean distance $\bar{\varepsilon}$ between the original and compensated images.

To show the behavior of the OLED DVS algorithm, we overlap Figures 7 and 8 on the same gray-level and V_{DD} plane as shown in Figure 9. Figure 9 shows the luminance and power consumption of an OLED under different gray levels and V_{DD} values. The points on the same contour line impliy the same luminance value. At the same time, the gray level where the point is located implies the amount of power consumption. The behavior of the proposed OLED DVS algorithm is as follows. The upper dot in the Figure 9 represents the original V_{DD} and gray level. The dot moves straight down by V_{DD} scaling ((a) in Figure 9), losing luminance and consuming less power. The image compensation ((b) in Figure 9) recovers the luminance with a higher gray-level value. This new gray-level incurs higher power consumption, but the final power consumption of OLED after V_{DD} scaling and image compensation is still lower than that of the original OLED. In fact, V_{DD} and gray level are not continuous but discrete. Algorithm 1 depicts how to iteratively derive the optimal discrete V_{DD} and gray scale level.

The major computational overhead of OLED DVS is the estimation of the image distortion and calculation of image compensation. We can derive them by using a pre-generated lookup table depending on the characteristics of the OLED panel and the driver architecture [1]. Size of the table is determined by the number of color values and the number of supply voltage levels. These parameters strongly affect the performance obtained by the proposed OLED DVS scheme such as delay penalty to display/update an image on the OLED panel and power saving.

5. EXPERIMENTS

We evaluate the actual power gain and resultant image quality from the proposed OLED DVS on real images. Figure 10 delivers important information about the original image and scaled image. It consists of i) image quality, ii) color histogram, iii) scaled V_{DD}, iv) power consumption, and v) power savings. We implement

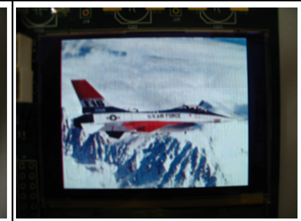
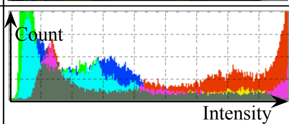
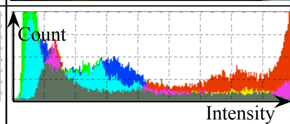
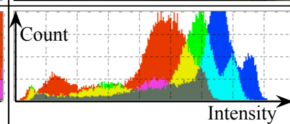
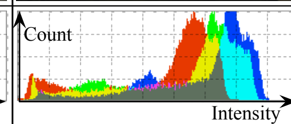
t_{image}	Original image	10	Original image	300
Viewed image				
Color histogram				
V_{DD} (V)	15.0	8.7	15.0	12.0
Power (mW)	399.9	189.8	731.7	572.5
Saving (%)	-	52.5	-	21.8

Figure 10: Image compensation results, color histogram, V_{DD}, and power consumption by image difference tolerance constraint $\bar{\varepsilon}$.

OLED DVS prototype and do the measurements on a real hardware testbed. In particular, we use the same experimental setup as that introduced in Section 3 to measure power consumption.

We work with two images, Lena and an airplane. The Lena image has a typical (balanced) color distribution while the airplane image has a severe skew toward the bright colors, which is very bad for the OLED DVS. The originally high luminance pixels are saturated to the maximum luminance as shown in the compensated images and histograms. The saturated pixels result in the image distortion, but the overall image quality is not appreciably altered within the threshold value. The Lena image shows up to 52.5% power saving compared to the original image, with the 15 V supply voltage being scaled down to 8.7 V and with nearly zero color distortion. A sort of the worst case, the airplane, still exhibits 21.8% power saving compared to the original image with 15 V supply voltage for the threshold value of t_{image} = 300. We determine the distortion threshold by the most distorted pixel. In practice, pixels in very bright areas of the displayed image are distorted even after compensation. We determine the value of distortion threshold so as to prevent the most distorted pixel from losing more than half of their original luminance

6. CONCLUSION

Organic light emitting diode panels are promising display devices capable of self-illumination and thus exhibiting high power efficiency. However, even such a high-efficiency OLED panel generally consumes more power than a microprocessor that is present in the same system. All previous OLED power saving methods change the pixel colors since the pixel color determines the OLED power consumption. Unfortunately, these methods result in significant degradation of the image.

This paper presented the first OLED power saving method that enables only minimal pixel distortion, small enough to work with natural images. Furthermore, the proposed technique can be applied to most OLED panel structures. We developed such a unique power saving technique based on a careful analysis of the OLED driver architectures. The proposed method is called OLED dynamic voltage scaling (OLED DVS). The idea is to scale down the supply voltage and, in turn, dramatically reduce the wasted power caused by the voltage drop across the driver transistor as well as internal parasitic resistance. The proposed OLED DVS may incur image distortion after the supply voltage scaling. In this case, we compensate the image data based on the human-perceived color space. We demonstrated the OLED DVS with a prototype implementation and confirmed a 52.5% power saving for the Lena image with virtually zero distortion.

As for future work, we will apply the proposed OLED DVS to AMOLED panels with amplitude modulation drivers. We will also complete the prototype implementation of a supply voltage control circuit and an image compensation method allowing OLED DVS and image compensation.

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