IEICE TRANS. ELECTRON., VOL.E93–C, NO.11 NOVEMBER 2010

INVITED PAPER *Special Section on Electronic Displays*

Reduction of Image Degradation due to Viewing Angle in Adaptive Dimming Technique

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SUMMARY An adaptive dimming technique controls both LCD panel transmittance and its backlight luminance adequately and locally according to the input TV signal. The technique reduces the power consumption and also improves the picture quality. However, a steep change in backlight luminance distribution due to the application of the technique causes image degradation around the boundary of the segments when the LCD is viewed from an angle. The main factor of image degradation is the illumination of a pixel by neighboring pixel's corresponding backlight when the LCD is viewed from an angle rather than normal direction. From the subjective evaluation of image quality and computer simulation, it is found that the gradient of the backlight luminance variation to luminance at the border of the segment should be less than 0.022 per pixel in order to suppress the image degradation.

key words: *image quality, viewing angle, adaptive dimming, local dimming*

1. Introduction

Recently several local dimming techniques have been developed to reduce the power consumption and to improve the image quality [1]–[4]. Among them is the adaptive dimming technique [1]. The basic principle of the adaptive dimming technique is explained in Fig. 1. In the conventional technique, transmittance of LCD is controlled while keeping the backlight luminance unchanged. Power consumption of the backlight unit is constant, independent of the TV signal. In contrast, the adaptive dimming technique controls both LCD panel transmittance and its backlight luminance adequately according to the input TV signal as shown in Fig. 1. The power consumption of the backlight, therefore, is reduced, while the original image can be reproduced. In addition, dark room contrast ratio is improved due to the reduction of leakage light.

Typically 2D local dimming operation with LED light sources is employed because it achieves maximum power reduction compared to 0D and 1D operations [5], [6]. Here a segment is defined as an individually controllable unit with a LED or group of LEDs of the sectioned backlight. The effect of power saving depends on the luminance distribution of a segment [7]–[9]. Figure 2 compares power reduction and picture quality for two cases of the backlight luminance distribution. Second row shows the cross-section of the luminance distribution when a segment is only ignited. As

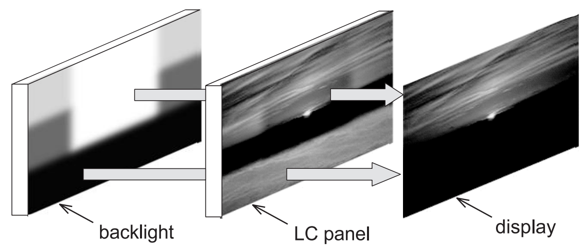


Fig. 1 Principle of the adaptive dimming technique.

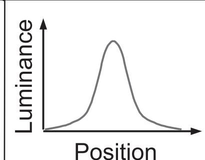
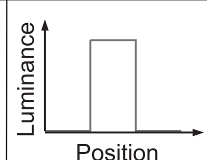
	(a) case 1	(b) case 2
distribution of backlight luminance of a segment		
power reduction	low	high
picture quality	high	low

Fig. 2 Comparison of power reduction and image quality for luminance distributions.

the spread of luminance distribution reduces the power reduction increases. The maximum reduction is attained when the spread is zero as shown in case 2. To suppress the spread of the distribution, the optical isolators are frequently placed between the light sources [5], [7]. The original image can be reproduced for both cases when the image is viewed from an anterior. However when the image is viewed from an angle, the degradation of image quality can be recognized around the border of the segments [9]. Especially, large image degradation causes with the distribution of case 2.

Figure 3 shows the examples of experimental results with the adaptive dimming technique when the image was viewed from 0° and 30°. A 19 inch-diagonal SXGA IPS-mode LCD having a pixel pitch of 0.294 mm was used. The backlight unit was divided into 3×4 segments by the 0.2 mm-thick optical isolators. When the viewing angle was 0°, the image reproduced satisfactory as shown in Fig. 3(a) although the backlight luminance of each segment was not same. However in (b), the vertical white and black shadows indicated by white arrows appeared along the boundary of

Manuscript received March 5, 2010.
Manuscript revised June 11, 2010.
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DOI: 10.1587/transele.E93.C.1572

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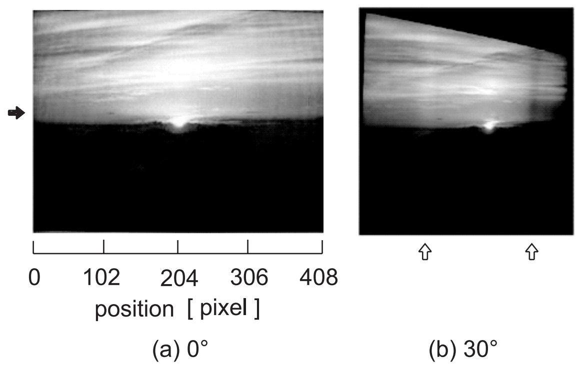

Fig. 3 Viewing angle dependence of displayed sample picture.

the segments when the viewing angle was 30°.

In this paper, the factor for the image degradation when the image is viewed from an angle is investigated [10]. In addition, the reduction technique is proposed.

2. Factors for Image Degradation

A detailed principle of the adaptive dimming technique is explained in Refs. [1] and [6]. The technique dims luminance of the LEDs in segment by a dimming factor k, $(0 \leq k \leq 1)$. At the same time the input signal to LCD for the segment is magnified by a factor $1/k$.

There are three candidates for the image degrading factor. They are viewing angle dependence of (1) transmittance of LC panel, (2) luminance of backlight unit, and (3) a pixel's corresponding position on backlight.

The effect of factor 1 is explained with Fig. 4. Dashed lines in the figure indicate the boundaries of the segments. Suppose that the LCD luminance of area A and B is identical but the dimming factors of the segment C and D are different. Since the dimming factors are different, the input signals to pixels of area A and B are different. For example, if the LCD luminance of area A and B is 14% of the peak value and backlight luminance of segment C and D are dim down to 70% and 35% of the peak value, respectively, then input signals to pixels are adjusted so that the LC panel transmittance of area A and B are 20% and 40% of the peak value, respectively. Generally, the transmittance of LC panel decreases as the viewing angle increases. If reduction rate of transmittance does not depend on the input signal, area A and B can be displayed with the same luminance level. If reduction rate of transmittance depend on the input signal, degradation occurs.

In the experiment of Fig. 3, backlight unit had the 0.2 mm-thick and 17 mm-height white optical isolators and a diffuser plate was directly attached to the top of the optical isolators. The isolators may degrade the luminance uniformity of backlight when it is viewed from an angle. This is the second degrading factor.

The effect of third factor is explained with Fig. 5. The figure is a cross-sectional view of LC panel and backlight unit. Adaptive dimming technique control both LC panel

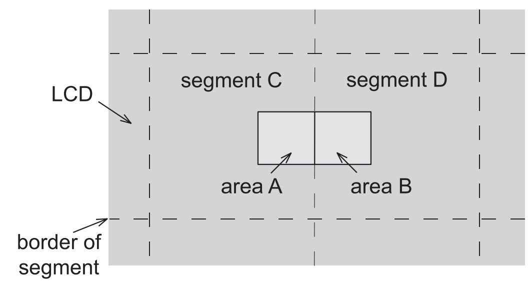

Fig. 4 Example of the adaptive dimming technique. The dimming factors of segment C and D are different but LCD luminance of area A and B is identical.

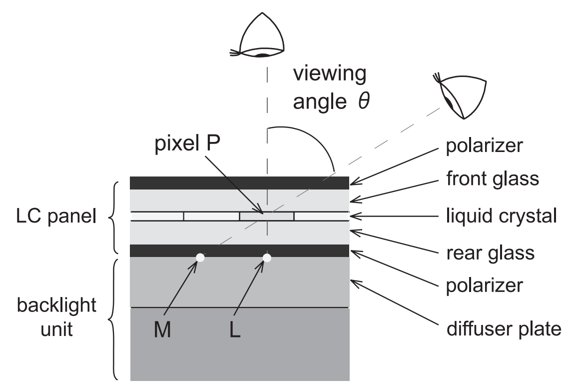

Fig. 5 Principle of image degradation caused by the adaptive dimming technique.

transmittance and its backlight luminance on assumption that viewer is perpendicular to the screen. For example, the input signal of a pixel P is determined according to a backlight luminance, B_L, at position L. When the image is viewed from an angle, pixel P's corresponding position on the backlight becomes position M. Thus the perceived luminance depends on a backlight luminance, B_M, at position M. The difference of a pixel's corresponding position on backlight is caused by the thickness of the rear glass and films. For example, when the pixel pitch is 0.294 mm and the thickness of the rear glass and films of the LC panel is 1.1 mm, the distance between L and M, for the viewing angle of 30° and 60° are 2.2 and 6.5 pixels, respectively. When the luminance difference between B_L and B_M is large, perceived pixel luminance largely changes.

3. Evaluation of Image Degrading Factors

3.1 Viewing Angle Dependence of LC Panel Transmittance

Image degrading factors 1 and 2 were evaluated by the experiment with the 2D dimming backlight. Size of the backlight unit was 120 mm × 90 mm. It was divided into 3 × 4 segments by using the 0.2 mm-thick optical isolators. A diffuser with a thickness of 2-mm was used on the top and in contact with the optical isolator, and two light collimating prism films were set on the diffuser plate. A 19 inch diag-

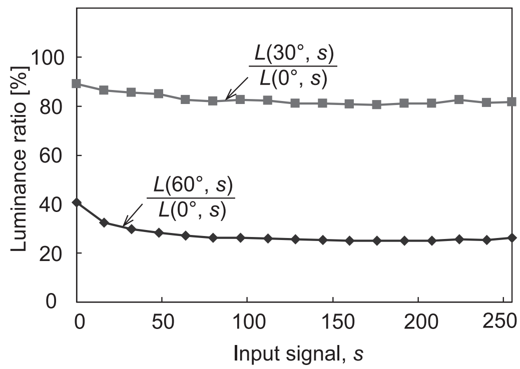

Fig. 6 Luminance vs. TV set input signal for various viewing angles.

onal SXGA IPS-mode LCD module having a pixel pitch of 0.294 mm was mounted on top of the backlight unit. The thickness of the rear glass and films of the LC panel was 1.1 mm. Each segment corresponds to 102 × 102 pixels. Since the area of the backlight unit was smaller than the LCD, only a portion of the LCD was used.

LCD luminance, $L(\theta, s)$, at the center of the display as a function of the TV set input signal, s, was measured for the viewing angles, θ, of 0, 30, and 60° from the left side of the display. Figure 6 shows the luminance ratios, $L(30°, s)/L(0°, s)$ and $L(60°, s)/L(0°, s)$. It is found from the figure that the luminance ratio almost does not depend on the input signal. There is a little difference at the low input signal level range. This may be caused by an error in measurement of low luminance levels. The influence of the difference, however, is small because the picture luminance is very low and thus the luminance difference between area A and B is small. Therefore the influence of this factor is small.

3.2 Viewing Angle Dependence of Backlight Luminance Distribution

Figure 7 show luminance distribution on the backlight unit along the horizontal direction for various viewing angles when the dimming factors of the segments are same or different. The vertical dashed lines indicate the position of optical isolators. The luminance was measured from the left side of the backlight unit. Dimming factors of the segments for case (b) were 0.67, 1.00, 1.00 and 0.22 from the left side of the figure. It can be seen from the figures that luminance decreases evenly according to the viewing angle. There is no large luminance change due to the optical isolators. Similar results were obtained when the luminance was measured from the right side of the backlight unit. Thus, the influence of this factor is negligible.

3.3 Viewing Angle Dependence of a Pixel's Corresponding Position on Backlight

The effect of third factor was evaluated with the computer simulation. The simulation conditions for the backlight unit

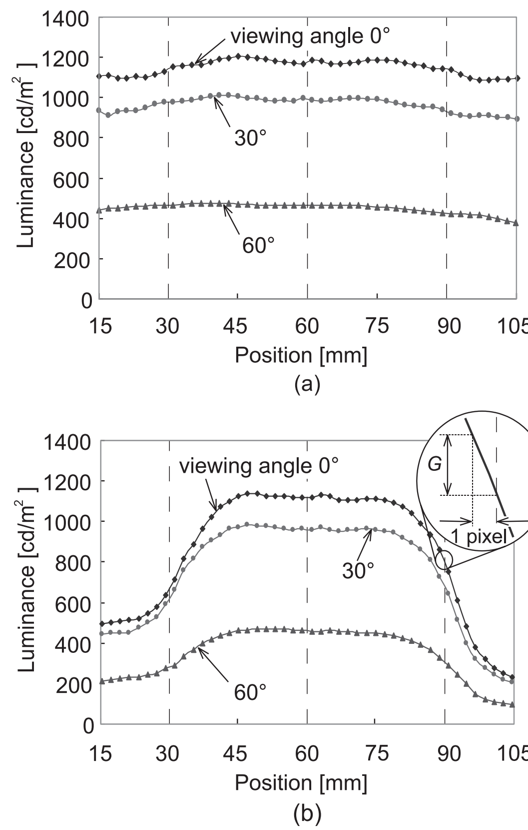

Fig. 7 Backlight luminance distribution along the horizontal direction for various viewing angles. Dimming factors of the segments are (a) same and (b) different.

and LC panel were identical to the experimental setup. In the calculations, the backlight luminance distribution of a segment was varied. Figure 8 shows example of cross section of the backlight luminance distributions when only a segment is fully ignited. These distributions were made based on the Gaussian point spread function. The constants of the Gaussian point spread function were adjusted so that the the following two conditions are fulfilled when all the segments were fully turned on. One is that luminance uniformity of the backlight unit, defined by the ratio of the minimum to the maximum luminance, becomes about 100%. The other is that total luminous flux is same for all the luminance distributions. The vertical dashed lines in Fig. 8 indicate the boundary of the segments. A width of the distribution, W, and a width of segment, D, are defined as depicted in Fig. 8. A broadening ratio of the luminance distribution, R, is defined as $R = W/D$. The luminance distribution of a segment of the backlight unit used in the experiments of Fig. 3 was almost same as the distribution of $R = 0.4$.

The sample image shown in Fig. 3 was used. First, luminance distribution of the images after dimming for viewing angle of 0° and 60° from the left side of the display were simulated by calculating the dimming factor and input signal to LCD. Then the evaluation value of the degradation, $\Delta L/L$, is obtained. Here ΔL is the difference of luminance between the simulated image for 0° and 60°, and L is the luminance of the image for 0°. Figure 9 shows the $\Delta L/L$ along the horizontal line indicated by the black arrow in Fig. 3(a). The dimming factors of segments (2, 1)–(2, 4) for each R are listed in Table 1. It can be seen from the figure that luminance differences are caused at the borders of segments. As the R becomes small, $\Delta L/L$ becomes large because luminance difference on the backlight explained in Sect. 3.3 become larger.

The simulated images when the viewing angle was 60° were displayed on a typical LCD and the subjective evaluation experiment of image quality was carried out by 6 observers. As a result, the degradation were clearly visible when $R = 0$. When R was 0.2 the degradation was small but it can be recognized. When R was over 0.4, the image degradation was almost negligible.

Above results indicate that the third factor is main factor for the image degradation when the image is viewed from an angle.

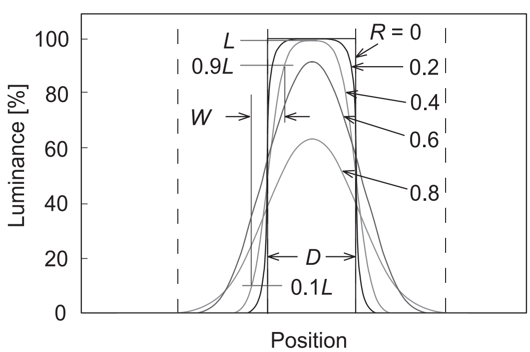

Fig. 8 Cross section of backlight luminance distribution when a segment is fully ignited. As a reference, W for $R = 0.4$ is depicted.

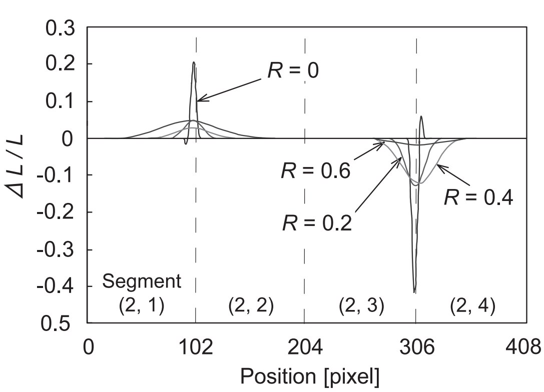

Fig. 9 $\Delta L/L$ *vs.* position along the horizontal line indicated by the black arrow in Fig. 3(a).

Table 1 Dimming factors of segments (2, 1) - (2, 4) for each R.

R	segment(2, 1)	segment(2, 2)	segment(2, 3)	segment(2, 4)
0	0.36	1.00	1.00	0.36
0.2	0.53	1.00	1.00	0.36
0.4	0.75	1.00	1.00	0.53
0.6	0.75	1.00	1.00	0.75

4. Reduction of Image Degradation

As explained in Sect. 2 with Fig. 5, luminance difference of backlight between B_{L} and B_{M} causes image degradation. The luminance difference is caused by the nonuniform backlight luminance distribution due to the application of the adaptive dimming technique. When R is small or difference in the dimming factor between the neighboring segments is large, the luminance difference becomes large. Namely, large backlight luminance difference between neighboring segments causes large image degradation. Magnitude of the backlight luminance difference between the neighboring segments can be represented by the gradient of backlight luminance distribution at the border of the segments. The gradient per pixel is defined as G as depicted in Fig. 7(b). Figure 10 shows examples of G/B as a function of R for various combinations of the dimming factors of the segments C and D in Fig. 4. Here B is backlight luminance at the border of segments. As shown in the figure, large difference in the dimming factor between neighboring segments and small R causes large G/B.

The relation between the spatial variation of backlight luminance distribution and image degradation was analyzed with the computer simulation. The simulation conditions for the backlight unit and LC panel were identical to the previous one. Figure 11 shows the normalized luminance difference, $\Delta B/B$, with respect to G/B when the viewing angle is 60°. Here, $\Delta B/B = (B_{\mathrm{L}} - B_{\mathrm{M}})/B_{\mathrm{L}}$. G/B and $\Delta B/B$ for various combination of the dimming factors are calculated and plotted in the figure. From the result, it is found that $\Delta B/B$ is proportional to G/B. Namely, as the spatial luminance variation between the segments becomes steep, large image degradation causes.

The subjective evaluation experiment of Sect. 3.3 indicates that the image degradation is negligible when R is over 0.4. From Fig. 9, maximum value of $|\Delta L/L|$ is 0.12 when R is 0.4. Therefore, $|\Delta L/L|$ of 0.12 is defined as the perceptible limit of image degradation. Here, $\Delta L/L$ is equivalent to $\Delta B/B$. For Fig. 11, $\Delta B/B$ of 0.12 is obtained when G/B is about 0.022 per pixel. Therefore it is concluded that the

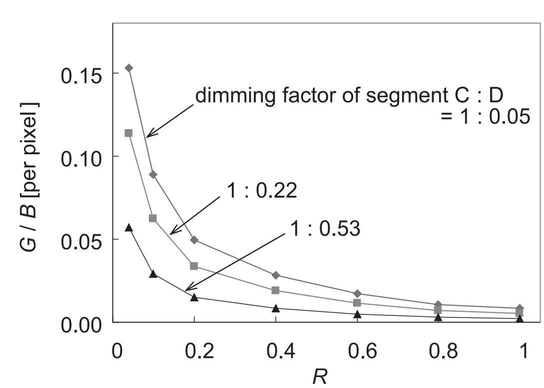

Fig. 10 G/B at the border of the segment as a function of R for various combinations of the dimming factors of segment C and D in Fig. 4.

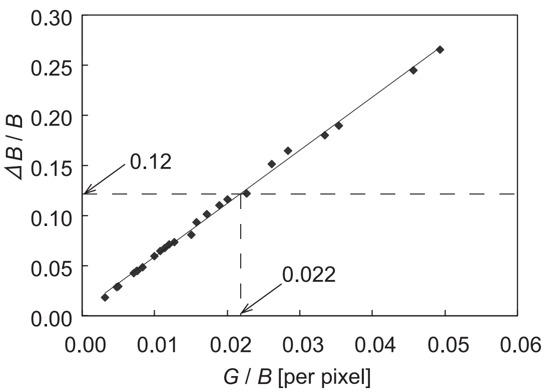

Fig. 11 $\Delta B/B$ *vs.* G/B when the viewing angle is 60°.

image degradation can be reduced when G/B is less than 0.022 per pixel. This condition is met by choosing the backlight luminance distribution of a segment having large R and by adjusting the difference of dimming factors of neighboring segments. When R is over 0.6, G/B is less than 0.022 per pixel for almost all the combination of the dimming factors. Note that even if R is 0.4, the degradation can be suppressed by limiting the difference of dimming factors between neighboring segments.

5. Conclusions

It was found that the illumination of a pixel by neighboring pixel's corresponding backlight causes image degradation around the boundary of the segments when the display is viewed from an angle. The magnitude of degradation strongly depends on the luminance distribution when the technique is applied. Small R and large difference in dimming factor between neighboring segments generate steep change in the backlight luminance distribution, resulting in large image degradation.

From the simulation work, it was found that G/B of less than 0.022 per pixel effectively suppress the degradation. By choosing the broadened luminance distribution of a segment and avoiding the large dimming factor difference between the neighboring segments, the image degradation can be suppressed. As explained in Sect. 1, the effect of power reduction with the adaptive dimming technique degrades when the above reduction technique is applied. Therefore R and limitation of the difference in dimming factor should be optimized for not only the image quality but also the power saving.

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