A Clipping Reduction Algorithm Using Backlight Luminance Compensation for Local Dimming Liquid Crystal Displays

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Abstract — Local dimming techniques cause clipping artifacts in liquid crystal displays. To overcome the problems associated with the artifacts, the backlight luminance should be adjusted, but this process increases power consumption. In this paper we propose a novel backlight luminance compensation algorithm to reduce clipping artifacts by minimizing the increment of backlight luminance.\(^1\)

Index Terms — Clipping artifacts, local dimming, backlight luminance, power saving

I. INTRODUCTION

Liquid crystal displays (LCDs) have been increasingly used in displays due to their low cost, lack of radiation emission, high video quality playback and light weight. In conventional LCDs, the backlight provides a constant light source and liquid crystals control the pixel brightness by changing their transmittance. However, the backlight is fully turned on to provide constant luminance on the whole panel. This means that the backlight is a significant source of power consumption. Moreover, light leakage and low contrast ratio (CR) are also serious problems because the light cannot be obstructed completely when displaying very dark images. The local dimming backlight technique enables LCDs to present images with high CR and low power consumption [1]-[9] by dividing the backlight into several local blocks and modulating them individually according to the input image, thus providing reduced backlight luminance for the display.

In the process of a local dimming backlight technique (Fig. 1) the pixel data of the input image are used to modulate the backlight dimming duty signals which determine the backlight luminance to reduce light leakage and power consumption. Backlight modulation reduces the luminance of the displayed image by reducing backlight luminance. To compensate for the reduced luminance of the displayed image, the pixel data of the input image must be adjusted according to the backlight luminance [1].

After the pixel data are adjusted, the displayed image is not exactly the same as the input image because the luminance of the displayed image cannot exceed the backlight luminance [2]. Therefore, the luminance at some high gray levels cannot be compensated and the gray levels are clipped. This is called the clipping artifact [1]. Images with clipped pixels look unnatural and sometimes exhibit several contours [10]. Therefore, in the local dimming backlight technique, the clipping artifact must be reduced.

Conventional backlight modulation algorithms focus on reducing either the backlight luminance or the clipping artifact. In the average [4] and square root [5] algorithms, the backlight luminance is determined by the average luminance and square root of the average luminance of the input image respectively; thus the backlight luminance is effectively reduced in the dark region of the image. However, the reduction in the backlight luminance is extremely large, so the clipping artifact in the bright region increases. In the max algorithm [4], the backlight luminance is determined by the maximum luminance of the input image; thus the backlight luminance is bright enough to cover the clipping artifact in the bright region. However, the backlight luminance is too sensitive to the noise from high gray levels and the benefits of the local dimming backlight, i.e. low CR and power consumption, are reduced.

Clipping can be reduced by increasing the backlight luminance, but this increase results in additional power consumption and a decrease in CR. Therefore, we propose a novel backlight luminance compensation (BLC) algorithm to reduce the clipping artifact by using the smallest possible backlight increase.

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II. PROPOSED ALGORITHM

A. Backlight Dimming and Backlight Luminance

LCDs are set to meet an ideal target luminance at each gray level (or ideal pixel luminance) when the backlight is fully turned on (Fig. 2, dashed line). However, LCDs have a light leakage problem due to the imperfect nature of liquid crystals, so the actual luminance is affected by the pixel transmittance which causes light leakage at low gray levels (Fig. 2, circles).

Therefore, we need a mechanism to control the backlight luminance when an input image is displayed on the LCD.

![Fig. 2. Luminance vs. gray-level, dashed line: ideal target luminance; empty circles: pixel transmittance.](image)

![Fig. 4. Dimmed pixel luminance and reduced light leakage according to the dimmed backlight luminance. Dashed line: ideal target luminance; empty rectangles, circles and empty triangles: dimmed pixel luminance of Fig. 3 a, b and c, respectively.](image)

In general, assuming that the backlight luminance \( B(i,j) \) of block \((i,j)\) is uniform, the dimming duties, \( d \), of several surrounding blocks and their influences can be evaluated as [6].

\[
B(i, j) = \sum_{m=-d}^{m} \sum_{s=-d}^{s} c_{r,s} \cdot d(i + r, j + s),
\]

where \( m = (M-1)/2 \), \( M \) is the size of the block mask including neighboring blocks, \( c_{r,s} \) is the backlight block spread function (BSF) coefficient which reflects the influence between the block \((i,j)\) and each neighboring block; \( c_{r,s} \) depends on the backlight structure and it is determined experimentally.

B. Pixel Compensation and Clipping artifacts

After the backlight is dimmed and the dimmed backlight luminance is evaluated, the pixel values are compensated to achieve the ideal target luminance. In the ideal target luminance, the maximum luminance is 1 which is the backlight luminance when the backlight is fully turned on. However in pixel luminance after backlight dimming, the maximum luminance is decreased to the level of the dimmed backlight luminance. In other words, after pixel values are compensated, the displayed image and input image are not exactly the same because the luminance of the displayed image cannot exceed the backlight luminance [2]. Therefore, the luminance at some high gray levels cannot achieve the target luminance and the high gray levels are clipped to a value of 255.

As shown in Fig. 5, gray levels between \( g_c + 1 \) and 255 are clipped. \( g_c \) is the critical gray level, which is the maximum gray level to be compensated as the ideal target luminance. If \( g_c \) becomes higher, the clipped pixels are reduced so that the compensated luminance approaches the ideal target luminance as shown in Fig. 6.

Therefore, \( g_c \) determines the clipping level which means that a low value of \( g_c \) has the potential to make serious clipping.

![Fig. 3. Example of local image blocks: (a): bright; (b): middle; (c): dark.](image)
artifact but high one does not. As mentioned above, the dimmed backlight causes clipping and the relationship between the critical gray level and backlight luminance after dimming can be expressed using the ideal target luminance.

\[
B(i, j) = f\left(g_c(i, j)\right) = \left(\frac{g_c(i, j)}{255}\right)^\gamma
\]

(2)

where \(f(g)\) is the mapping function from the gray level \(g\) to the ideal target, which is a monotonically increasing function and usually a gamma function as shown in (2), and \(g_c(i,j)\) is the critical gray level of the \((i,j)\) block when the backlight luminance is \(B(i,j)\) as evaluated in (1). As a result, the critical gray level of a block is highly related to the backlight luminance of the block. From (2), the critical gray level can be derived as:

\[
g_c(i, j) = f^{-1}(B(i, j)) = B(i, j)^{1/\gamma} \times 255.
\]

(3)

D. Clipping Measure and Optimum Backlight Luminance

Now, we can quantify the clipping artifacts by defining a clipping measure \(N\) as the number of clipped pixels as follows:

\[
N(i, j) = \sum_{g=g_c(i, j)+1}^{255} n(i, j, g).
\]

(4)

where \(n(i,j,g)\) is a histogram of block \((i,j)\) at gray level \(g\) in the given input image. The clipping measure can be different between two local blocks even if the critical gray levels are identical. This is because the critical gray level is determined by several surrounding blocks from the evaluated backlight luminance in (1) and (3) while the histogram is only determined by the \((i,j)\) block. As shown in Fig. 7 and Fig. 8, the two local blocks of the image have the same critical gray level, but one of the blocks has a large portion of pixels whose gray levels are above the critical gray level. In this case, the clipping measure of the block could be larger than that of another block.

We can reduce the clipping artifacts at block \((i,j)\) by restricting the clipping measure \(N(i,j)\) to be less than a threshold \((\text{TH})\). \(\text{TH}\) is the maximum number of allowable clipped pixels in a block which can be a predefined parameter depending on the manufacturer’s requirements. To
satisfy the restriction, the critical gray level should be increased because \(N(i,j)\) decreases when \(g_e(i,j)\) is increased as shown in (4). As the critical gray level and the backlight luminance are closely related as shown in (2), the backlight luminance also increases when the critical gray level is increased. However, the incremental change in backlight luminance causes additional light leakage and additional backlight power consumption. Therefore, the increment of the critical gray level or the backlight luminance should be minimized. Using this logic, \(g_e(i,j)\) is increased until \(N(i,j)\) is less than \(TH\). In other words, the optimum \(g_e(i,j)\) is obtained by maximizing \(N(i,j)\) in (4) subject to \(N(i,j) \leq TH\) such that:

\[
g_e^{\text{opt}}(i, j) = \max_{g_e(i,j)} \sum_{g_e(i,j)=1}^{255} n(i, j, g).
\]

subject to

\[
\sum_{g_e(i,j)=1}^{255} n(i, j, g) \leq TH.
\]

The solution for \(g_e^{\text{opt}}(i,j)\) is iteratively obtained. \(g_e(i,j)\) is controllable by adjusting \(B(i,j)\) as shown in (3). Therefore, the valid solution that we want is related to backlight luminance. A compatible matched backlight luminance \(B^{\text{opt}}(i,j)\) corresponding to \(g_e^{\text{opt}}(i,j)\) can be obtained by using (2). The final result, \(B^{\text{opt}}(i,j)\) is the optimum backlight luminance at block \((i,j)\) on the clipping constraint. Specifically, the backlight luminance should be larger than the optimum backlight luminance to prevent the gray levels from being clipped but the values should be as close as possible.

C. Backlight Luminance Compensation (BLC)

The final stage is to compensate for backlight luminance by adjusting the dimming duties of entire local blocks in the display to satisfy the optimum backlight luminance condition, \(B^{\text{opt}}(i,j)\) at each block. This process is called backlight luminance compensation (BLC). To satisfy the \(B^{\text{opt}}(i,j)\) requirement, all the dimming duties of \(M \times M\) neighboring blocks surrounding \((i,j)\) should be compensated in cooperation because the backlight luminance is influenced by neighboring blocks at the same time as shown in (1). Multiplying the dimming duties by some scaling factors can compensate for the backlight luminance. In this paper, we are interested in just increasing in cases where the scaling factor should be larger than or equal to 1.

\[
d^{\text{opt}}(i+r, j+s) = \alpha_{r,s}(i, j) \cdot d(i+r, j+s), \quad \alpha_{r,s}(i, j) \geq 1
\]

where \(\alpha_{r,s}(i, j)\) is the scaling factor that determines the ratio by which dimming duty \(d(i+r, j+s)\) is increased and the resultant \(d^{\text{opt}}(i+r, j+s)\) is the optimum dimming duty of the BLC. To compensate for the backlight luminance of block \((i,j)\), not only the dimming duty of block \((i,j)\) but also the surrounding \((i+r, j+s)\) blocks should be increased as shown in (1). Therefore, our objective is to determine the scaling factors that minimize the increment of the dimming duties while satisfying the requirement that the compensated backlight luminance should be larger than or equal to the optimum backlight. The aim of the BLC is to find the optimum scaling factors as follows:

\[
\{ \alpha_{r,s}^{\text{opt}}(i, j) \}_{r,s\in[-m,m]} = \arg \min_{\{ \alpha_{r,s}(i,j) \}_{r,s\in[-m,m]}} \sum_{r=-m}^{m} \sum_{s=-m}^{m} d(i+r, j+s) \cdot (\alpha_{r,s}(i, j) - 1),
\]

subject to

\[
\sum_{r=-m}^{m} \sum_{s=-m}^{m} c_{r,s} \cdot \alpha_{r,s}(i, j) \cdot d(i+r, j+s) \geq B^{\text{opt}}(i, j).
\]

To minimize the increment of the dimming duties, they should be increased according to the magnitudes of the BSF coefficients. In other words, the optimum scenario is to increase the dimming duty of a block which has a larger BSF coefficient because its increment is smaller than one that has a smaller BSF coefficient. Therefore, the index of the BSF coefficient \((r,s)\) should be simplified and this index simplification results in index rebuilding of the scaling factors and dimming duties. We use the following index rebuilding method which is a different positional representation of the \(M \times M\) blocks that surround \((i,j)\). Indices \(r\) and \(s\) are rebuilt as \(k\) and \(u\). First, the blocks are sorted in the decreasing order of the BSF coefficient. \(k\) is the block’s index in this list, thus \(c_{r,s}\) is simply rebuilt as \(c_k\). In this paper, \(k\) is calculated on the assumption that \(M\) is a value of 3 and each \(c_{r,s}\) has the same value when both \(r\) and \(s\) are not zero. Then, for blocks that have the same BSF coefficient \(c_k\), the blocks are sorted in a decreasing order according to dimming duty. \(u\) is the block’s index in this list (as in Fig. 9). A summary of index rebuilding definition is shown in Table I.

Fig. 9. Example of index rebuilt BSF coefficients and the dimming duties of the surrounding blocks. The block’s positional notation in the dimming duty is omitted, i.e. \(d_{0,0}\) in the figure means \(d_{0,0}(i,j)\).

<table>
<thead>
<tr>
<th>Index</th>
<th>Definition of Index Rebuilding</th>
</tr>
</thead>
<tbody>
<tr>
<td>((r,s))</td>
<td>((k,u))</td>
</tr>
<tr>
<td>BSF coefficient</td>
<td>(c_{r,s})</td>
</tr>
<tr>
<td>Dimming duty</td>
<td>(d(i+r, j+s))</td>
</tr>
<tr>
<td>Scaling factor</td>
<td>(\alpha_{r,s}(i,j))</td>
</tr>
<tr>
<td>Index range</td>
<td>(r=s=0, \pm 1, \pm 2, \ldots, \pm m)</td>
</tr>
</tbody>
</table>

By using the rebuilt indices, the constrained optimization problem in (7) can be rewritten by
\[
\{ \alpha_{k,u}^{\text{opt}}(i,j)\}_{k=0,u=0}^{8} = \arg \min_{\{u_{k}(i,j)\}_{k=0,u=0}^{8}} \sum_{k=0}^{8} \sum_{u=0}^{8} d_{k,u}(i,j) \cdot (\alpha_{k,u}(i,j) - 1)
\]
subject to
\[
\sum_{k=0}^{8} \sum_{u=0}^{8} \alpha_{k,u}(i,j) \cdot d_{k,u}(i,j) \geq B^{\text{opt}}(i,j).
\]

(8)

Hence, the optimum scaling factors are obtained by solving the reformulated constraint optimization problem. The backlight luminance can be viewed as the area of a rectangle with a value of 1 in width and \(B(i,j)\) in height (Fig. 10 (a)). As shown in (1), the backlight luminance is evaluated by summing the BSF coefficient weighted by dimming duties and the area in the diagram is equal to the total area of the 3 separate long rectangles whose width is the BSF coefficient and height is the dimming duty (Fig. 10 (b)). Now, the optimization problem is to find the minimum increment in total heights that satisfies the area, \(B^{\text{opt}}(i,j)\). The increment of height is generated when the dimming duty is multiplied by the scaling factor.

![Fig. 10. 1-dimensional diagram of the constrained optimization problem in (8).](image)

However, this increased height, \(\alpha_{k,u}^{\text{opt}}(i,j)\), might exceed the maximum value of \(d_{\text{max}}=55\). If this happens, the increased height is fixed as \(d_{\text{max}}\) and the surplus, \(c_{0}[(\alpha_{k,u}^{\text{opt}}(i,j)-1) \cdot d_{0,0}(i,j)]\), is compensated for by adjusting the neighboring rectangles in step 2. The surplus is added as a supplement of rectangles with a width of 1, as shown in Fig. 11 (c). The ratio of heights in the supplement is \(\alpha_{0,0}(i,j)-1\) and its area is \(1 \cdot [\alpha_{0,0}^{\text{opt}}(i,j)-1] \cdot d_{1,0}(i,j)+d_{2,2}(i,j)]\). As the areas of the surplus and supplement in step 2 are equal, \(\alpha_{0,0}^{\text{opt}}(i,j)\) is acquired by using the equality. In this way, the general solution of the optimum scaling factor \(\alpha_{k,u}^{\text{opt}}(i,j)\) in step 2 can be acquired as:

\[
\alpha_{k,u}^{\text{opt}}(i,j) = 1 + \left( \frac{d_{1,0}(i,j)}{c_{0}} \right) \cdot \frac{[\alpha_{k,u}(i,j) \cdot d_{1,0}(i,j) - d_{\text{max}}]}{\sum_{u=0}^{8} d_{1,u}(i,j)}.
\]

(10)

Fig. 11. Solution of the constrained optimization problem in (8) in 1-dimensional diagram.

Here, the height of the supplemental rectangles can also exceed \(d_{\text{max}}\). In contrast to the adjustment of neighboring rectangles to compensate for the surplus in step 2, the surplus in step 3 is compensated for in rectangles that have width because it is more effective than covering the surplus in the next rectangles that have a smaller width. The area of the surplus and supplement are \(c_{1} \cdot [\alpha_{1,0}^{\text{opt}}(i,j) \cdot d_{1,0}(i,j) - d_{\text{max}}]\) and \(c_{1} \cdot [\alpha_{1,0}^{\text{opt}}(i,j) - \alpha_{1,0}^{\text{opt}}(i,j)] \cdot d_{1,1}(i,j)\), respectively. In a similar way to step 2, the general solution of the optimum scaling factor \(\alpha_{k,u}^{\text{opt}}(i,j)\) in step 3 can be acquired as:

\[
\alpha_{k,u}^{\text{opt}}(i,j) = \alpha_{k,u}^{\text{opt}}(i,j) + \alpha_{k,u+1}^{\text{opt}}(i,j) \cdot d_{k,u+1}(i,j) - d_{\text{max}} - \sum_{u=0}^{8} d_{k,u}(i,j).
\]

(11)

If the height of the supplemental rectangle does not exceed \(d_{\text{max}}\), the rest of the scaling factors are as shown below:

\[
\alpha_{k,u}^{\text{opt}}(i,j) = \alpha_{k,u}^{\text{opt}}(i,j), \quad t = u+1, u+2, \ldots, 8k.
\]

(12)

The scaling factors whose first index are larger than \(k\) are unity (=1).

### III. Experimental results

We have tested the proposed algorithm using three sample images. Sample images with a 1920 \times 1080 resolution were simulated with a local dimming backlight system of 16 \times 8 blocks using MATLAB R2008a. The images were simulated by using APL, Max [5] and the proposed algorithm
(TH=0.0001) shown in Fig. 12. The backlight power consumption percentage, total clipping measurement (sum of clipping measures of each local block) and clipping ratios of images in Fig. 12 are shown in Table II and Table III, respectively. The clipping ratio is derived as:

\[
\text{Clipping ratio} = \frac{\text{Total clipping measure}}{\text{Total number of pixels}} \times 100\%.
\]

For a bright image (a countryside shot), the backlight power consumption was 57.07, 76.87 and 63.35% and the clipping ratio was 1.8918, 0.0172 and 0.0038% when using APL, Max and the proposed algorithm, respectively as shown in Table II (a) and Table III (a). The APL algorithm is effective for reducing power consumption but it causes a serious clipping artifact. The Max algorithm is effective in reducing the clipping artifact but it increases power consumption. On the other hand, the proposed algorithm is more effective in reducing the power consumption than the Max algorithm, despite the fact that it is still effective at clipping reduction. For a dark image (a storehouse), the proposed algorithm saves on power consumption considerably compared to the APL algorithm and reduces the clipping artifact when compared to the APL algorithm as shown in Table II (b) and Table III (b).

### TABLE II

<table>
<thead>
<tr>
<th>Images</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APL</td>
<td>57.07</td>
<td>17.54</td>
<td>7.79</td>
</tr>
<tr>
<td>Max</td>
<td>76.87</td>
<td>39.98</td>
<td>51.60</td>
</tr>
<tr>
<td>Proposed</td>
<td>63.35</td>
<td>24.01</td>
<td>41.10</td>
</tr>
</tbody>
</table>

### TABLE III

<table>
<thead>
<tr>
<th>Images</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APL</td>
<td>39228(1.8918)</td>
<td>11335(0.5466)</td>
<td>153858(7.4198)</td>
</tr>
<tr>
<td>Max</td>
<td>356(0.0172)</td>
<td>3765(0.1816)</td>
<td>46(0.0022)</td>
</tr>
<tr>
<td>Proposed</td>
<td>79(0.0038)</td>
<td>37(0.0018)</td>
<td>71(0.0034)</td>
</tr>
</tbody>
</table>

For a high contrast image (a street vendor), the APL algorithm reduces the backlight luminance by too much which results in severe clipping artifact as shown in Fig. 12 (c) and Table III (c). To compensate the backlight luminance, the proposed algorithm increases the backlight luminance enough to constrain the clipping artifact, thus the power consumption is increased significantly. However, the proposed algorithm still has the advantage on power consumption when compared to the Max algorithm as shown in Table II (c). The proposed algorithm is optimized to reduce the clipping artifact subject to

![Fig. 12. Sample image: (a) dark image (storehouse), (b) bright image (countryside) (c) high contrast image (street vendor).](image-url)
minimize the increment of the backlight luminance.

Considering all aspects, we did not want to exclude the method of determining the threshold (\(TH\)) from the proposed framework because another threshold could produce better results according to the brightness of the input image, and we leave the investigation of this as a future work.

IV. CONCLUSION

We have proposed a novel BLC algorithm which determines the optimal increment of backlight luminance by solving the proposed constraint minimization problem to reduce the clipping artifact. Experimental results show that the proposed algorithm reduces the clipping artifact in a cost-effective manner compared to the “Max” algorithm.

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REFERENCES


BIOGRAPHIES

Seong-Eun Kim (S’08) was born in Changwon, Korea, on August 9, 1980. He received his B.S. degree in electronic and electrical engineering from Pohang University of Science and Technology (POSTECH), Korea, in 2004. Since 2004, he has been a Research Assistant at the Department of Electronic and Electrical Engineering, POSTECH, where he is currently working toward the Ph.D. degree. His research interests include multimedia signal processing, signal processing for display, and adaptive signal processing.

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