

Mini-LED Backlighting Technologies for High-Dynamic-Range LCDs: Local Dimming and Performance Optimisation

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Abstract:

The increasing demand for high-dynamic-range (HDR) displays has driven the development of more precise backlight control technologies for liquid crystal displays (LCDs). The paper discusses the advantages of mini (Mini-LED) backlighting for HDR LCDs and highlights local dimming as an effective approach for improving contrast and display performance. The paper begins with a description of the Mini-LED backlight and its dimming zones, followed by an explanation of local dimming, which reduces luminance in dark areas while enhancing bright regions. It then discusses optical crosstalk and halo effects due to reduced spatial resolution of the light source as compared to the LCD pixel grid and spreading of the light through the optical films. There are also other current solutions, such as higher density of the dimming zones, enhanced containment of light, compensation of pixels, and adaptive local dimming algorithms, which are contrasted. According to the results of the review, the density of the zones can be increased, but the quality of the image will depend on the design of the optics, complexity of driving, power consumption, and performance of the algorithm. It is not only because of the smaller size of LEDs that mini-LED HDR improvement becomes a system-level optimization issue. Further development requires improved optical confinement, more adaptive dimming control, and balanced power and thermal design.

Keywords: Mini-LED backlighting; liquid crystal display; local dimming; high dynamic range; halo effect.

1. Introduction

Liquid crystal displays (LCDs) are still popular in televisions, monitors, notebook computers, and

vehicle displays due to the mature manufacturing process, high resolution, and long operating life. An LCD is not self-emissive and thus needs a separate backlight unit. In a traditional LCD, the backlight

tends to illuminate a significantly bigger area as compared to one pixel. Although even with the liquid-crystal layer being forced to block an area that is dark, some of the backlight will pass through the panel. This leftover light increases the black level and reduces the contrast ratio, particularly when bright and dark contents exist within the same image. Mini-light-emitting diode (Mini-LED) backlighting solves this drawback by employing a large number of small LEDs and partitioning the backlight into numerous local dimming areas that can be controlled individually. The advantage of this method lies in the fact that it enhances the backlight instead of replacing the LCD panel, and HDR performance can be increased without discarding established LCD materials, thin-film transistor (TFT) backplanes, and colour-filter processes [1].

The studies on the Mini-LED backlit LCD have been concentrated on enhancing dynamic range as well as minimizing the effects of local dimming. Huang et al. did a comparison between the technologies of Mini-LED, Micro-LED, and organic light-emitting diode (OLED) displays and demonstrated that the use of Mini-LED lighting will increase the contrast and peak luminance of the LCDs but still maintain the developed LCD panel design [1]. Tan et al. have studied high-dynamic-range LCDs with a two-dimensional Mini-LED backlight and revealed that the visibility of halos is highly dependent on the inherent LCD contrast ratio and the quantity of zones in local dimming [2]. The research they did was an important one to relate the quality of high-dynamic-range (HDR) images perceived to the resolution of the backlight spatially.

This connection was further investigated in later studies. The performance of Mini-LED backlit LCDs is strongly influenced by both the number of local-dimming zones and the contrast ratio of the LC panel. Increasing the zone density enables finer spatial control of the backlight and generally suppresses the halo effect, while a higher panel contrast ratio can further reduce the number of dimming zones required to achieve high image quality [3]. Lei et al. examined the latest developments of the Mini-LED backlighting and found that local dimming, driving, optical design, and halo suppression are interrelated [4]. The structures of Mini-LED displays were also described by Miao et al., who concluded that the phenomenon of halo is associated with the massive size of a zone of lighting relative to an LCD pixel as well as leakage of light in bright areas into dark ones [5]. More recently, Zhou et al. performed some experiments on how the algorithms of local dimming and the number of zones affect the appearance of halo and demonstrated that increasing the number of zones reduces the area of visible halo, but cannot eliminate this issue [6].

The research shows that the Mini-LED is not capable of

being explained by LED size. A smaller emitter allows a tighter backlight; however, the ultimate picture depends on the interplay between zone density and optical light dispersion, the LCD panel, and the algorithm of control over the backlight. An increased number of zones can be used to achieve greater spatial control, but it also has the potential to use more driving channels and increase system complexity and cost. The diffusion of the light enhances the uniformity of the backlights; however, it may also enhance the optical crosstalk, whereas the confinement can decrease the crosstalk but complicates the illumination. Local dimming algorithms have another trade-off between detail, power consumption, and computational resources. The operating principle, HDR enhancement mechanism, and the primary limitations of Mini-LED backlighting in LCD systems are assessed in this paper. In Section 2, the structure of the Mini-LED backlight, zone-based control, and the connection between local dimming and dynamic range are described. Section 3 is concerned with optical crosstalk and halo formation, the impact of zone density and optical confinement, image compensation and dimming algorithms, and trade-offs between contrast, power, cost, and complexity. The last part of the paper summarizes the key findings and suggests the future research in the field of optical design, adaptive local dimming, and high-brightness display applications.

2. HDR Enhancement in Mini-LED LCDs

Mini-LED backlighting works on the principle of high-density local dimming. The resolution of the backlight is not as fine as the resolution of the LCD pixel in traditional LCDs. Mini-LED emitters are smaller, and they can be placed more densely within the same area of display, and a greater number of them can be controlled to dim independently [1,4]. The intensity of the background light may thus be decreased in dark areas and increased in bright areas. High density of the backlight elements will be achieved with the help of small emitters that improve the local dimming resolution and spatial luminance control and therefore the contrast and HDR performance.

2.1 Mini-LED Backlight Structure

A Mini-LED backlit LCD is still an LCD system, where the array of Mini-LEDs is primarily used as a source of light instead of being used to create the final image. Mini-LED backlights are usually based on LED chips with sizes around 100200 micrometers, and this enables more light sources to be positioned behind a particular display space than traditional LED backlighting [4]. A direct-lit Mini-

LED backlight typically consists of a Mini-LED array, driving circuits, a reflector, diffuser layers, and brightness enhancement films (BEFs) [4]. The Mini-LED array is used to create the backlight, and the reflector reflects light that is emitted downward onto the LCD panel. The individual emitters are diffused with the help of diffuser layers to enhance the uniformity of luminance, and BEFs change the angular distribution such that more useful light reaches the LCD panel [4]. Fig. 1 shows that the LCD panel is placed above the backlight unit and has red, green, and blue (RGB) sub-pixels controlled by thin-film transistors

(TFTs). The liquid-crystal layer also controls transmitted backlight intensity at the pixel level [1]. The two sections hence play complementary roles whereby the Mini-LED layer offers control over illumination on a region basis, whereas the LCD layer offers finer modulation on a pixel basis. This architecture is what constitutes the physical foundation of local dimming. Meanwhile, there should be enough spreading of light so as not to leave bright spots visible, which balances the design between even lighting and local confinement of light.

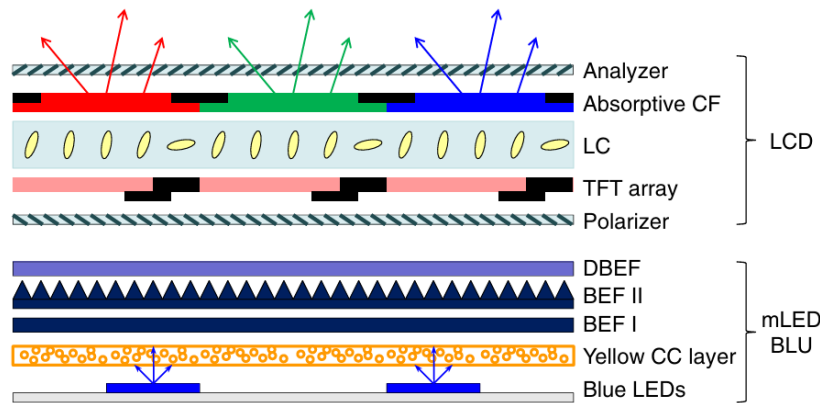


Fig. 1 Mini-LED backlit LCD design with the backlight unit and LCD modulation layers [1].

2.2 Zone-Based Backlight Control

Mini-LED technology, in comparison to traditional backlighting, offers a more precise spatial control through an increase in the number of local dimming zones that can be addressed independently. One or more Mini-LED emitters are present in each zone, and it is possible to control them separately to modify the distribution of the local luminance [1,5]. This is unlike global dimming, where the entire brightness of the backlight changes simultaneously. A dark image may be dimmed globally, but it cannot keep a bright area on its own when bright and dark content appear in the same frame [4]. Instead, local dimming assigns varying levels of backlighting to various areas of the image.

A dimming zone is not equivalent to an LCD pixel. The LCD panel usually has millions of pixels and the Mini-LED backlight has significantly fewer dimming zones; thus, a single zone tends to illuminate numerous LCD pixels [1,5]. Mini-LED backlit LCDs can hence be viewed as a two-level modulation system: the first stage is the backlight, which modulates luminance in relatively large areas of the image, and the second stage is the LCD layer, which modulates further at the level of individual pixels. The main benefit is not only that the size of the emitter is smaller but also that it has greater spatial resolution

of control over the backlight. The tighter the set of independently controlled regions, the less the discrepancy between desired image luminance and the luminance provided by the backlight, which gives more grounds for HDR reproduction.

2.3 Local Dimming and Dynamic Range Enhancement

Local dimming is especially significant in the case of HDR displays as the performance of HDR relies on the concurrent reproduction of high-luminance highlights and low-luminance dark regions. The backlight can be left to operate behind dark image areas in a conventional LCD. Despite the fact that the light transmission is reduced by the LCD layer, it is hard to completely block it, so the remaining light leakage adds to the black level [1,4]. In the case of local dimming, the intensity of the backlight behind dark areas may be decreased prior to reaching the LCD panel, whereas bright areas behind are still at high luminosity. The display will thus be able to decrease the black level without compromising the brightness of the highlight, which enhances the available range of luminance and contrast.

It is reported that LCDs with local dimming and mini-LED backlighting can reach contrast ratios of over

10,000:1 as well as high luminance peaks to be used in HDR [4]. Two-dimensional local dimming splits the backlight not only horizontally but also vertically, and the brightness of various parts can be regulated separately [4]. But it is impossible to produce a pixel-level luminance by using local dimming. The size of a dimming zone is many times larger than one pixel of an LCD, and light diffuses through optical layers into other areas [5,6]. The same designs that enhance the uniformity of backlights are therefore likely to cause loss of independence between zones and optical crosstalk and halo effects.

3. Local Dimming Limits and Engineering Trade-offs

Local dimming is a good way of enhancing the HDR capabilities of the Mini-LED backlit LCDs, but the backlight and the LCD panel are not at the same spatial resolution. One dimming zone can be used to illuminate several pixels of the LCD screen, and diffuser and optical films distribute light on adjacent areas. The resulting luminance distribution that comes out of the backlight is thus not perfectly aligned with the pixel-based image. This variation may result in haloing and crosstalk between high-contrast borders [4,6]. To minimize these effects, it is necessary to alter the density of zones, optical design, as well as the algorithm for controlling the backlight, which all add more engineering requirements.

3.1 Formation of Optical Crosstalk and Halo

The crosstalk of light can be achieved by optical dimming zones in the process of local dimming. The diffuser layers and other films are required to achieve uniformity, but it is hard to restrict the output of light per zone to a sharp boundary [4]. This issue is most noticeable when an object of low brightness is placed on a black background. The luminance distribution of the bright backlight area is not limited to the picture space, but instead increases the luminance of the dark region surrounding the picture space, which leads to a blooming effect or halo effect [5,6].

The other reason is the size of the dimming zone and that of the LCD pixel. It is possible to light up a lot of pixels with a single backlight zone, which means that the backlight will not be able to recreate the same sharpness in the boundary as the high-resolution layer of the LCD [1,5]. The ultimate picture is thus determined by the spatial extent of the area as well as the quantity of light dispersion across the optical stack. In experimental research, it has been observed that the halo area reduces with an increase in the number of local dimming zones [6]. This suggests that the fundamental design rule is that the smaller the

areas, the more closely the distribution of the backlights follows the image, but the decrease is not total since there is still an opportunity to have the lights spill over the boundaries between the zones.

3.2 Effect of Zone Density and Light Confinement

Increasing zone density is perhaps the most straightforward approach to reducing halo. A greater number of zones reduces the area under the control of each backlight region, thereby better matching the spatial correlation between the backlight and LCD image. Both experimental and review studies indicate that higher zone density tends to improve image fidelity and reduce visible halo [3,6]. However, optical crosstalk cannot be eliminated by zone density alone since the light distribution for each zone still exhibits a finite spread.

The local confinement of light can be enhanced by using optical structures. The one that is reported to have been made in the design is based on physically segmented light guiding plates with U-shaped grooves, where each sub-light-guide plate serves as a local dimming area. It was found that the experimental results were illuminance uniformity around 81 percent and about 83 percent of the light extraction efficiency, and crosstalk less than 0.2% between neighboring areas [7]. A third type of design has a zero-optical-distance configuration and microstructures in the form of cones for coupling the light. Two-dimensional local dimming was implemented through nine sub-modules, and it was achieved with an illuminance uniformity of 91.47 percent, 77.09 percent of light extraction efficiency, and 0.29 percent of crosstalk [8]. These findings indicate that the density of zones increases the resolution of control, and optical structures prevent unnecessary diffusion of light. A practical system will need both, not only the number of zones.

3.3 Image compensation and backlight control strategies

The local dimming performance is also determined by the way the backlight value of every zone is calculated. A standard process comprises two primary steps: extraction of backlight values and compensation of LCD pixels [4]. As it can be seen in Fig. 2, the input image is first split according to the layout of the dimming zones, and a backlight value is computed per region. Since decreasing the backlight may also decrease the luminance shown, the LCD pixel values are adjusted to offset this shift. The two operations collaborate: the backlight minimizes unnecessary illumination, whereas pixel compensation assists in maintaining the desired image.

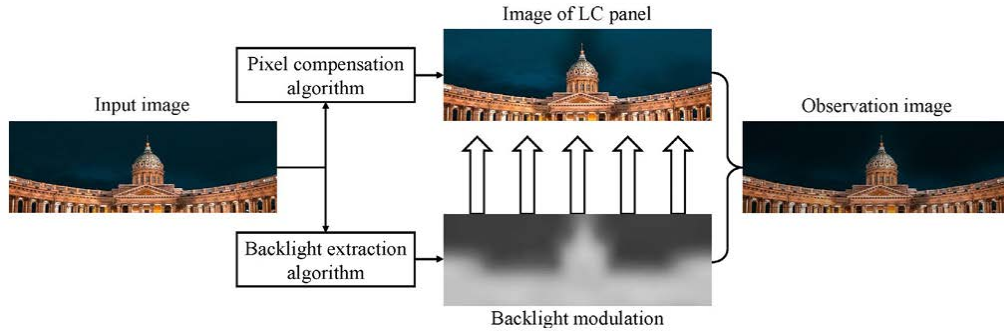


Fig. 2 General local dimming process with backlight value extraction and LCD pixel compensation [4].

The earliest of the local dimming techniques had a tendency to use basic statistical measures like the maximum or average gray scale value in every zone [4]. The maximum-value technique is capable of retaining bright features, but can have an unnecessarily high backlight, and the average-value approach can lower power consumption, but may also lose details when it comes to high contrast. To enhance the tradeoff between brightness, detail retention, and power usage, other methods such as root-mean-square, histogram-based, inverse-mapping-function, and error-correction approaches were developed [4].

Other techniques are more complicated in that they seek to optimize a number of objectives simultaneously. A genetic algorithm was also created to find the values of backlights that would not only maintain HDR image quality but also lower the power consumption [9]. It was proposed to train a convolutional neural network and consider the diffusion of backlight and leakage of light through the LCD as training features [10]. An experimental paper has been conducted on a 55-inch 4K LCD with 2304 Mini-LED partitions of the backlight using a statistics-RMS algo-

rithm [11]. The prototype had a maximum luminosity of around 2197.5 cd/m² and a minimum luminosity of about 0.00135 cd/m², which is a dynamic contrast ratio of approximately $1.63 \times 10^6:1$ [11]. These findings demonstrate that the local dimming issue is not merely an optical issue; the display control algorithm plays a significant role in the final display output.

3.4 Trade-offs in Contrast, Power, Cost, and Complexity

There are a few trade-offs in the Mini-LED backlight design as shown in Table 1. The more local dimming zones there are, the better the performance of the luminance of space and the less the halo, but it also results in more LEDs, driving channels, interconnections, and control actions. There are 1000 to 4000 dimming regions that are normally used by commercial Mini-LED TVs, with some products reaching 10,000 [4]. It can be increased further, which is an increase in the control resolution as well as the manufacturing cost and complexity of the system.

Table 1. Primary engineering trade-offs in Mini-LED local dimming systems.

Design approach	Main benefit	Main limitation
More dimming zones [4,6]	Better spatial control; less halo	More LEDs, drivers, cost and control complexity
Stronger optical confinement [7,8]	Lower crosstalk between zones	More complicated optical structure; uniformity may be easier to maintain
High-end local dimming algorithms [9-11]	More detail preservation and power-quality balance	Higher computational demands

Power consumption is another trade-off. Local dimming can save power since dark areas do not need to be fully lit. Nevertheless, more Mini-LEDs and driving circuits mean higher electrical and thermal-management demands [4]. Optical design balances similar issues: stronger diffusion makes luminance uniformity better but increases crosstalk; stronger light confinement reduces crosstalk

but makes uniform illumination harder [7,8]. Algorithm design also involves a balance between performance and computational cost. More advanced methods can give more accurate backlight values and better detail preservation, but they require additional processing resources [9-11]. The main trade-offs. Overall performance therefore depends on coordinated optimization rather than on maxi-

mizing a single parameter.

4. Conclusion

The paper considers the operating principle, HDR improvement of the Mini-LED system in LCD systems, and the primary disadvantages. The Mini-LED backlights are able to increase the number of locally controllable areas of light intensity, which increases the local contrast and dynamic range. The modulation is done at the regional level by the backlight, whereas the panel modulates it at a finer pixel scale. Its only disadvantage is that the resolution of the spatial image of the backlight is not as high as the resolution of the array of pixels of the LCD. Optical crosstalk and halo around the boundaries with high contrasts are formed due to the spreading of light between adjacent zones. These effects can be minimized through increased density of zones, better optical containment, and enhanced dimming algorithms, but all these approaches require extra cost, power, or system complexity. It is possible to view the performance of Mini-LED as an optimization issue on the system level and not the enhancement of one component. Further Mini-LED backlighting developments are reliant on enhanced optical confinement, which inhibits halo without compromising uniformity, as well as adaptive local dimming, which balances detail retention, power consumption, and real-time computation. The joint optimization of the power and thermal performance is still significant with increasing density of zones. Mini-LED backlighting will also continue to be applicable to high-brightness applications like automotive displays, head-up displays, and near-eye systems where varying thickness, viewing angle, ambient readability, and power requirements introduce new design constraints.

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