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Abstract. An adaptive one-dimensional (1-D) dimming technique for liquid crystal displays that compensates for nonuniform backlight distribution is proposed. Dimming techniques that do not consider luminance distribution may cause severe visual artifacts, such as a block artifact. However, an adaptive 1-D dimming technique that considers luminance distribution can reduce power consumption without causing any visual artifacts. Hardware implementation results verified that our method achieved lower power consumption compared to nondimming techniques and removed block artifacts from International Electrotechnical Commission 62087 standard images. The power consumption using the proposed method ranged from 85.5% to 94.7% compared to nondimming techniques. Furthermore, the contrast ratio increased by up to 231% and 165% on average compared to nondimming techniques. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.54.7.073111](https://doi.org/10.1117/1.OE.54.7.073111)]

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1 Introduction

Recently, the increased power consumption of liquid crystal displays (LCDs) has become a concern.^{1–6} To reduce power consumption while increasing image quality in LCDs, various technologies have been studied such as backlight dimming,^{7–15} inversion methods,^{16–18} and charge sharing methods.^{19–24} Based on a demand for slim designs and low power consumption, a side-lit light-emitting diode (LED) backlight unit (BLU) has been widely adopted not only in mobile LCD applications but also in large LCDs.^{9–14}

To further reduce power consumption in LCDs, a dimming technique was developed. Dimming techniques can be generally categorized as three types: zero-dimensional (0-D), one-dimensional (1-D), or two-dimensional (2-D) dimming techniques. The 0-D dimming technique has been widely used in various devices, such as mobile devices and LCD televisions (TVs), because of low cost and simple implementation. For higher image quality and higher power savings, the 2-D dimming technique also has been adopted for large-sized LCDs. With a demand for slimmer design and lower power driving, a side-lit LED BLU has been widely adopted not only in mobile devices but also in large-sized LCDs. For this reason, the 1-D dimming technique has been widely studied. Conventional dimming techniques compensate for the luminance of each LED unit depending on the contents of the image block. Thus, the luminance of the image block area is considered to be uniform.^{25–29} However, the luminance gradually varies across the image block depending on the distance from each LED unit. Thus, the luminance of an image block may not be uniform throughout the block when some LED units are on and others are off.

This phenomenon often causes the boundaries between image blocks to be visible.¹⁰ In this report, we approximate the distribution with polynomial expressions based on measurements and propose a new algorithm that can be implemented easily in hardware. In addition, we demonstrate how the block artifact is eliminated, how the image quality improves, and how much power consumption is reduced.

In this paper, we propose an adaptive 1-D dimming technique for reducing the power consumption and increasing the image quality of LCDs. Through the analysis of input image data and BLU luminance distribution, our proposed 1-D dimming technique selectively dims LEDs only when the compensated image guarantees a net power benefit and higher image quality. In Sec. 2, we propose the basic principle of the adaptive 1-D dimming technique. In Sec. 3, we present the experimental results. Finally, Sec. 4 provides a summary and conclusion.

2 Distribution of Side-Lit Light-Emitting Diode Backlight Unit and Pixel Compensation

An adaptive dimming technique dims a BLU according to input image data. In this paper, we assume that LEDs are placed at the lower edge of the LCD panel and are divided into eight units. Figure 1 shows the schematic image of luminance distribution for dimmed LED units over an LCD panel with a side-lit LED BLU.

In Fig. 1, a sample image is divided into eight blocks (i 'th image block, $i = 1$ to 8). Moreover, LEDs are divided into eight regions (i 'th LED unit, $i = 1$ to 8). Figure 1(a) shows the ideal luminance distribution of four turned-on LED units while the other four are off. However, we found that the actual luminance distribution appears as shown in Fig. 1(b).

A severe visual artifact, such as a block artifact, may be unavoidable if the ideal luminance distribution of the turned-on LED units is used. To eliminate this problem, we need to

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Fig. 1 Schematic diagrams of (a) ideal and (b) actual luminance distributions of side-lit light-emitting diode (LED) backlight when four LED units are turned on.

determine the actual luminance distribution over the entire panel. Figure 2(a) shows the measured luminance distribution of one LED unit. We measured the luminance data of the panel along the x - and y - directions using a BLU module inspection system, BLU-1000. To represent the backlight distribution in a compensation algorithm, we approximated the luminance distribution of the i 'th LED unit by two simple polynomial expressions for the x - and y -directions:⁹

$$Y_i^y = A \times y^4 + B \times y^3 + C \times y^2 + D \times y + \alpha, \quad (1)$$

$$Y_i^x = \left[1 + \left\{ \frac{1 - y}{64 + (769 - x_{i' \text{th LED}} - x)} \right\}^2 \right]^{-2}, \quad (2)$$

$$Y_i^{xy} = Y_i^x \times Y_i^y, \quad (3)$$

where Y_i^x and Y_i^y are the luminance distributions of the i 'th LED unit in the x - and y -directions, respectively; x and y range from 1 to 1024 and from 1 to 768, respectively; $x_{i' \text{th LED}}$ is the location of the i 'th LED unit ranging from 1 to 1024; Y_i^{xy} is the entire luminance distribution of the i 'th LED unit obtained from Eq. (1) and (2); and Y^{xy} , the actual luminance at location (x, y) , is the sum of luminance contributions by eight LED units as in Eq. (4):

$$Y^{xy} = \sum_{i=1}^8 \text{BLU}_i \times Y_i^{xy}. \quad (4)$$

Fig. 2 (a) Measured luminance distribution of one LED unit and (b) the luminance distribution model of one LED block unit.

Using these equations, we modeled the luminance distribution of one LED block unit based on the Eqs. (1)–(3), as shown in Fig. 2(b).

$$\text{BLU}_i = \text{Avg}_i + \frac{\{(\text{Max}_i - \text{Avg}_i)^2 + \alpha_i\}}{(2^8 + \alpha_i)}, \quad (5)$$

where BLU_i , divided into 256 levels from 0 to 255, is the backlight level of the i 'th LED unit that is determined by our proposed Eq. (5); Max_i and Avg_i are, respectively, the maximum and average values of the input image corresponding to the i 'th image block; and α_i is an adjusting value. When the average value of the i 'th block is higher than the average value of the entire image, it means that the highlight such as star light is mainly located in the i 'th block. To maintain the image quality, the adjusting value α_i is adjusted to α_H . When the average value of the i 'th block is lower than the average value of the entire image, it means that the highlight is not mainly located in the i 'th block. To reduce the power consumption, the adjusting value α_i is adjusted to α_L . To maintain the same luminance after dimming the backlight, G_{Reduced} is introduced and calculated using Eq. (6).⁷ G is an image data level that ranges from 0 to 255. G_{Full} and BLU_{Full} are the image data and BLU level, respectively, when the backlight is fully turned on.

$$G_{\text{Reduced}} = \left(\frac{\text{BLU}_i}{\text{BLU}_{\text{Full}}} \right)^{1/\gamma} \times G_{\text{Full}}. \quad (6)$$

Conventional methods compensate for the dimmed luminance by increasing image data as in Eq. (6) without considering the nonuniform luminance distribution of the BLU.⁷ If pixels are compensated based on Eq. (6), severe block artifacts may be caused because BLU_i does not fully reflect the luminance distribution over the screen. Therefore, we suggest a novel pixel compensation as follows:

$$G_{\text{Reduced}} = \left(\frac{Y^{xy}}{\text{BLU}_{\text{Full}}} \right)^{1/\gamma} \times G_{\text{Full}}. \quad (7)$$

3 Experimental Results

3.1 Simulation Result

In order to verify the elimination of the block artifact, we simulated a 1-D dimming technique with nonuniform luminance distribution and measured the luminance distribution using MATLAB. Figure 3(a) shows the simulated image of a block artifact caused by this 1-D dimming technique using conventional pixel compensation as in Eq. (6). Using our proposed pixel compensation from Eq. (7), the image has no block artifact, as can be seen in Fig. 3(b).

3.2 Hardware Implementation

In this paper, we performed experiments using an 11-in. XGA (1024 × 768) thin film transistor LCD with eight LED drivers that controlled eight LED units. A field-programmable gate array (FPGA) board was used to analyze image data and generate eight pulse-width modulation signals to dim eight BLU units independently. Equations (3) and (4) are considerably complex to be implemented on the FPGA board, therefore, we made eight look-up tables (LUT) corresponding to the LED units. The size of each LUT was 46,080 bits. Furthermore, to prevent the visual artifacts such as flicker and light leakage caused by rapid change of BLU level, we adjusted BLU level using the lowpass filter. We also implemented 0-D dimming in which LEDs were

placed at the lower edge of the LCD panel and divided into eight units; however, we assumed 1-D dimming techniques for comparison.

3.3 Power Consumption Reduction

Figure 4 depicts the 24 KODAK images and 10 test images used to compare power consumption among different driving techniques. We determined the BLU levels using Eq. (5) for both 0-D and the proposed 1-D dimming schemes. We measured power consumption for four cases: no dimming, 0-D, 1-D,¹⁰ and the proposed 1-D. Table 1 shows the relative power consumption for the 24 static images compared with no dimming. When our 1-D dimming was adopted, power consumption was reduced to as low as 45.2% (for image 34), as shown in Table 1. On average, our proposed 1-D dimming technique saved 8.0% power compared with no dimming for the 24 KODAK images. Our 1-D dimming saved 3.3% and 3% more power compared with its 0-D and 1-D¹⁰ dimming counterparts for the 24 KODAK images. Furthermore, due to the dimmer LED in dark areas, power consumption was reduced to as low as 45.2% (for image 34), as shown in Table 1. On average, due to the dimmer LED, particularly in dark images, our proposed 1-D dimming technique saved 25.0% power compared with no dimming for 10 test images. On average, our proposed 1-D dimming technique saved 13.0% power compared with no dimming for 34 images. Our 1-D dimming saved 8.0% and 0.9% more power compared with its 0-D and 1-D¹⁰ dimming counterparts for 34 images. Moreover, we measured power consumption based on the International Electrotechnical Commission (IEC) 62087 standard.³⁰ The IEC 62087 standard defines a method for measuring the power consumption of a display unit when displaying a moving picture. Figure 5 shows the comparison results of power consumption based on the IEC 62087 standard. When we applied 0-D dimming, power consumption was reduced to 93.8% compared with no dimming on average. When we applied our 1-D dimming method, power consumption was decreased to 78.9% on average. These results show that power measurement based on the 10 selected images matched very well with that based on the video clip provided by IEC.

Fig. 3 (a) Simulated image of a block artifact caused by a one-dimensional (1-D) dimming technique that does not consider luminance distribution of the backlight and (b) the simulated image of a 1-D dimming technique that considers the luminance distribution of the backlight.

Fig. 4 24 KODAK images and 10 test images used for power consumption measurement.

Table 1 Power consumption comparison for 24 KODAK images and 10 test images between zero-dimensional (0-D) and one-dimensional (1-D) dimming techniques.

KODAK image	0-D (%)	1-D ¹⁰ (%)	Proposed 1-D (%)	Test image	0-D (%)	1-D ¹⁰ (%)	Proposed 1-D (%)
1	94.9	75.2	85.5	25	92.5	100	92.9
2	95.0	98.1	92.8	26	92.5	75.8	86.1
3	94.9	97.6	92.8	27	92.5	98.0	93.8
4	95.0	93.0	90.5	28	92.5	93.3	91.5
5	95.2	100	93.7	29	91.3	59.0	76.0
6	95.1	96.0	92.1	30	93	61.3	59.0
7	95.0	80.4	87.5	31	96.5	60.6	70.3
8	95.2	100	93.9	32	97.1	82.0	81.3
9	95.0	96.3	92.6	33	92.5	45.6	53.7
10	95.0	100	93.7	34	99.4	33.0	45.2
11	95.1	92.9	91.7	Avg	94.0	70.9	75.0
12	96.1	93.3	91.8				
13	95.0	100	93.4				
14	95.0	98.4	93.6				
15	98.0	100	94.0				
16	94.9	91.3	90.0				
17	95.4	75.5	86.6				
18	95.4	100	94.2				
19	95.0	100	93.3				
20	96.3	100	94.7				
21	95.0	100	93.2				
22	95.0	100	93.3				
23	96.0	91.3	90.0				
24	95.1	100	93.0				
Avg	95.3	95.0	92.0				
				Total Avg	95.0%	87.9%	87.0%

3.4 Contrast Enhancement

To evaluate whether our proposed method enhances the contrast ratio (CR), we measured CRs using four test patterns, as shown in Fig. 6. When the LCDs display a black color on the screen, light is generated by BLU. However, there is always small amount of transmitted light called light leakage. Thus, the CR of LCDs is relatively low because of the light leakage. When the dimming technique is adopted, the luminance of the dark area drops significantly because of the dimmed backlight, which then leads to higher CR. Therefore, to represent the deep black color and improve the CR, local dimming technology should be adopted. We measured

luminance at the locations indicated by the dashed circles shown in Fig. 6. Table 2 shows the CR comparison between no dimming and 1-D dimming. When 1-D dimming was adopted, the CR increased by up to 231% and 165% on average compared to the undimmed image.

3.5 Block Artifact Elimination

We evaluated whether our proposed method could eliminate a block artifact. Figure 7 shows photos of an LCD screen before and after application of our proposed method. Pixel data were compensated by using Eq. (7). As shown in Fig. 7(b), the block artifact was invisible.

Fig. 5 Power consumption comparison for IEC 62087 between zero-dimensional and proposed 1-D dimming techniques.

Fig. 6 Four test patterns used for contrast ratio measurement.

Fig. 7 Zoomed photos of the moon when 1-D dimming techniques were applied (a) without and (b) with the luminance distribution of the backlight taken into account.

4 Conclusion

We proposed an adaptive 1-D dimming technique for LCDs that considers the actual luminance distribution of a dimmed BLU. By considering the luminance distribution of the BLU and the input image, the simulation result and hardware implementation showed that the proposed 1-D dimming technique reduced power consumption significantly while maintaining the image details of static and moving pictures and also achieved a higher CR. As the performance of displays becomes a greater issue, especially for mobile applications, our proposed method could contribute to displays with significantly lower power consumption and longer battery life than currently available displays. We foresee our proposed method being applicable to mobile devices, monitors, and televisions.

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References

1. Y. Yamauchi et al., "A novel pixel memory using integrated voltage-loss-compensation (VLC) circuit for ultra-low-power TFT-LCDs," *J. Soc. Inf. Disp.* **19**(1), 57–62 (2011).
2. J. H. Ahn, "Implementation of an LED tile controller for high-quality image display," *Displays* **34**(1), 17–26 (2013).

Table 2 Contrast ratio (CR) comparison between nondimming and 1-D dimming.

Test pattern	Color	Nondimming		1-D dimming		Article I · CR _{1-D} /CR _{ND}
		Luminance (cd/m ²)	CR _{ND}	Luminance (cd/m ²)	CR _{1-D}	
a	White	145.7	416.3	115.4	961.7	231%
	Black	0.35		0.12		
b	White	110.7	235.5	109.7	296.5	125.9%
	Black	0.47		0.37		
c	White	144.1	259.3	116.6	376.1	145%
	Black	0.44		0.31		
d	White	136.7	325.4	114.5	520.5	159.9%
	Black	0.42		0.22		

3. S. I. Cho, S. J. Kang, and Y. H. Kim, "Image quality-aware backlight dimming with color and detail enhancement techniques," *J. Disp. Technol.* **9**(2), 112–121 (2013).
4. X. Wang et al., "Autostereoscopic 3D pictures on optically rewritable electronic paper," *J. Soc. Inf. Disp.* **21**(2), 103–107 (2013).
5. C. Mantel et al., "Controlling power consumption for displays with backlight dimming," *J. Disp. Technol.* **9**(12), 933–941 (2013).
6. E. Song and H. Nam, "Shoot-through current reduction scheme for low power LTPS TFT programmable shift register," *J. Soc. Inf. Disp.* **22**(1), 18–22 (2014).
7. L. Kerofsky and S. Daly, "Brightness preservation for LCD backlight dimming," *J. Soc. Inf. Disp.* **14**(12), 1111–1118 (2006).
8. K. Kälantär, "A monolithic segmented functional light guide for 2-D dimming LCD backlight," *J. Soc. Inf. Disp.* **19**(1), 37–47 (2011).
9. S. R. Kim et al., "Adaptive 1D dimming technique compensating for non-uniform side-lit backlight profile," in *Proc. of Int. Meeting in Information Display*, pp. 31–32 (2011).
10. H. Nam, "Low power active dimming liquid crystal display with high resolution backlight," *Electron. Lett.* **47**(9), 538–540 (2011).
11. Y. Sano, R. Nonaka, and M. Baba, "Wide gamut LCD using locally dimmable four-primary-color LED backlight," *J. Soc. Inf. Disp.* **20**(9), 539–546 (2012).
12. S. C. Hsia et al., "High-performance local dimming algorithm and its hardware implementation for LCD backlight," *J. Disp. Technol.* **9**(7), 527–535 (2013).
13. S. J. Kang, "Processor-based backlight dimming using computation reduction technique," *J. Disp. Technol.* **9**(10), 819–824 (2013).
14. S. J. Kang, "SSIM preservation-based backlight dimming," *J. Disp. Technol.* **10**(4), 247–250 (2014).
15. M. Kim, J. M. Kim, and S. W. Lee, "Standard color liquid crystal displays by a dimming technology," *Color Res. Appl.* **39**(5), 480–485 (2014).
16. K. Meinstein et al., "A low-power high-voltage column/dot inversion drive system," in *Symposium Digest of Society for Information Display*, Vol. 28, pp. 391–396 (1997).
17. C. W. Lu and K. J. Hsu, "A high-speed low-power rail-to-rail column driver for AMLCD application," *IEEE J. Solid-State Circuits* **39**(8), 1313–1320 (2004).
18. C. W. Lu and L. C. Huang, "A 10-bit LCD column driver with piecewise linear digital-to-analog converters," *IEEE J. Solid-State Circuits* **43**(2), 371–378 (2008).
19. J. S. Kim, D. K. Jeong, and G. Kim, "A multi-level multi-phase charge-recycling method for low-power AMLCD column drivers," *IEEE J. Solid-State Circuits* **35**(1), 74–84 (2000).
20. S. S. Yang et al., "A multi-phase charge-sharing technique without external capacitor for low-power TFT-LCD column drivers," in *Proc. of IEEE Int. Symposium on Circuits and Systems* Vol. 5, pp. 365–368 (2003).
21. S. S. Kim et al., "An 82-in. ultra-definition 120-Hz LCD TV using new driving scheme and advanced super PVA technology," *J. Soc. Inf. Disp.* **17**(2), 71–78 (2009).
22. D. Lee et al., "Novel driving and panel design of frame inversion method for high aperture ratio in the large size and high resolution LCD TV panel," *Soc. Inf. Disp. Symp. Digest* **42**(1), 342–345 (2011).
23. H. Nam and J. H. Shim, "Image independent driving power reduction for high frame rate LCD televisions," *ETRI J.* **34**(3), 470–473 (2012).
24. S. R. Kim et al., "A new smart charge sharing method for liquid crystal displays with lower power consumption in z-inversion," in *Proc. of Int. Display Workshops*, pp. 1454–1455 (2013).
25. S. Tomokazu, S. Sho, and M. Shigeo, "Power savings and enhancement of gray-scale capability of LCD TVs with an adaptive dimming technique," *J. Soc. Inf. Disp.* **16**(2), 311–316 (2008).
26. S. I. Cho, S. J. Kang, and Y. H. Kim, "Image quality-aware backlight dimming with color and detail enhancement techniques," *J. Disp. Technol.* **9**(2), 112–121 (2013).
27. S. J. Kang and Y. H. Kim, "Multi-histogram-based backlight dimming for low power liquid crystal displays," *J. Disp. Technol.* **7**(10), 544–549 (2011).
28. S. C. Hsia et al., "High-performance local dimming algorithm and its hardware implementation for LCD backlight," *J. Disp. Technol.* **9**(8), 656–665 (2013).
29. H. Chen, "Evaluation of LCD local-dimming-backlight system," *J. Soc. Inf. Disp.* **18**(1), 57–65 (2010).
30. International Electrotechnical Commission, IEC 62087:2008 (E), *Methods of Measurement for the Power Consumption of Audio, Video and Related Equipment* (2008).

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