

Saliency aware display power management

Yang Xiao, Kevin Irick, Vijaykrishnan Narayanan

Dept. of Computer Science and Engineering
The Pennsylvania State University
University Park, PA
{yux106,irick,vijay}@cse.psu.edu

Donghwa Shin, Naehyuck Chang

Dept. of Electrical Engineering and Computer Science
Seoul National University
Seoul, Korea
{dhshin,naehyuck}@elpl.snu.ac.kr

Abstract— In this paper, a bio-inspired technique of finding the regions of highest visual importance within an image is proposed for reducing power consumption in modern liquid crystal displays (LCDs) that utilize a 2D light-emitting diode (LED) backlighting system. The conspicuity map generated from this neuromorphic saliency model, along with an adaptive dimming method, is applied to the backlighting array to reduce the luminance of regions of least interest as perceived by a human viewer. Corresponding image compensation is applied to the saliency modulated image to minimize distortion and retain the original image quality. Experimental results shows average 65% power can be saved when the original display system is integrated with a low-overhead real-time hardware implementation of the saliency model.

Keywords—FPGA and ASIC design; LED; LCD; system level power management

I. INTRODUCTION

Modern multimedia entertainment applications are pervasive in a wide spectrum of digital visualization platforms including personal computers, notebooks, smartphones and large screen flat panel televisions. Common among these devices is the integration of Thin-Film Transistor (TFT) Liquid Crystal Displays (LCDs) for delivering rich and engaging user interfaces.

The liquid crystal elements in an LCD panel themselves do not emit light and require a separate light source. Traditional transmissive LCD devices use a backlight panel as the lighting source. Currently two classes of lighting sources are employed as the backlight component. The fluorescent lamp class consists of the Cold Cathode Fluorescent Lamp (CCFL) and the Hot Cathode Fluorescent Lamp. The newer class of backlighting technology is based on light-emitting diodes (LEDs). This latter technology offers many advantages including greater dynamic contrast, wider color gamut, and higher power efficiency.

Among all display components, however, the backlighting system is the dominant power consumer regardless of the particular lighting technology or class. For this reason, many display power saving approaches actively dim the backlight. In [1], dynamic luminance scaling is presented, which modulates the luminance of the CCFL backlight source according to the current image being displayed on the LCD panel. In addition, it adaptively applies brightness compensation and image

enhancement based on the class of images being displayed. The authors report that 20% to 80% power savings can be achieved from the proposed system. In [2], an X-Y channel dimming strategy is proposed, in which the LCD panel is partitioned into an X-Y grid of LED zones. Within each zone, the luminance level is determined as the maximum luminance level of all pixels within the zone. For each zone the resultant luminance is set to the minimum zone luminance across the row and the column driver of that given zone. By using this method the number of LED drivers is linear to the sum of the block numbers along rows and columns. Besides dimming, image compensation is also applied to each pixel to retain image quality as perceived by a human observer.

In addition to active backlight dimming techniques, passive methods have been proposed for LCD power reduction. In [3], low power sensors are used to detect user intent and behavior for energy management of laptops. The authors of [4] introduce a camera based power saving strategy that utilizes a camera system to track a user's attention and accordingly control pixel luminance. The screen is brightest when the system determines that the user is paying attention and dim otherwise. This approach is primarily useful for single user laptop and smartphone displays rather than LCD monitor and television displays due to the complexity of tracking multiple viewers' eye gaze from arbitrary distances.

Dimming the LCD at the granularity of backlight zones is presented in [5] and [6]. In [5] the luminance level is set as the ratio between the average grayscale value of each pixel and the maximum pixel value representable: 255 for an 8-bit representation. The method, however, does not apply subsequent image compensation. The authors of [6] propose a three steps object recognition scheme for local backlight dimming on LED panels. The first step is object recognition in which the largest object based on color similarity is located and its majority color is used as a bias for subsequent dimming. Secondly, local dimming is applied based on the majority color. The backlight is dimmed on the constraint that the value of the major color does not exceed the representable limit of a single color channel (i.e., 255 in an 8-bit representation). Finally, image enhancement is applied to remove significantly visible artifacts on the image.

In this paper, we propose a visual saliency mechanism for scaling the backlight of LCD displays with 2D LED backlight arrays. Moreover, we propose an adaptive image compensation technique for preserving quality of viewer experience.

This work was supported in part by NSF grants 0916887, 1205618 and the Intel Science and Technology Center on Embedded Computing.

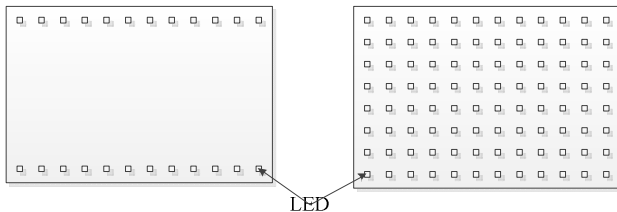
This work was also sponsored by grants from the BK21 Project and the NRF of Korea funded by the MEST (No. 20110030512)
978-3-9815370-0-0/DATE13/©2013 EDAA

Although our approach has similarities to [6], it is fundamentally different in methodology. The key distinction is that our approach utilizes a neuromorphic saliency measure based on a comprehensive set of image features to localize regions of attention rather than based simply on color variances. As far as we know, this is the first paper that applies a model of the parietal or dorsal stream in the visual cortex for power saving within LCD displays. The main organization of the paper follows: Section II presents a short survey of the principal backlight sources used in modern LCD display technology. Section III provides a fundamental introduction of the neuromorphic saliency algorithm. Section IV details the system level aspects of the neuromorphic power saving model and discusses the image compensation technique. Section V provides experimental results.

II. LED BACKLIGHT SYSTEM

A. LED Display Array

LED display technology is becoming increasingly more common than LCD technology due to its higher dimming ratios, and lower operating voltage. Because of those benefits, we consider LED display technology in this work.



Left: backlight panel with Edge LED
Right: back light panel with LED array

Figure 1. Different types for backlight panel

Among the LED display technology, there are two categories that are distinguished by the backlight organization [8]. The first category, edge-lit panels, consists of panels that organize the LED backlights along the edges of the panel. The second category consists of panels that organize the backlights as a 2D array across the entire panel. As the name suggests, the LEDs of the first category are installed behind the edges of the LCD panel: one, two, or all four possible installations. A light guide is used for spreading light evenly across the LCD panel. Although edge-lit displays can be made more power efficient and ultra-thin, they are limited in applicable dimming strategies because they can only be dimmed at the panel level. This problem is solved by the 2D LED array panel inherently. On the LED panel, a dense array of LEDs is distributed across the area. To simplify the control of pixel, the LED array is divided into zones. As a result, dimming the luminance is at the granularity of zones making the 2D array LED panel a good candidate for applying region-of-interests algorithms such as the one we are using for power saving. An example of a LED backlight panel is shown in Figure 2 according to [8]. As the figure illustrates, an LED panel is divided into $M \times N$ zones, where $M = 8$, $N = 8$ in this case, and each zone has a chain of LEDs controlled by the same driver circuit. Totally 576 LEDs are embedded with each zone containing 9 LEDs. In our experiments, an LED panel with 128 zones ($M = 8$, $N = 16$) is

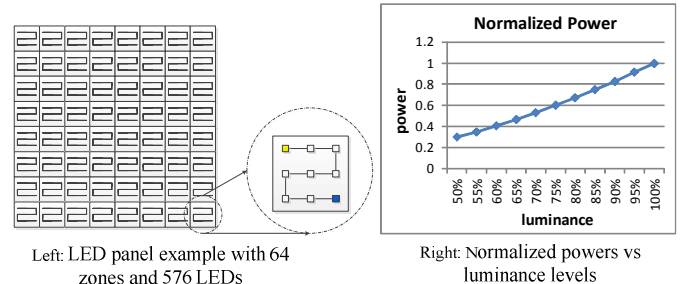
used with each zone having 9 LEDs. All the experiments are done based on this LED model.

B. LED Power Model

With the appropriate luminance distribution model, we derive the power consumption based on the luminance of the backlight panel. A power model from [13] which uses the relationship between the luminance and power consumption shown in (1) is adopted for computing normalized power saving. We scale the result considering the area of display and the number of LED in the panel.

$$P = (0.00374b^2 + 3.2194b - 10.576)(mW) \quad (1)$$

Here b is the average luminance in the zone and the total power of the panel is the sum across all the LED zones. We calibrate our model carefully so that the power is similar to 100W for a typical 40 inch LED-TV [14] when all the backlight LEDs illuminate at full level. Furthermore the corresponding power estimations of luminance levels from 100% to 50% are computed and shown in the right side of Figure 2. Those data inspire us that there is a big opportunity to have substantial power consumption via dimming.



Left: LED panel example with 64 zones and 576 LEDs

Right: Normalized powers vs luminance levels

Figure 2. LED panel example and estimated normalized power

III. SALIENCY ALGORITHM

The saliency-based attention model originates from the work of Itti, Koch, and Niebur [7]. In their work, a bottom-up saliency model was derived that mimics the ability of primates to focus visual attention to important areas in the field-of-view in a short period following the initial exposition of the view. The system diagram of the bottom-up saliency algorithm containing three major computing steps is shown in Figure 3. In the first step, the original input image is low-pass filtered and sub-sampled according to the step sizes in $\{0..8\}$ to create a nine scales image pyramid for supporting scale invariance described in [7]. From the image pyramid, three types of conspicuity pyramids, color, intensity, and orientation, are generated scale by scale (from Scale 0 to Scale 8). The color conspicuity pyramid, including the red-green, green-red, blue-yellow, and yellow-blue, is generated by applying a pixel-wise color opponent process between the respective color channels of the original image pyramid. The intensity pyramids is created by averaging the sum of R, G, and B channel values for each pixel on each scale of image pyramid. The last pyramid, orientation type, is acquired by projecting oriented Gabor filters on each scale of the image pyramid of certain degree. In our case, the Gabor filters are used for detecting the angles of $[0^\circ, 45^\circ, 90^\circ, 135^\circ]$.

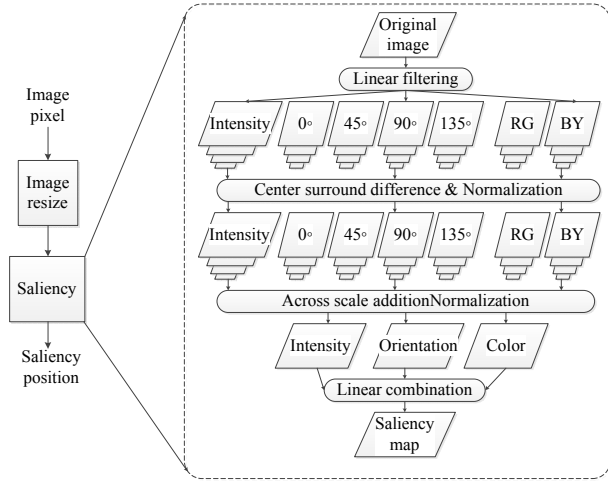


Figure 3. Overview of saliency algorithm

In the second step, each conspicuity pyramid is subsequently passed through an operation called ‘center-surround difference’ to compute feature map. The purpose of this operation is to compute the differences between the feature responses at the finer scales $\alpha = \{2, 3, 4\}$ and the corresponding feature responses in the coarser scales $\beta = \alpha + \gamma$, $\gamma = \{3, 4\}$. We refer to this across-scale difference operator as Θ . Passing those conspicuity pyramids will generate the intensity feature map $I(\alpha, \beta) = |I(\alpha) \ominus I(\beta)|$, the color feature maps $RG(\alpha, \beta) = |(R(\alpha) - G(\beta)) \ominus (G(\beta) - R(\alpha))|$, $BY(\alpha, \beta) = |(B(\alpha) - Y(\beta)) \ominus (Y(\beta) - B(\alpha))|$, and the orientation feature map $O(\alpha, \beta, \theta) = |O(\alpha, \theta) - O(\beta, \theta)|$ correspondingly. Here, a feature map normalization operator denoted by $\mathcal{S}(\cdot)$ is applied to each of the resulting feature map. This operation promotes the maps that have strong value peaks compared to mean value and suppresses those contains many similar peaks.

The third step is a sum-up procedure across scales; we call this operation ‘across-scale addition’, denoted as \oplus . It will reduce the feature maps at all scales to one single center scale (4th scale in the case of a pyramid with 9 scales). Three of them, aka ‘conspicuity channels’, are composed at scale $\sigma = 4$ from the feature maps via across-scale addition as shown in the following three equations:

$$\bar{I} = \bigoplus_{\alpha=2}^4 \bigoplus_{\beta=\alpha+3}^{\alpha+4} \mathcal{S}(I(\alpha, \beta)) \quad (2)$$

$$\bar{C} = \bigoplus_{\alpha=2}^4 \bigoplus_{\beta=\alpha+3}^{\alpha+4} [\mathcal{S}(RG(\alpha, \beta)) + \mathcal{S}(BY(\alpha, \beta))] \quad (3)$$

$$\bar{O} = \sum_{\theta \in [0^\circ, 45^\circ, 90^\circ, 135^\circ]} \mathcal{S} \left(\bigoplus_{\alpha=2}^4 \bigoplus_{\beta=\alpha+3}^{\alpha+4} \mathcal{S}(O(\alpha, \beta, \theta)) \right) \quad (4)$$

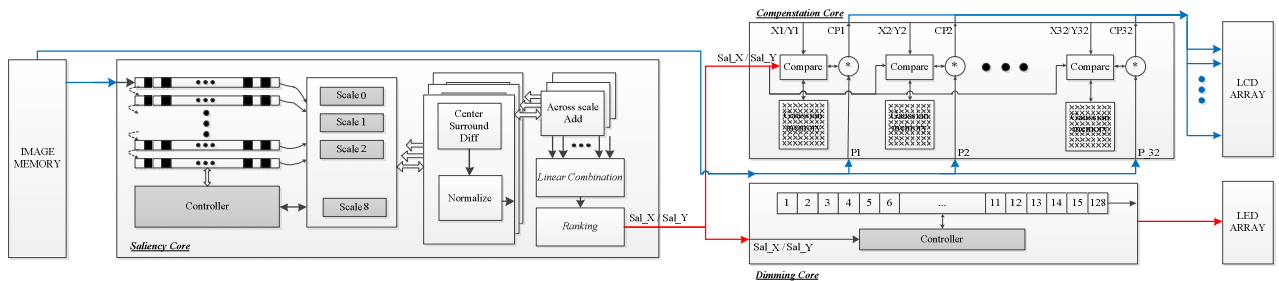


Figure 4. System overview of neuromorphic power saving methodology

With the three separate conspicuity channels, the final saliency map is obtained from equation (5).

$$S = \frac{1}{3} (\mathcal{S}(\bar{I}) + \mathcal{S}(\bar{C}) + \mathcal{S}(\bar{O})) \quad (5)$$

IV. APPLY SALIENCY FOR LCD POWER SAVING

The entire saliency adaptive LED panel control system is depicted in Figure 4. The system is partitioned into two paths. The first path, highlighted in red, involves the saliency accelerator which processes the entire frame identifying the most salient regions and corresponding LED zones and sets the luminance level in the zones that overlap with the salient region. The second path, highlighted in blue, performs pixel compensation within the saliency modulated regions. Among the three processing modules saliency, dimming, and compensation, saliency block is the most computing intensive part and occupies 98% of the total operation time. Simply using the SW implementation can’t support 30 fps videos. Consequently, we explored the saliency algorithm in a custom accelerator as drawn in the left part of Figure 4. The dimming module, bottom-right part in Figure 4, is responsible for computing the distance between each LED zone (total 128 zones) and the closest saliency LED zone and assigning the luminance level accordingly. This will be explained in Section 4.B. The compensation module, up-right part in Figure 4, performs image compensation. It takes in 32 pixels position at one time, computes their distances to the saliency location in the image, picks up a proper Gaussian weight from memory and modifies the color value via multiplying the Gaussian weight. This operation is explained in Section 4.C.

A. Saliency Core

A prototype of the saliency accelerator is implemented on Virtex6 SX475T FPGA with its resource utilization shown in Table I. It takes in a typical High Definition (HD) images, finds the saliency regions, and identifies the corresponding LED zone on the panel. Operating at 100MHz allows it to process 31 frames per second even with consideration to image fetching and saliency result storing. The power consumption, estimated by Xilinx Xpower Analyze, is around 9.1 W. To increase the frame rate to 60 frames per second, we duplicate the accelerator and double the power consumption to 18.2 W which is 18.2% of the power consumption of the LED panel. We represent the upper bound of the power consumption realizable with an ASIC implementation based on the power values from the FPGA prototype. According to [12], the dynamic power consumption ratio from FPGA to ASIC is approximately 14 times. So roughly the accelerator’s power would only occupy a negligible portion, 1.3%, of the total LCD power.

TABLE I. RESOURCE UTILIZATION ON VIRTEX 6 SX475T

	SLICE REGS	SLICE LUTS	BRAM36S	BRAM18S	DSPS
Saliency Core	159,394 (26%)	173,811 (58%)	589 (55%)	404 (18%)	785 (38%)

B. LED Dimming Strategy

The saliency map is used to set the luminance of the corresponding LED regions. The LED regions corresponding to the “n” most salient regions in the image are set to a new luminance level, $L_{initial}$, which is determined by scaling the original luminance by a pre-determined fraction. This fraction is set based on required power savings. Other LED regions within a defined fading range of these salient LED regions receive a luminance value that scales down linearly as a function of their distance from the salient region. A scaling factor γ is used for this linear scaling. This technique results in gradual dimming around the salient regions. The LED regions beyond the defined fading region are not dimmed any further and are assigned the same luminance as those regions at the boundary of the fading distance. So the luminance of a LED zone can be represented by equation (6).

$$L_{zone} = L_{initial} - \gamma \times dist_{ToCenter}, \forall dist_{ToCenter} \in [0, dist_{fading}] \quad (6)$$

Figure 5a (5b) illustrates the luminance setting achieved when with parameter settings of $L_{initial} = 80\%$, $\gamma = 10\%$, and $dist_{fading} = 3$ for a single (two) salient LED region(s) located at grid point [5,5] (grid points [4,9] and [5,5]). The small boxes in these images depict the LED zones, and the shades are used to depict the luminance levels. We identified the influence of the three parameters: $L_{initial}$, γ , and $dist_{fading}$ on the power savings potential by performing several experiments with them. Figure 6(left) shows the influence of different $L_{initial}$ and γ values for a given $dist_{fading}$ of 3. A higher $L_{initial}$ value or increase in the number of salient regions in the image reduces the potential for power saving. The effectiveness of a larger value of γ is observed when the number of salient regions is small.

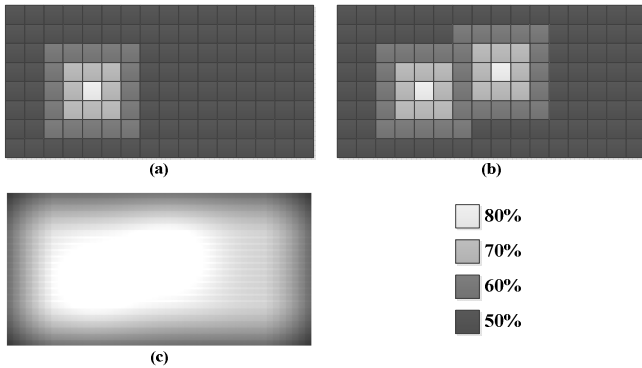


Figure 5. Luminance level distribution based on

$$L_{initial} = 80\%, \gamma = 10\%, dist_{fading} = 3$$

- (a): one salient region at [5, 5] on LED panel
 (b): two salient regions at [5, 5] and [9, 4] on LED panel.
 (c): light distribution of luminance of (b) after diffusing

Since a region receives the luminance corresponding to its closest salient region, the impact of a large value of γ reduces with a larger number of salient regions. A similar behavior is noticed for larger fading distances in Figure 6(right) when number of salient regions increases.

Having understood these power saving tradeoffs, we limit the reported experiment results in the rest of the paper using the values of: $L_{initial}$, γ , and $dist_{fading}$ to 80%, 10% and 3 respectively. Further, we choose two salient regions for our evaluation.

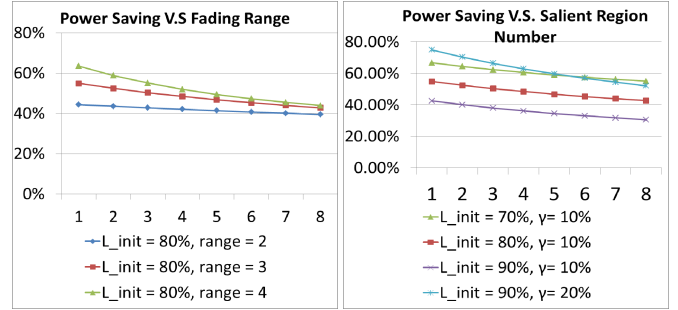


Figure 6. Power Saving vs. Salient Region Number (left) Power Saving vs. Fading Range (right)

C. Image Compensation

The luminance of images received by the human eyes depends on mainly three factors: emitted luminance of the backlight, the transmittance of the liquid crystal in the LCD panel, and the image intensity Y . The perceived luminance by eyes is the product of them as shown in equation (7).

$$L_{perceived} = L_{emitted} \times \rho \times Y \quad (7)$$

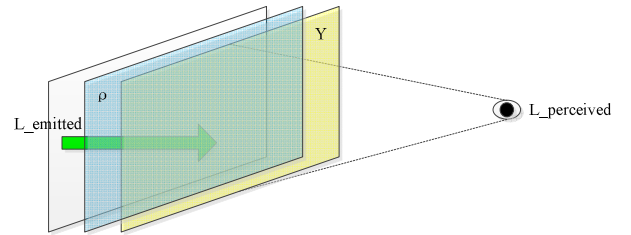


Figure 7. Relationship between emitted luminance from backlight panel with perceived luminance at human eyes

$$L_{perceived} = L_{emitted} \times \rho \times Y$$

$L_{perceived}$: Luminance perceived by human eye

$L_{emitted}$: Luminance emitted by LED panel

ρ : Transmittance of liquid crystal, Y : Image intensity

When we dim the backlight source, the other two factors, transmittance and image intensity should be correspondingly modified to maintain the perceived luminance. Much effort has been dedicated to understand this tradeoff between luminance and perceived image quality. [9] proposes to change the transmittance to compensate for the reduced luminance. In [10], a pixel compensation using a piecewise smoothing function based on the pixel luminance of input image is used.

In [11], the luminance compensation is done via the image RGB value. Inspired by [11], we maintain the perceived luminance by modifying the RGB value. In our settings, the salient LED zones are dimmed to 80% of the initial luminance. Hence, the image compensation coefficient is set to 1.2 for the salient zones. As a result the new perceived luminance is 96% of the original image after dimming. For the neighbor LED zones around the salient zone, the compensation degree of a neighbor zone is controlled based on its distance to the closest salient LED region similar to our settings in the luminance dimming strategy. Consequently, the image compensation coefficients are set to 1.2, 1.3, 1.4, and 1.5 from the center to boundary. The new perceived luminance after compensation is: 96%, 91%, 90%, and 85%. Figure 8(a) illustrates the compensation coefficients of the neighbor LED zones around the salient zone with distances of {1, 2, and 3} region(s) away.

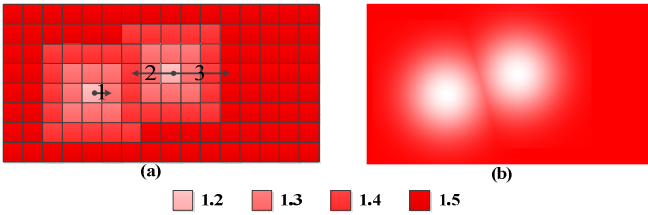


Figure 8. Gaussian distribution of image compensation coefficients

As shown on Figure 8(a), we observe many sharp changes at the edges between two salient zones. To solve this problem, a finer level compensation is used. An inverse-Gaussian function is used for this purpose: the pixel at the center of the salient zone gets the least compensation since it has highest luminance level; the pixel beyond the three-block away zone will have the same largest compensation level since they get dimmed most. The finer granularity compensated image is showed in Figure 8(b). The result shows smoother transitions.

V. EXPERIMENTS RESULTS

A. Image Distortion Verification

For quantitative metrics, we plotted the saliency maps for all the images and observed that the most salient points remain unchanged for 95% of the images, with 4% causing only a small translational shift in most salient point without significant distortion. A small fraction ($\sim 1\%$) shifts the saliency to a new location. Even for these images, 15 users were picked to perform a visual inspection. Every user was asked to pick one of three choices ‘different, dimmed, and same’ for 20 image pairs (original and compensated). As indicated by the test result, the visual perception was not significantly distorted (see Table II). For the other images with no saliency shift there was not an observable visual distortion either. Several images, Figure 9, 10, 11, and 12, randomly are chosen to provide a qualitative assessment of image distortion. The image sets are shown here and the sub-pictures (a), (b), (c), and (d) represent the original image, salient maps, dimmed image, and compensated image respectively. With the help of color compensation, no significant difference can be noticed between the (a) and (d).

TABLE II. USER EXPERIENCE WITH IMAGE

	<i>Different</i>	<i>Dimmed</i>	<i>Same</i>
Ratio	4.33%	41.33%	54.33%

B. Power Saving Comparison to Prior Work

Besides computing the power from our own model, the consumptions are also estimated based on the methods presented in [5], [6]. In Figure 9, the power savings we have achieved is 64.96% compared to 23.60%, and 39.62% for [5] and [6], respectively. While for the mountain scenario in Figure 10, the power saving is 67.45% with our method, 46.31% with [5], and 51.58% with [6]. Beach picture, Figure 11, gives power saving at 66.65%, 21.24%, and 39.86% respectively. The last picture, Figure 12, shows the similar trend on power with saving 65.22%, 34.44%, and 44.37%.

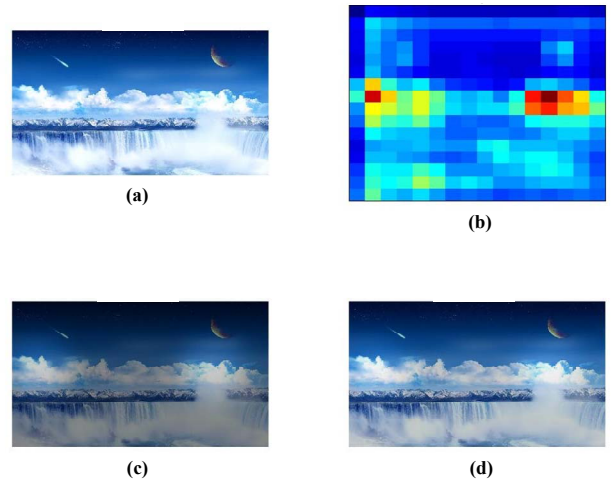


Figure 9. Moon picture before and after dimming LED regions: [4, 2], [4, 12]

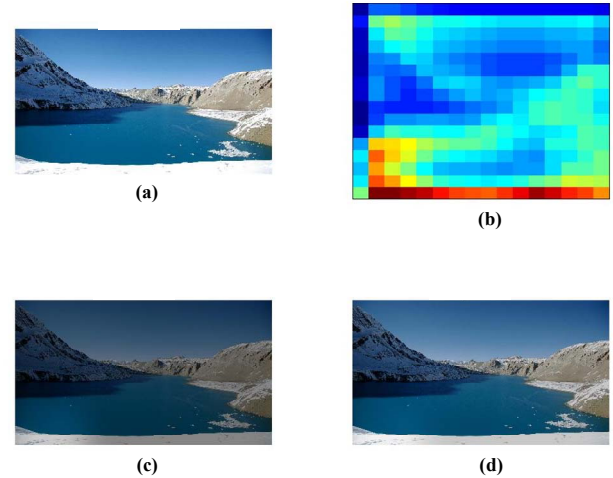


Figure 10. Mountain picture before and after dimming LED regions: [8, 2], [8, 3]

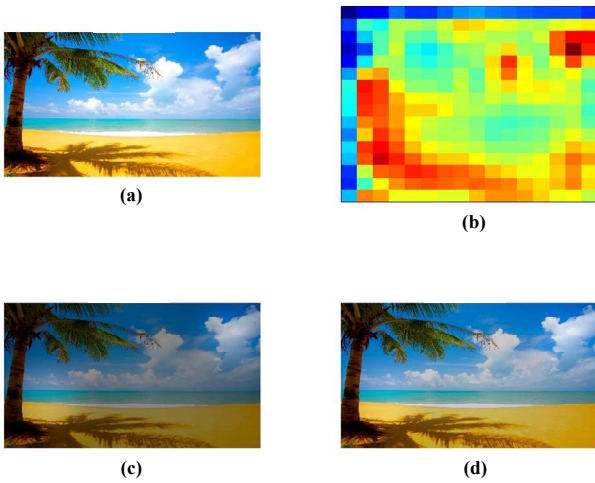


Figure 11. Beach picture before and after dimming
LED regions: [6, 3], [2, 15]

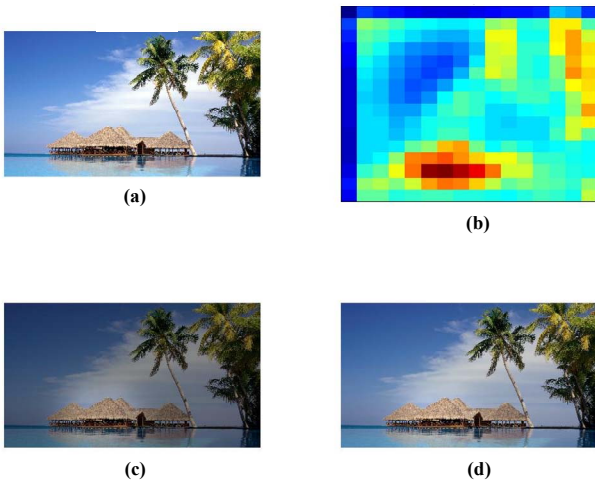


Figure 12. Palm tree and island picture before and after dimming
LED regions: [7, 6], [7, 7]

Figure 13 displays the comparison of average power saving among three methods using 3000 HD test images.

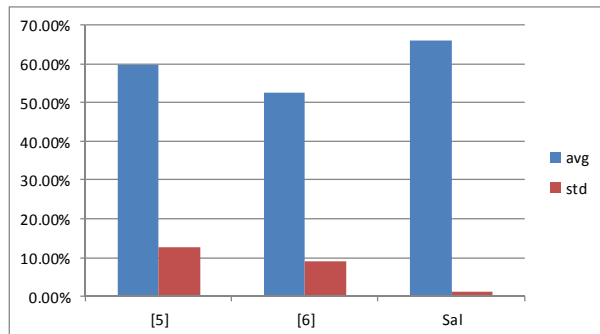


Figure 13. Average power saving and standard deviation among three methods

We can clearly notice not only does our method can achieve the higher saving ratio but also it gives the most stable power saving with 1.26% standard deviation. In general, our model provides a reasonable power saving on both bright and dark images.

VI. CONCLUSION

This paper proposes a new biological power saving method to reduce the power consumption of LED backlit panels. Our methodology dims the LED zones based on the saliency regions found via the saliency accelerator at real-time frame rates. Moreover, the proposed technique does not distort the quality of the original image as validated by pre-post saliency maps check and user experience test. We evaluate this method with 3000 random HD pictures across a broad range of content and the potential power saving is around 65%.

REFERENCES

- [1] Naehyuck Chang, Inseok Choi and Hojun Shim, "DLS: Dynamic Backlight Luminance Scaling of Liquid Crystal Display," *IEEE Trans on VLSI Systems*, vol. 12, pp. 837-846, Aug 2004.
- [2] Won-Sik Oh, and Daeyoun Cho, "A Novel Two-Dimensional Adaptive Dimming Technique of X-Y Channel Drivers for LED Backlight System in LCD TVs," *Journal of Display Technology*, vol. 7, Jan 2009.
- [3] Angela B. Dalton and Carla S. Ellis, "Sensing User Intention and Context for Energy Management," in *Proc. Hot Topics in Operating Systems*, Volume 9, vol. 9, pp. 26-26, 2003
- [4] Vasily G. Moshnyaga and Eiji Morikawa, "LCD Display Energy Reduction by User Monitoring," in *Proc. ICCD*, pp. 94-97, 2005
- [5] Wonbok Lee, Kimish Patel, and Massoud Pedram, "White LED Backlight Control for Motion Blur Reduction and Power Minimization in Large LCD TVs," *Journal of Society of Information Display*, 2009.
- [6] Aldhino Anggorosesar and Young Jin Kim, "Object-based Local Dimming for LCD Systems with LED BLUs," in *Proc. ISLPED*, pp. 315-320, Aug 2011
- [7] Laurent Itti, Christof Koch, and Ernst Niebur, "A Model of Saliency-Based Visual Attention for Rapid Scene Analysis," *IEEE Trans. on Pattern Analysis and Machine Intelligence*, vol. 20, pp. 1254-1259, Nov 1998.
- [8] Noel Giamello, "LED Backlighting for LCDs: options, Design Consideration, and benefits," *Informational document of SHARP Microelectronics of The Americas*, 2010
- [9] Franco Gatti and Andrea Acquaviva, "Low Power Control Techniques for TFT LCD Displays," in *Proc. CASES*, pp. 218-224, 2002.
- [10] Hyunsuk Cho and Oh-Kyong Kwon, "A Backlight Dimming Algorithm for Low Power and High image Quality LCD application," *IEEE Transactions on Consumer Electronics*, vol. 55, pp. 839-844, May 2009
- [11] Inseok Choi and Naehyuch Chang, "Low-Power Color TFT LCD Display for Hand-Held Embedded Systems," in *Proc. of ISLPED*, pp. 112-117, 2002.
- [12] Ian Kuon and Jonathan Rose, "Measuring the Gap between FPGAs and ASICs," *IEEE Trans. Computer-Aided Design of Integrated Circuits and Systems*, vol. 26, pp. 203-215, Feb 2007
- [13] Wei-Chung Cheng, Chih-Fu Hsu and Chin-Fu Chao, "Temporal Vision-Guided Energy Minimization for Portable Displays," in *Proc. ISLPED*, pp. 89-94, Oct 2006
- [14] SONY 40" LED EX640 Internet TV Specification