Evaluation and Improvement of the First Frame Ratio under Extremely Low Luminance in AMOLED Displays

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Abstract

Evaluation and improvement of the first frame ratio (FFR) of active-matrix organic light emitting diode (AMOLED) displays became very important particularly for mobile devices with extremely low display brightness. We have developed reliable FFR evaluation methodologies for extremely low luminance, and quantified the luminance and color FFR performances. In addition, we proposed the practical solutions to mitigate the low FFR issues which showed the 3 times higher luminance FFR, and 37% improved color accuracy for the steady state luminance 0.127 cd/m^2 image.

Author Keywords

AMOLED; first frame ratio; luminance drop; color shift; low luminance.

1. Introduction

The display brightness range of the AMOLED displays has increased in the industry for both maximum/peak brightness and minimum brightness. Several consumer mobile devices support a peak 2,000 cd/m^2 or 3,000 cd/m^2 for outdoor readability (high display contrast ratio) under strong ambient light, and minimum 1 cd/m^2 for the eye comfort under dark ambient [1].

When AMOLED display brightness is set extremely low, like 1 cd/m^2 or lower, the pixel luminance and the color accuracy can easily be degraded due to the low first frame ratio (FFR, a.k.a. first frame dimming, FFD) when the screen contents are moving. The FFR has been defined as the luminance ratio of a display between the first frame of the image and the steady state image when the screen contents are changing. Traditionally, this ratio has been calculated by luminance waveform analysis methods. Figure 1(a) shows an example luminance waveform where the screen contents change from the first image (black) to the second image (12 cd/m^2, steady state average luminance) at time zero. The luminance is supposed to go up to 12 cd/m^2 right after the image content changes to the second image at time zero but the first frame of the second image exhibits only 61% of its target luminance in this particular example, thus the FFR of this example is 61%. This non-ideal FFR is due to the hysteresis effects of the thin film transistors (TFTs) in the pixel circuit. Figure 1(d) shows one of the pixel circuits that has been widely used in the industry, and the core part of this pixel circuit remains unchanged in the recent AMOLED displays [2]. The transistor T1 in the pixel circuit, which generates the pixel emission current is the most sensitive transistor from the pixel emission current point of view, and the low first frame ratio is known to originate from hysteresis effects in this transistor. The first frame ratio issue has been explored in the industry for a long time as this issue causes motion blur in moving images, and videos [3-6]. In addition to the general motion blur symptom, low first frame ratio causes color shift or separation (or colored edge) in moving images at low pixel luminance. It is due to different FFR values of each primary color (red, green, and blue). Figure 1(c) shows an example of the color separation/color shift at the leading edge of low luminance moving images (north of the icon image this case, indicated by the red arrow) while it does not show up in the still image in Figure 1(b). This example photo was captured with a moving graylevel 48 (W48) image at a display brightness 5 cd/m^2 (actual W48 pixel luminance 0.127 cd/m^2) when sliding with a speed of 10 pixels/frame. The leading edge of the moving icon shows a purple edge as well as a luminance drop. It is because green luminance drops more than red and blue as green emission current is lower, and this produces a purple edge.

Since extremely low luminance support has become more and more common in the industry, it is important to reliably quantify the FFR of both luminance and color of low luminance, and to mitigate the issues to maintain high image quality in mobile devices. In this paper, we propose two new FFR evaluation methods: pattern toggling and pattern sliding, to evaluate extremely low luminance cases accurately, reliably, and consistently. In addition, we propose strategies for display optical tuning methods, and the design of screen user interface images in order to mitigate low luminance FFR issues.

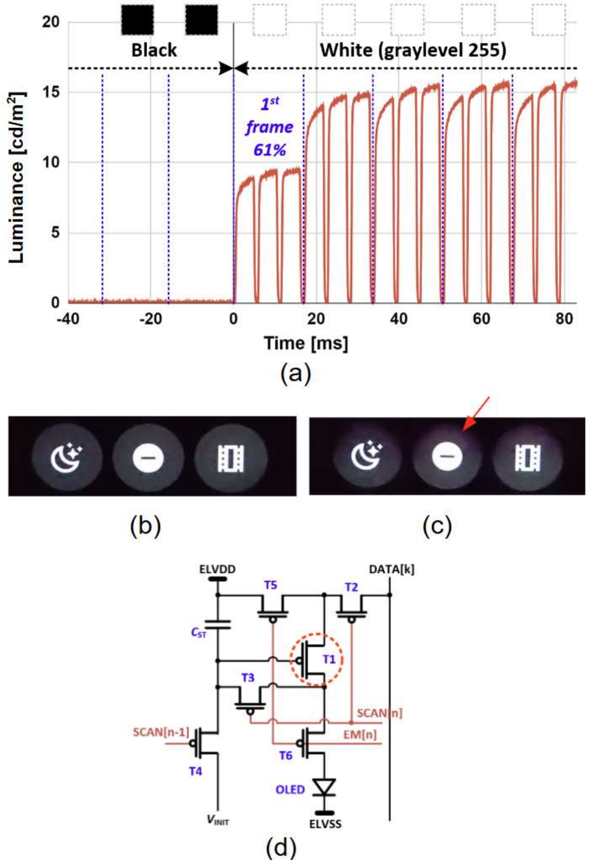


Figure 1. (a) Luminance waveform when the screen contents change from black to white (graylevel 255), (b) example screen image when not moving (still), (c) example screen image when moving up, and (d) a schematic view of one of AMOLED pixel circuits

ISSN 0097-996X/25/5601-0358-$1.00 © 2025

2. Discussions

The FFR has traditionally been evaluated as a luminance ratio using the luminance waveform analysis methods as mentioned above. In this case, the color shift, the purple edge in Figure 1(c), can be calculated by measuring the FFR of each primary color (e.g. red, green, and blue FFRs separately) and combining them into white luminance and color, which has been demonstrated by Zhang et al [6]. However, it becomes very challenging to use the waveform analysis method for extremely low luminance cases. In the example in Figure 1(a), the waveform was captured with a very thin horizontal line pattern (8 pixel rows) on the screen with Admesy Prometheus LF (800,000 sample per second luminance and flicker meter) to clearly distinguish the frame boundary, and the luminance signal (average 12 cd/m^2) gives good signal to noise ratio. However, when the target luminance is extremely low, a much larger measurement spot is needed to increase the signal, which makes unclear frame boundaries in the waveform. This increases the chance of inconsistent FFR calculation. Moreover, the blue pixels fall into the undistinguishable luminance range quickly as its luminance contribution in white is very low in most OLED displays. In turn, blue FFR evaluation results and the color shift calculation become unreliable. Figure 2 presents one of the extreme low luminance waveforms, measured by the same Admesy Prometheus LF, when the screen content changes from black to solid graylevel 48 (not a thin line) at a 5 cd/m^2, corresponding 0.127 cd/m^2. Red and green luminance waveforms show a reasonably clear signal, but it is very challenging to reliably analyze the blue luminance waveform for the FFR evaluation.

In order to overcome this challenge, we developed two new FFR evaluation methods: pattern toggling and pattern sliding. Neither methods require high speed waveform sampling, thus, the accuracy is not limited by the sampling rate of the instrument. Instead, both methods use the direct readout values of X, Y, and Z (CIE 1931 color space, or L, x, y) from the colorimeter. As a result, those methods can evaluate the luminance and color shift FFR at extremely low luminance. Pattern toggling methods use the toggling image patterns as shown in Figure 3(a), and the colorimeter is measuring the X/Y/Z values for one second duration while the image patterns are toggling between black (the first image pattern) and the target graylevel (e.g. W48, the second image pattern). The luminance waveform example in Figure 3(a) is just to explain the display behaviors in this method, and this method does not require any luminance waveform measurement. The luminance FFR is calculated as shown in Equation (1) where L_{toggle} is the measured toggling image luminance, $L_{steady1}$ is the measured steady state luminance of the first image (e.g. black), and $L_{steady2}$ is the steady state luminance of the second image (e.g. W48). Also, the color shift (delta u'v') can be derived from the u' and v' value difference between the toggling image, and the steady state second image, assuming that the first image (e.g. black) contribution to the toggling image measurement results (X, Y, and Z) is negligible.

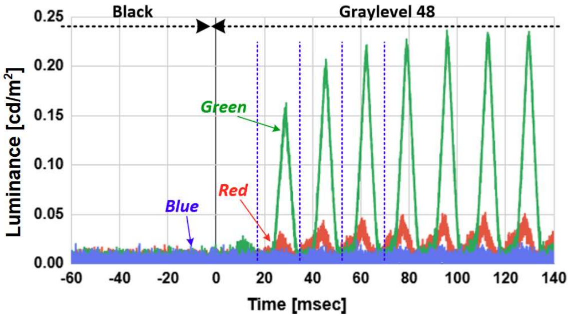


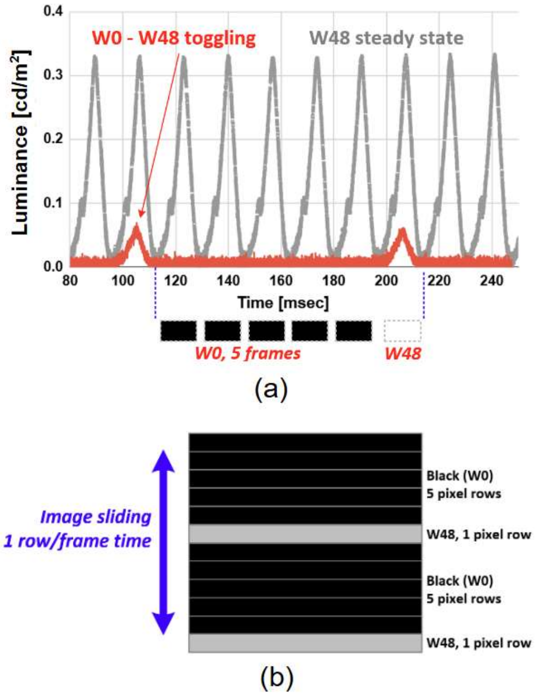
Figure 2. Luminance waveform of solid red, green, and blue images when switching from black to the primary colors (graylevel 48) with a display brightness 5 cd/m^2 (white graylevel 255 = 5 cd/m^2)

$$FFR_{Lum} = \frac{\left(6 \times L_{toggle} - 5 \times L_{steady1}\right)}{L_{steady2}} \times 100\ \% \qquad (1)$$

The second proposed method is to slide a stripe pattern image with the two different graylevel stripes. Figure 3(b) shows an example of the repeated stripe images with 5 rows of black and 1 row of white graylevel 48. With this image pattern on the screen, if the W48 stripe slides up or down at a speed of one row line per frame, the pixels with graylevel 48 exhibit only the first frame responses. That way, we can measure only the first frame responses from the colorimeter from this test setup (assuming that the colorimeter measurement spot is significantly larger than 6 pixel rows of the display), and calculate the luminance FFR as shown in Equation (2) where L_{slide} is the measured luminance of the stripe pattern when sliding, and the $L_{steady3}$ is measured luminance of the steady state stripe pattern.

$$FFR_{Lum} = \frac{\left(6 \times L_{slide} - 5 \times L_{steady1}\right)}{\left(6 \times L_{steady3} - 5 \times L_{stead}\ \ \right)} \times 100\ \% \qquad (2)$$

Compared with the pattern toggling method, the pattern sliding



(a)

(b)

Figure 3. Two proposed FFR evaluation methods: (a) pattern toggling methods waveform example, and (b) an example image pattern for the pattern sliding methods with black and W48 stripes

method is not limited by the dynamic range of the colorimeter and the measurement duration, and it is the best way to visualize the FFR impacts on the screen. However, when evaluating displays with sub-pixel rendering, the FFR accuracy could be affected as the rendering logic may alter the sub-pixel luminance of the one row stripe line image.

Table 1 shows the luminance FFR and color shift evaluation results with two different display conditions, 200 cd/m^2 and 5 cd/m^2, of a 322 ppi AMOLED display (display ‘A’) at 60 Hz refresh rate when the screen images change from black (W0) to solid graylevel 48 (W48). The X/Y/Z values of the steady state images and the toggling/sliding patterns were measure with Admesy Hyperion for the luminance and color FFR calculation. As shown in the table, the pattern toggling and sliding methods showed consistent and well aligned luminance/color FFR results for both 200 cd/m^2 and 5 cd/m^2 conditions.

Table 1. Evaluated FFR comparison between three different methods

	First frame (luminance) rate [%]			First frame color shift [JNCD]		
	Waveform analysis	Pattern toggling	Pattern sliding	Waveform analysis	Pattern toggling	Pattern sliding
Graylevel 48 at 200 cd/m^2 (5.074 cd/m^2)	60.0	59.6	59.8	1.5	2.2	2.1
Graylevel 48 at 5 cd/m^2 (0.127 cd/m^2)	Not reliable	13.6	14.0	Not reliable	28.2	29.0

Figure 4 shows the evaluated FFR of the display ‘A’ at various luminance conditions using the pattern toggling method, which clearly shows the FFR degrades when the steady state luminance decreases.

In order to improve the FFR and to enhance the user experience at extremely low display luminance use cases (e.g. bed time mode), many engineering teams proposed and implemented overdriving methods [3-4], in which the first frame luminance is intentionally boosted exceeding the original image luminance by the display driver ICs (DDICs) when image contents change. Though this method successfully demonstrated mitigation of the low FFR issues, this solution requires the DDICs with this compensation feature, and fine adjustment of overdriving parameters per different brightness in the display module level.

For more universally applicable mitigation solutions for the low FFR issues in the AMOLED displays, we analyzed the FFR values with respect to the stress conditions, the first image. Particularly, the focus of the analysis is on the optimization of the black pixel data voltage (V_{BLACK}), which causes the most severe FFR degradation at extremely low luminance. In order to mimic the conditions of applying different V_{BLACK} voltages in existing displays, different graylevels (graylevel 1-17) were used for the first image (stress image) instead of black, and the FFR values were extracted using the pattern toggling method when the steady state luminance of the second image is 5.3 cd/m^2, 0.5 cd/m^2, 0.3 cd/m^2, and 0.1 cd/m^2 (graylevel 48 image of brightness setting 200 cd/m^2, 20 cd/m^2, 10 cd/m^2, and 5 cd/m^2). As shown in Figure 5(a) and 5(b), the higher the first image graylevel, the higher the FFR values for the second image, as anticipated, thanks to the smaller pixel data voltage, V_{DATA}, change between the two images. Though this V_{BLACK} adjustment may increase the risk of screen image contrast degradation, the measured luminance delta between black and those low/non-zero graylevels was still kept around 0.0004 cd/m^2 or lower as shown in Figure 5(c). This indicates that the current V_{BLACK} in this display is much higher (p-channel TFT circuit) than necessary, and there is room to optimize (reduce) V_{BLACK} without compromising image contrast. Figure 6(a) presents the luminance waveform comparison between the steady state (gray), black-to-W48 (red), and

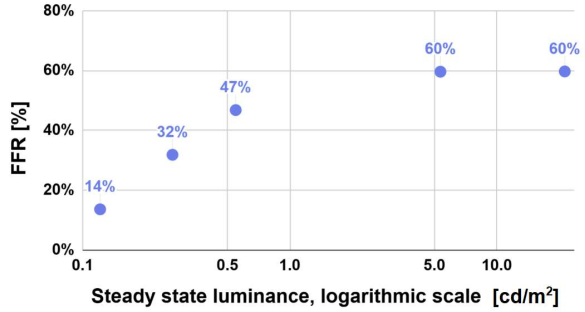


Figure 4. FFR evaluation results using the proposed pattern toggling method at various luminance conditions from the display ‘A’

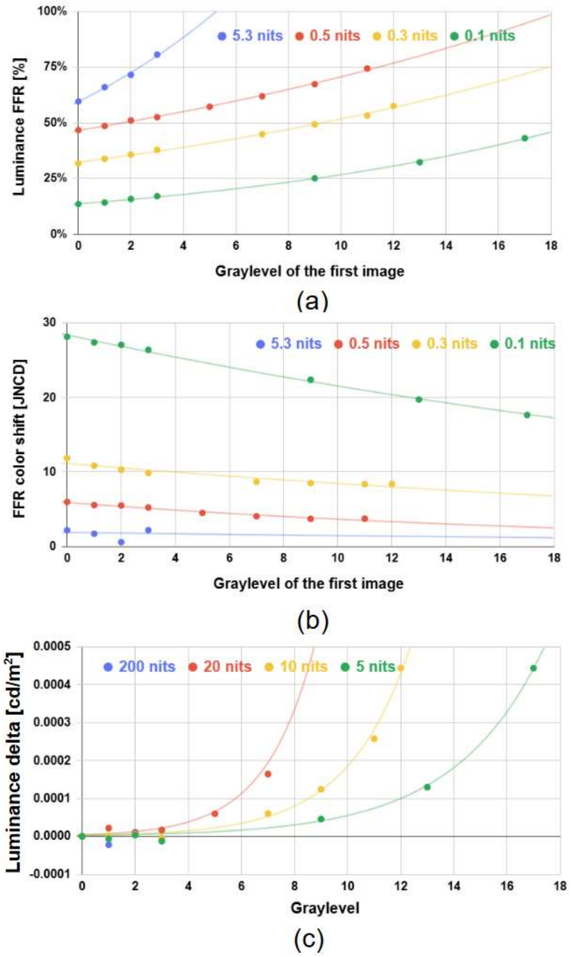
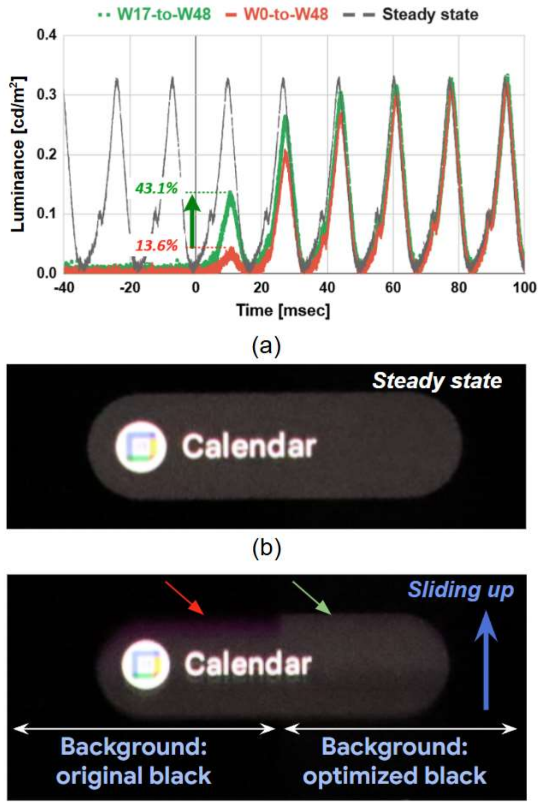


Figure 5. FFR evaluation results with different graylevels for the first image: (a) luminance FFR (higher is better), (b) color shift (lower is better), and (c) luminance delta between black (graylevel 0) and the low graylevels at a steady state from the display ‘A’



(a)

(b)

(c)

Figure 6. (a) Luminance waveform comparison from the display 'A', and photos of a demo UI image on the screen (b) when not moving, and (c) when the screen is sliding (moving) with the display 'B'

graylevel 17 (W17)-to-W48 (green) image transition cases. This shows a potential case that V_{BLACK} is better optimized (to the V_{DATA_W17} level) in the display. Not only does the FFR increase from 13.6% to 43.1% (around 3 times higher FFR), the second and third frame luminance also increased from this optimization. Together with the luminance FFR improvement, the color shift has reduced from 28.2 JNCD to 17.7 JNCD (37% improved). Figure 6(b) shows a photo of the demo static UI image in which the right half of the image has the optimized black background, and the left half has the original black background. When sliding the image on the screen at a speed of 10 rows per frame, the leading edge of the right half (indicated by the green arrow) showed much clearer image boundaries with less purplish tint than that of the left half (indicated by the red arrow) on a 321 ppi AMOLED display, display 'B' as shown in Figure 6(c).

Optimizing V_{BLACK} in the display module could also be a very delicate process in display manufacturing due to the risk of elevated black luminance as mentioned. Thus, optimizing the system graphic user interface (GUI) image could be another approach to improve the FFR. Applying slightly increased, non-zero graylevel (non-black) background in the GUI should improve the FFR in the device, providing better user experience, particular for the GUI images that have high chance of screen sliding user gestures. In addition, the non-black background in the GUI images could be partially applied only around the low graylevel image patterns with gradual changes from/to the rest of the black background, in order to minimize any potential user perceptions on the elevated background luminance.

3. Conclusions and future work

In order to provide a high quality screen experience to users at extremely low luminance conditions, we introduced two new FFR evaluation methods, pattern toggling and pattern sliding, that can quantify display FFR performance in those extreme conditions, and can provide direct readout of the luminance and color degradation. Based on the low luminance FFR evaluation results, we proposed mitigation methodologies: V_{BLACK} optimization in the display module manufacturing process, and FFR enhancing system GUI design guidance. While the previously reported solutions are to compensate for the degraded pixel luminance, the proposed approaches are to lower the stress (the first image) on the pixels to mitigate the degradation. The lab test results of emulating the optimized display settings/GUI images were presented in this paper, which showed around 3 times higher luminance FFR, and about 37% color shift reduction from a 322 ppi AMOLED display for steady state 0.127 cd/m^2 images. Though the basic principles to improve the FFR were proposed in this paper, detailed execution methods may need further investigations to avoid degradation in image contrast.

4. References

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