Application Note

Common LED Display Challenges, Root Causes and Workarounds in Narrow Pixel Pitch Matrix LED Display

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ABSTRACT

The Mini- / Micro-LED display is getting more and more popular in variant EEs, such as Narrow Pixel Pitch (NPP) LED display, LED green screen, LED cinema screen, AR/VR, and animated automotive rear lighting. The increasing popularity of the LED display in these EEs is due to the advantages of high brightness, high contrast ratio, outstanding image quality, and long life.

Behind the LED display, there are many design challenges with the LED driver. What new challenges about display performance are you going to meet when the resolution and pixel density of the display gets higher and higher? What are the root causes of these display challenges and what circuits and algorithms inside the driver are used to solve them?

This application note can firstly bring you a thorough understanding of display technology, LED driver topology, matrix LED display driver architecture and system. Then the discussion goes deeper into root causes and designs of several typical LED display challenges, from IC circuits and algorithm perspectives, based on TI's latest Common Cathode Matrix LED Display Driver TLC6983 and TLC6984.

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1 Display Technology Overview

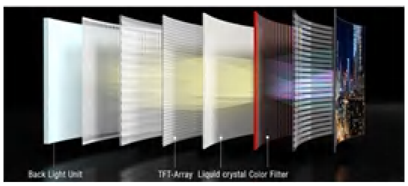
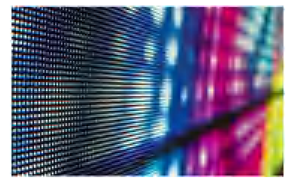
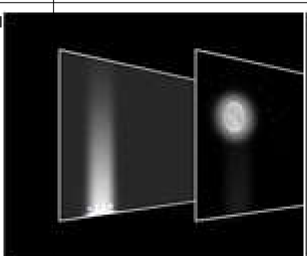
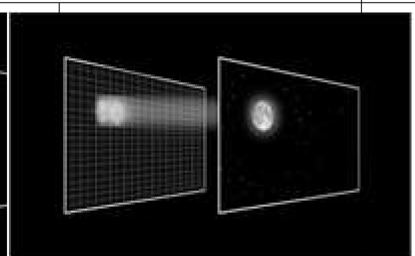
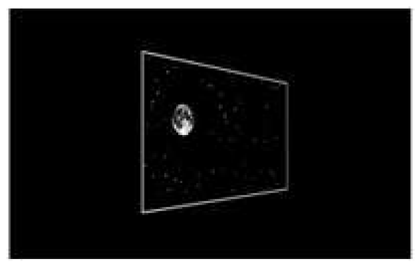
1.1 Display Technology Comparison

Currently there are three mainstream display technologies, Liquid-crystal display (LCD), organic light-emitting diode (OLED), Mini-LED and Micro-LED. Table 1-1 shows the comparison.

These display technologies use a variety of dimming methods. LCD traditionally uses global dimming (Edge backlight). However, local dimming (direct backlight) is getting more and more popular in high-end products due to advantages in contrast ratio and peak brightness. Both OLED and Mini- / Micro-LED uses pixel dimming, which means each pixel directly lights up and shows picture, there are no backlight anymore.

Mini- / Micro-LED has advantages of high brightness, high contrast ratio, outstanding image quality and long life. Mini- / Micro-LED are getting more and more popular in variant EEs, such as Narrow Pixel Pitch (NPP) LED display, LED green screen for virtual production, LED cinema screen, AR/VR, and animated automotive rear lighting, despite drawbacks of production and system complexities.

Table 1-1. Display Technology Comparison

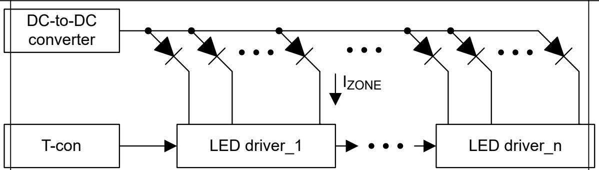
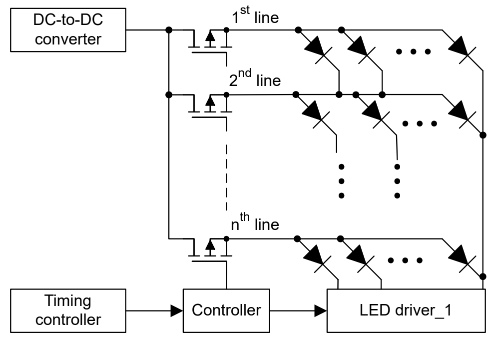
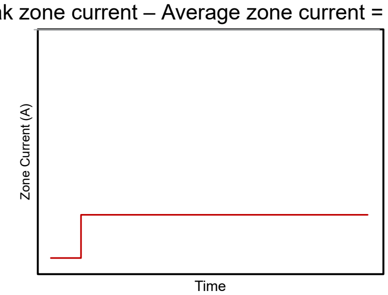
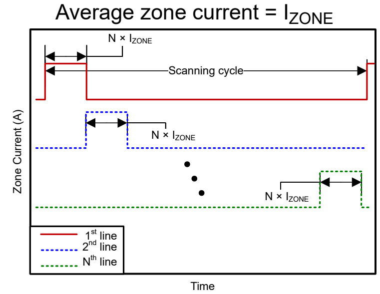
	LCD		OLED	Micro-LED
Structure				
Dimmi				
Feature	• Contrast Ratio: Low • Peak Brightness: Medium • Life time: Long • Production complexity: Low	• Contrast Ratio: Medium • Peak Brightness: High • Life time: Long • Production complexity: Medium	• Contrast Ratio: High • Peak Brightness: Low • Life time: Low • Production complexity: Medium	• Contrast Ratio: High • Peak Brightness: High • Life time: Long • Production complexity: High

1.2 LED Driver Topology

Table 1-2 describes two common LED Driver topologies. In the direct drive topology, each LED has own drive channel. In the time-multiplexing topology, a group of LEDs (in column) share one drive channel and each LED lights up in turn by time-multiplexing way. In detail, after the first line of LEDs are lighted up, the second line of LEDs are then lighted up, and so on, up until the last line of LEDs are lighted up, and then the scan returns to the first line and enters the next cycle. Time-multiplexing uses persistence of vision of human eye and makes human eye can feel continuous image even LEDs light up in turn.

In a mini- or micro-LED display application, each pixel corresponds to an RGB LED, direct drive is not practical when the screen resolution getting higher and higher. For instance, a 4K screen has 3840 × 2160 pixels and each pixel needs three channels (red, green and blue). Considering using a 48-channel direct drive LED driver, which needs 3840 × 2160 × 3 / 48 = 518,400 pcs drivers that is almost impossible from PCB layout and costs perspectives.

Table 1-2. LED Driver Topology Comparison

<table>
<tr><th></th><th>Direct</th><th>Time-Mutliplexing</th></tr>
<tr><td>Structure</td><td>
</td><td>
</td></tr>
<tr><td>Componnet</td><td>N × LED Driver</td><td>(1 × LED Driver) + (1 × Controller) + N ×(Switch MOSFET)</td></tr>
<tr><td>Zone Current</td><td>Peak zone current – Average zone current = I_{ZONE}

</td><td>Peak zone current = N × I_{ZONE}
Average zone current = I_{ZONE}

</td></tr>
</table>

The time-multiplexing design using the single driver IC to turn on more LEDs and then saves PCB layers and cost, is more practical and essential for narrow pixel pitch (NPP) LED display. In fact, the smaller the pixel pitch, the greater the number of time-multiplexing in the design.

Though the time-multiplexing design saves PCB layers, cost and also has great challenges on display performance. Because the high efficiency of time-multiplexing is at the sacrifice of the display refresh rate. Note that the definition of refresh rate in LED display is different from that in LCD or OLED display. Usually, the refresh rate of your LCD or OLED display refers to how many times per second the display is able to draw a new image. This is measured in Hertz (Hz). For example, if your display has a refresh rate of 144Hz, that means refreshing the image 144 times per second. However, the refresh rate defined in LED display is the reciprocal of the amount of time that all LEDs are lighted up one time in turn (same measured in Hertz). Normally, the refresh rate of LED display needs to be very high up to 2000Hz or higher, such as 1920Hz, 3840Hz and even 7680Hz, to avoid dark scan lines or brighter/dimmer lines when using the camera to capture the LED display image.

The refresh rate depends on the number of time-multiplexing (or number of scan lines). From the IC design perspective, supporting more scan lines can use less drivers and then further saves PCB layers and cost, that makes the driver product be more competitive in the market. However, when there is more scan lines, for example, doubled scan lines, the total time needed to light up all LEDs in one cycle doubles without changing the average brightness of the display, therefore, the refresh rate is halved.

Both high refresh rate and large quantities of scan lines are not easy to achieve. Fortunately, TI's matrix LED display driver TLC6983 and TLC6984 have built-in SRAM to support more multiplexing and also increase the refresh rate by shortening the grayscale (GS) data transmission time. In addition, TLC6983 and TLC6984 have an internal frequency multiplier to generate the GCLK by SCLK, up to 160MHz, which makes higher refresh rate support be possible. The application note Example of LED Display Screen Design Requirements Based on TLC6983 shows a display example achieving 7680Hz refresh rate, 120Hz frame rate, 18 scan lines and 16-bit grayscale intensity.

2 Mini- / Micro-LED Display System Introduction

2.1 Matrix LED Display Basics

Before discussing the LED display system, knowing about the basic concept of LED and LED driver structure is necessary.

There are two kinds of RGB LED shown in Figure 2-1 and Figure 2-2, common anode and common cathode. Common anode LED means the anodes of LED are tight together, and vice-versa for the common cathode. Note that LED forward voltage varies by color. Typically, 1.8V to 2.2V for red LED and 2.8V to 3.4V for blue/green LEDs.

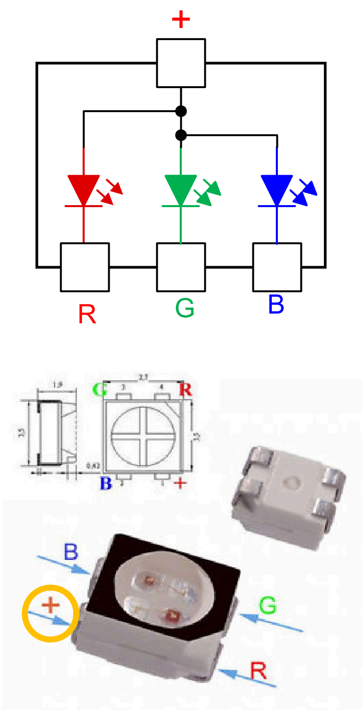


Figure 2-1. Common Anode LED

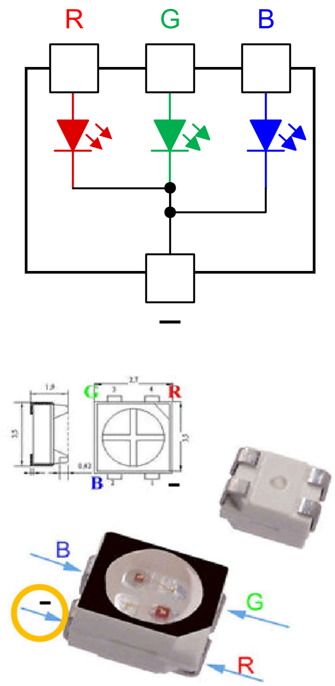


Figure 2-2. Common Cathode LED

So, when talking about LED drivers, there is common anode or common cathode LED driver, as the driver architectures shown in Figure 2-3 and Figure 2-4. Traditionally, common-anode LED driver is more common due to the sink driver with NMOS structure which has lower cost than that of source driver with PMOS structure. While now common-cathode LED driver is more popular due to saving power.

The biggest difference between them is that common-anode LED driver has only a single rail for all RGB, but common-cathode LED driver has 2 split rails. One is for red LED and another is for green and blue LEDs.

Common cathode LED driving method can significantly save power because the red LED has much lower forward voltage than that of green and blue LEDs. In addition, LED display surface temperature reduces more than 10 degrees and has better color uniformity and longer LED life. Usually, the total power consumption can be reduced by 30% to 75%.

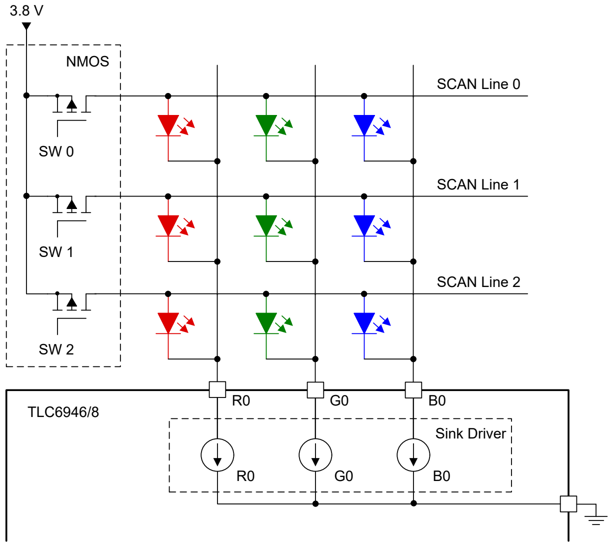


Figure 2-3. Common Anode LED With Sink Driver Architecture

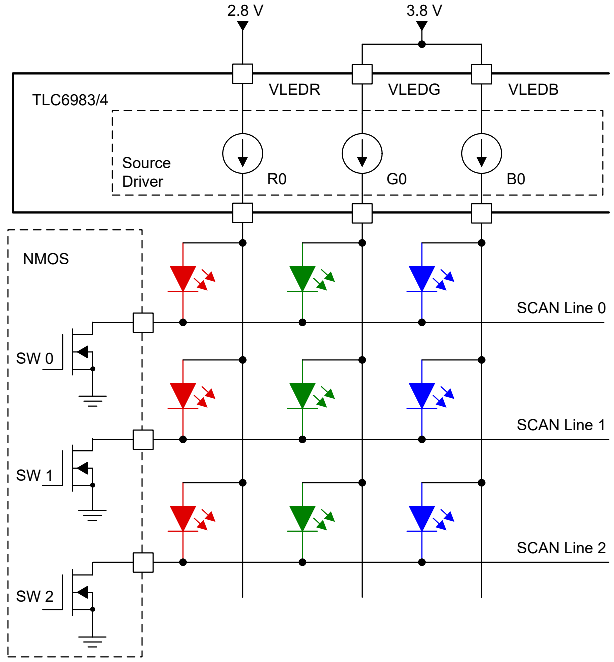


Figure 2-4. Common Cathode LED With Source Driver Architecture

2.2 LED Display Emerging EEs and System Overview

Because of the excellent display performance of LED display, there are some emerging end equipment applications, such as LED green screen for virtual production, LED Cinema Screen, LED commercial display and animated automotive flexible rear light.

The LED display system, the breakdown drawing and the typical block diagram are shown in Figure 2-5, Figure 2-6 and Figure 2-7, respectively. In this example, a 4K screen has around 30Ku LED drivers, without counting FPGA, LED drivers take more than 98% BOM cost.

The main opportunity is LED driver. One LED Panel has 36pcs LED Drivers. One 4K Screen has approximately 30Ku LED drivers.

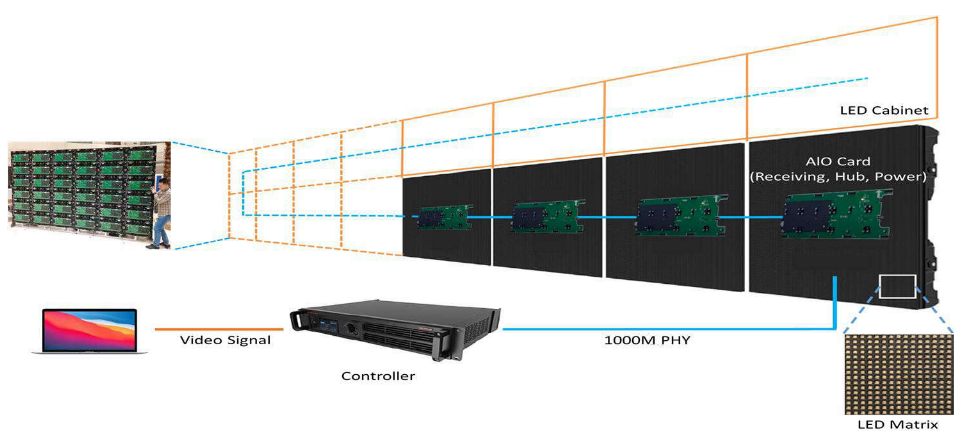


Figure 2-5. LED Display System

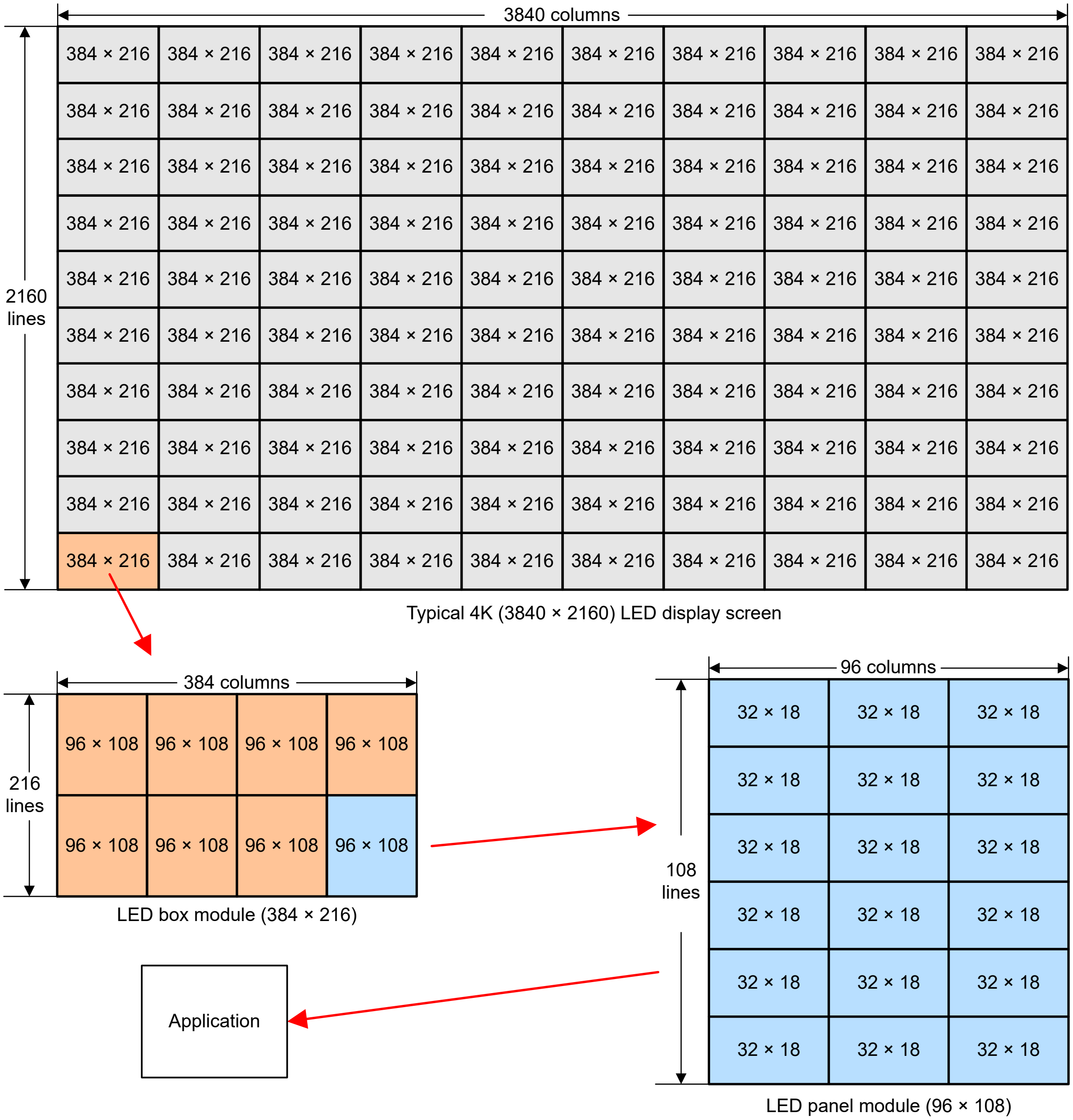


Figure 2-6. Application in the LED Display System

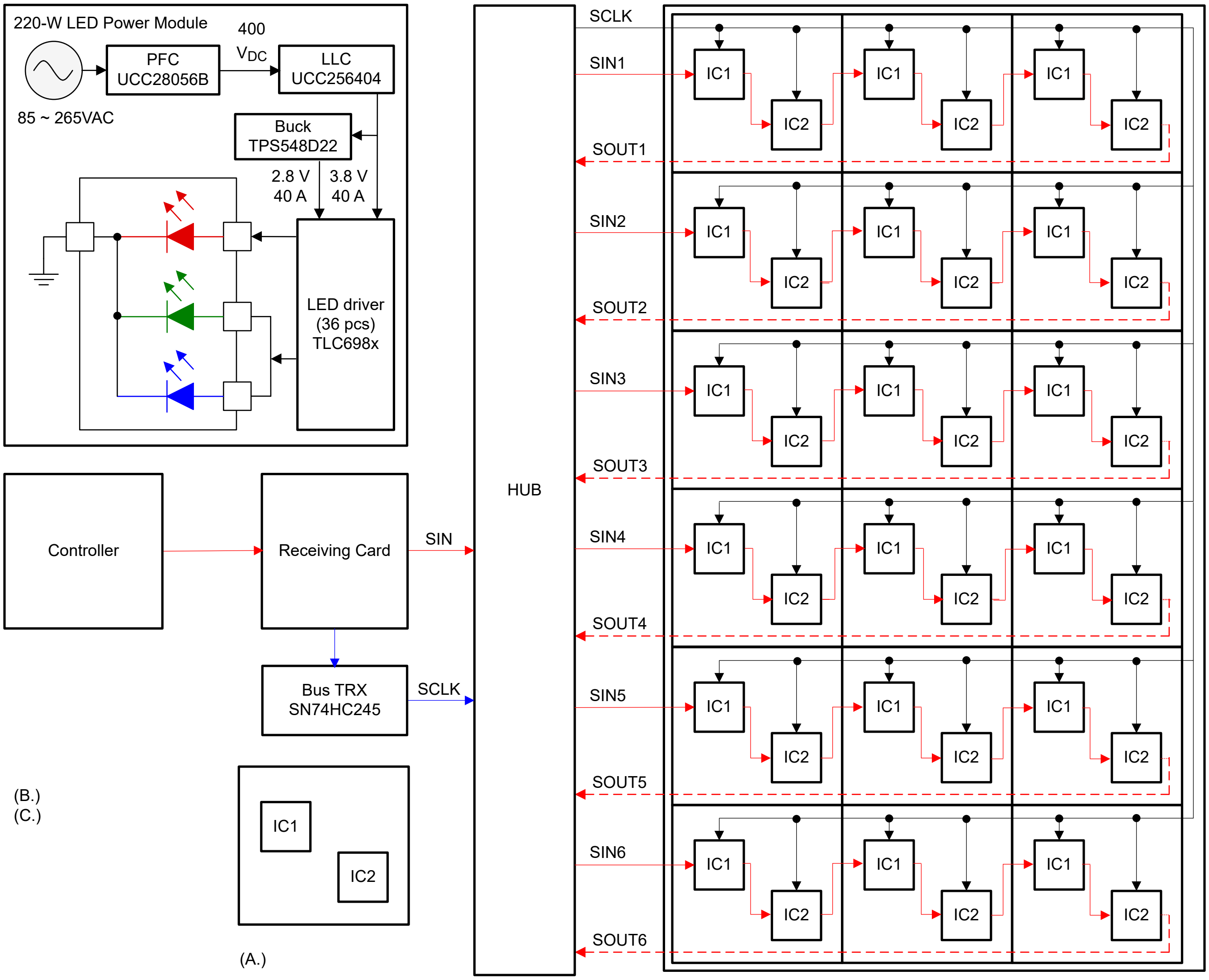


Figure 2-7. LED Display Panel Block Diagram

A. Two drivers control 32 × 18 RGB LED array
B. One LED panel uses 36 pcs TLC698x
C. One 4K screen uses 28.8Ku driver.

2.3 Common Issues in High-Density Matrix LED Display

Figure 2-8 shows seven common issues in high-density matrix LED displays. Some examples are shown in Figure 2-9 and Figure 2-10. The following session goes deeper into root cause analysis and TI designs of those typical LED display challenges from IC circuits and algorithm perspectives based on TI's latest Common Cathode Matrix LED Display Driver, TLC6983 and TLC6984. Meanwhile, you can also refer to the application note The Common LED Display Challenges in Narrow Pixel Pitch Matrix LED Display for a rough overview about these issues.

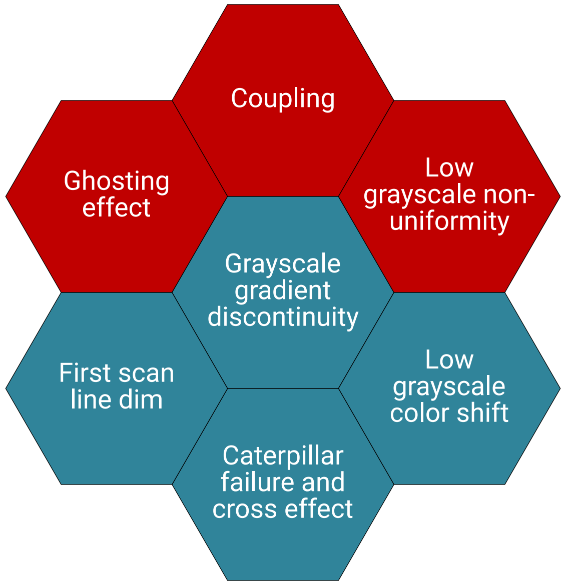


Figure 2-8. Common Issues in High-Density Matrix LED Display

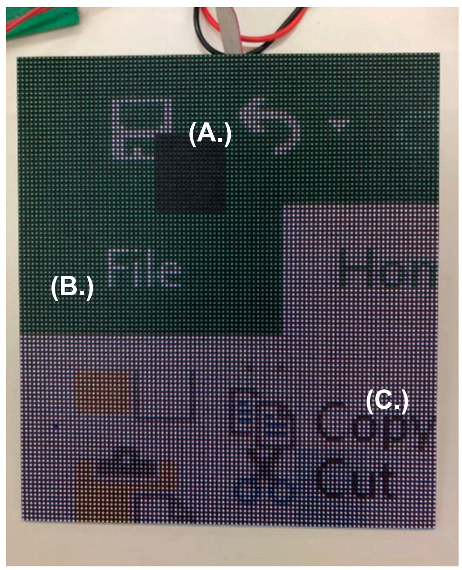


Figure 2-9. LED Display Issues - Coupling, Non-uniformity and Ghosting

A. Coupling
B. Non-uniformity
C. Ghosting
D. Caterpillar

Figure 2-10. LED Display Issue - Caterpillar

3 Root Cause Analysis and TI Designs

3.1 Ghosting Issue

Ghosting means some LEDs illuminate unintentionally. Ghosting is primarily attributed to the charging or discharging of lumped parasitic capacitance in row or column of the LED matrix, during the row or column changing process, which causes some LEDs to illuminate unintentionally. This issue is easier to be identified in low grayscale images.

The ghosting is even more pronounced using the left or right slash grid test pattern shown in Figure 3-1 and Figure 3-2. LEDs in green slash are the normal display, we don't see any LEDs are lighted up between 2 slash. Figure 3-2 is the abnormal display with ghosting. Figure 3-2 has unwanted LEDs lit up between the normal slashes. If the unwanted LEDs are in the upside of the normal slash, this is known as upside ghosting. The opposite is named as downside ghosting.

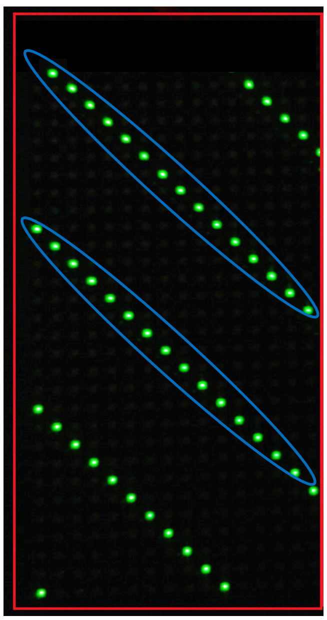


Figure 3-1. Normal Display without Ghosting

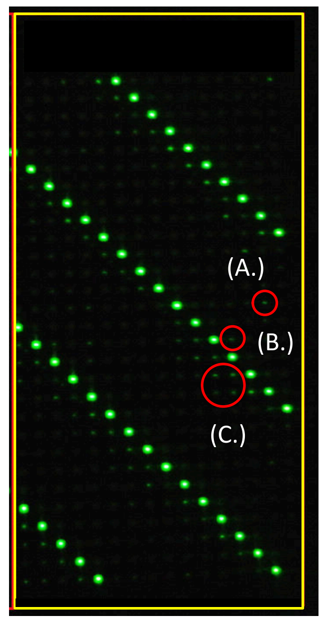


Figure 3-2. Abnormal Display with Ghosting

A. Unwanted LED illuminated (upside ghosting)
B. Unwanted LED illuminated (downside ghosting)

3.1.1 Downside Ghosting

The main cause of downside ghosting is the buildup charge in the parasitic capacitance on OUTn when transitioning between scan lines, the charge on the parasitic capacitance discharges through the LED causing the LED to light up when the LED is not supposed to be.

Figure 3-3 lists the LED legend that is used in the following analysis.

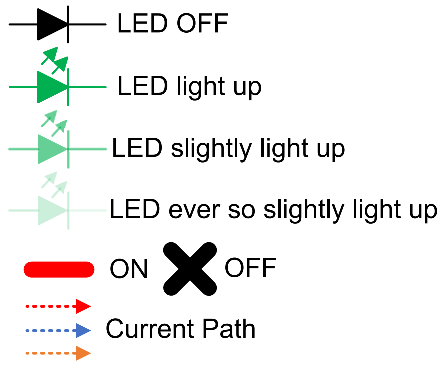


Figure 3-3. LED Legend

Figure 3-4, Figure 3-5 and Figure 3-6 show the root cause analysis of downside ghosting with the simplified time-multiplexing LED driver structure for easier understanding.

So, in P1 operation, when only wanting to light up LED_{02}, the driver turns ON SW_0 and the current path is shown in red dotted line. At this moment, the yellow parasitic capacitor on channel OUT_2 is charged.

During P1 operation, SW_0 is ON, LED_{02} lights up.

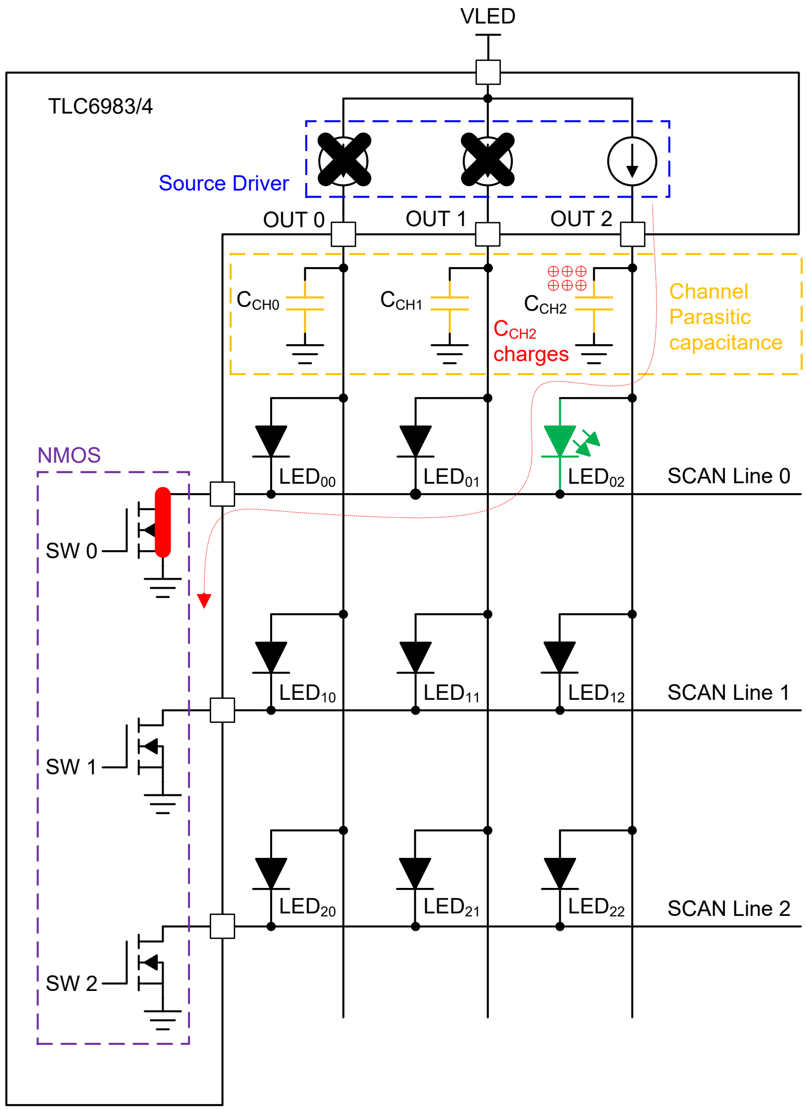


Figure 3-4. Downside ghosting - P1 Operation

Next, in P2 operation, when only wanting to light up LED_{11}, the driver turns on SW_1 and the current path is shown in red dotted line. And at this moment, the yellow parasitic capacitor on channel OUT_1 is charged. However, LED_{12} is also slightly lit up even channel OUT_2 is closed. Because the parasitic capacitor has been charged previously, and LED_{12} is lit up through the current path in blue dotted line. So, LED_{12} is called downside ghosting.

During P2 operation, SW1 is ON, LED11 lights up, and LED12 slightly lights up.

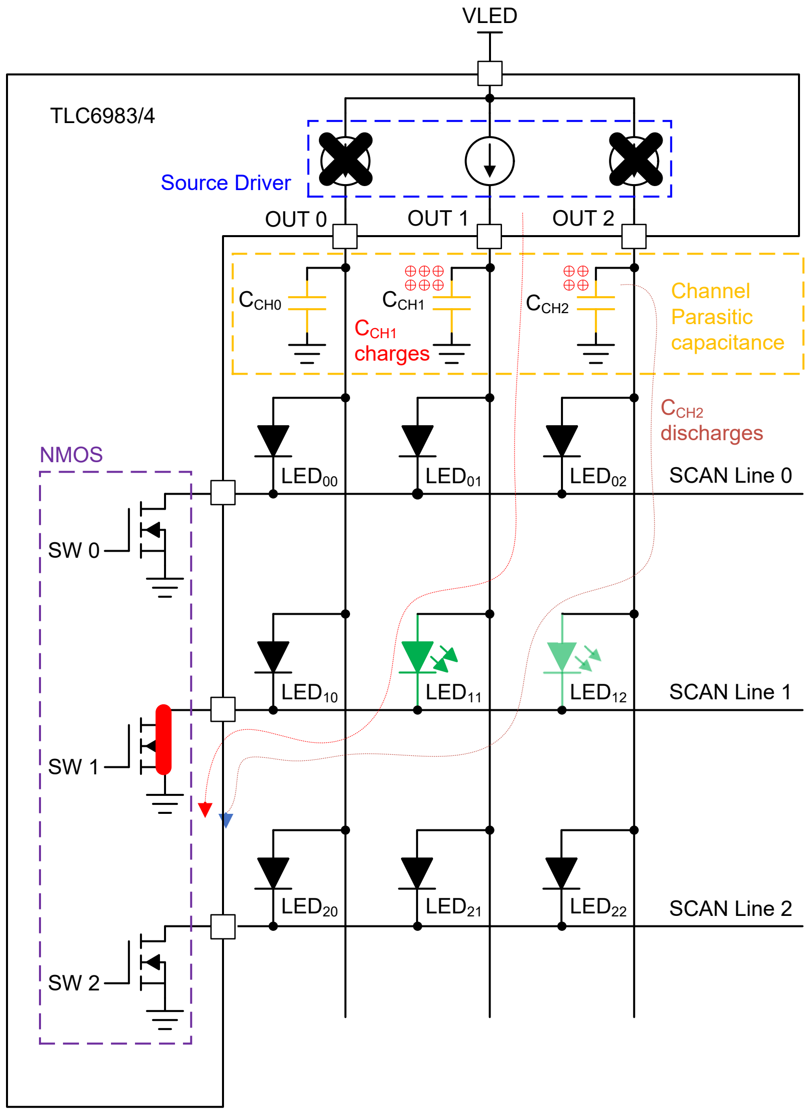


Figure 3-5. Downside ghosting - P2 Operation

Similarly, in P3 operation, when only wanting to light up LED_{20},LED_{21} is also slightly lit up and LED_{22} is slightly lit up, through the current paths in blue and orange dotted line, respectively. The reason is the same as previously due to the channel parasitic capacitors.

The reason that LED_{21} and LED_{22} have different brightness is that the corresponding channel parasitic capacitors have different charges to light up the LED. Different quantities of charge flow through the LED to discharge the corresponding channel parasitic capacitor.

During P3 operation, SW2 is ON, LED20 lights up, LED21 slightly lights up, LED22 ever so slightly lights up.

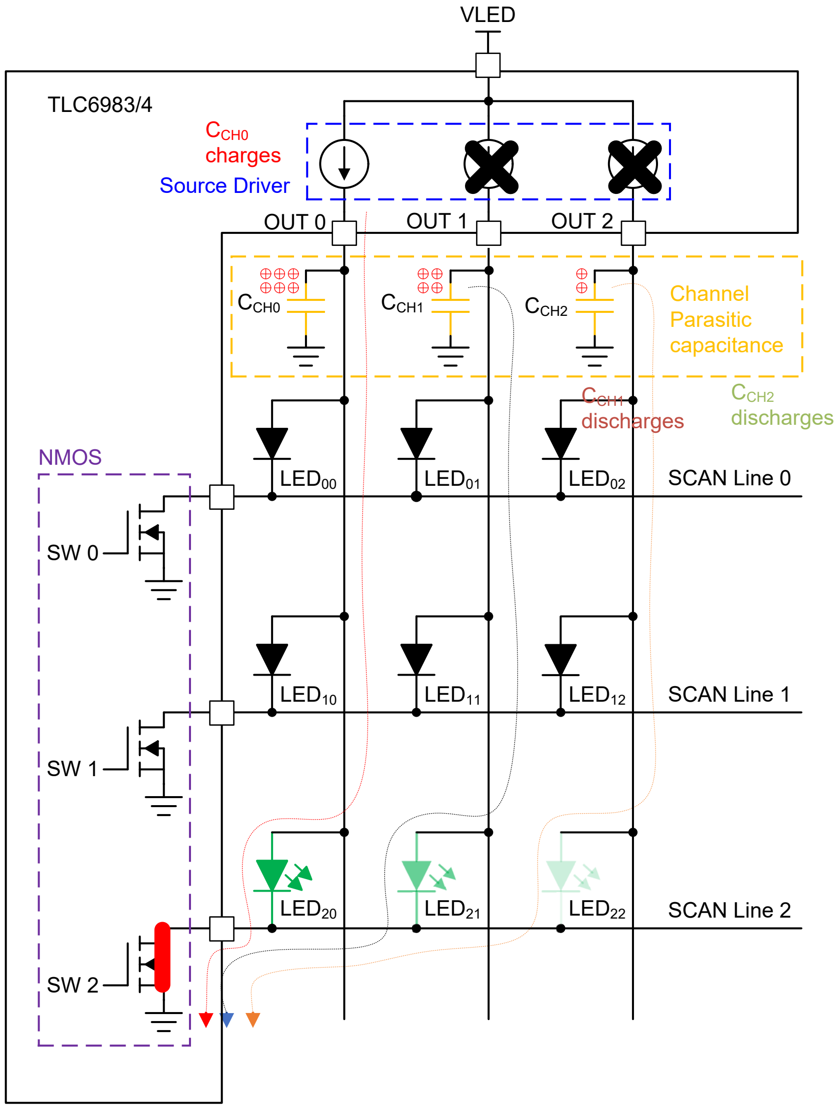


Figure 3-6. Downside ghosting - P3 Operation

So, how to solve this issue? We know that the downside ghosting is because of charges on channel parasitic capacitors. So, if we can remove these charges, then we can possibly to solve this issue.

As shown in Figure 3-7, TLC698x uses a pre-discharge circuit to pull all channels OUT_n down to the set level (Vpd) during the line switch period to maintain LEDs in the next scan line are not lit up, thus eliminating downside ghosting.

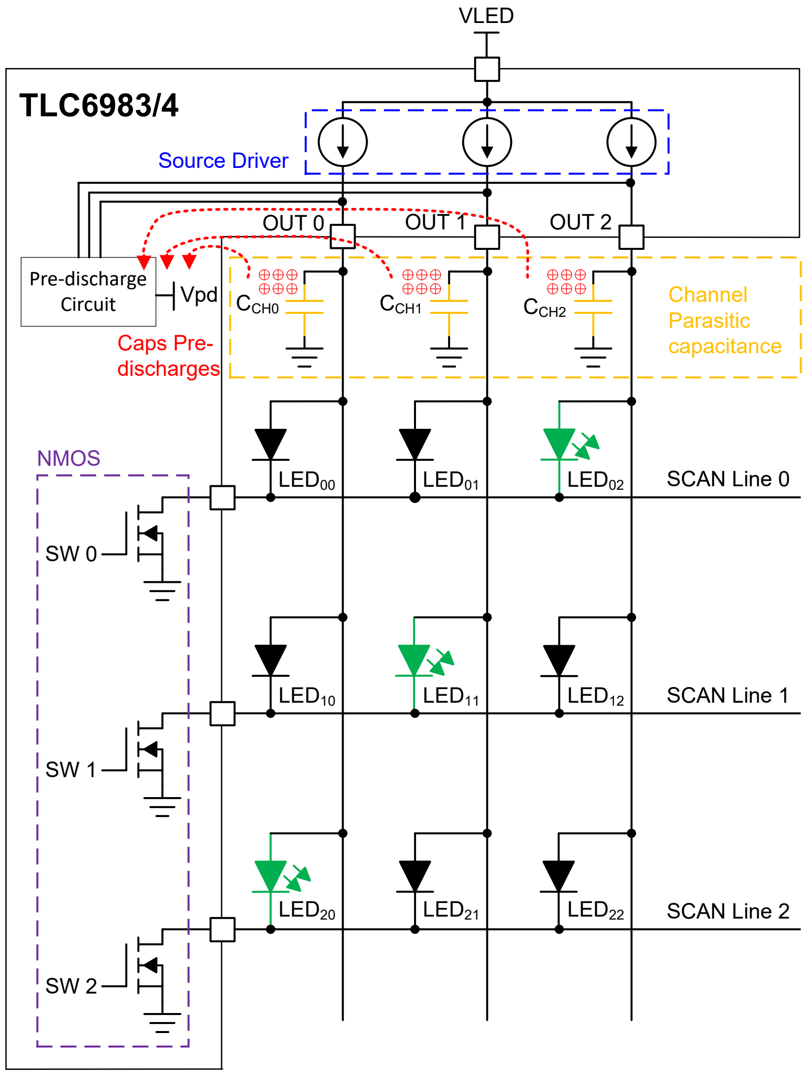


Figure 3-7. Downside Ghost Effect Elimination by Pre-discharge Circuit

Figure 3-8 shows the comparison demo with or without downside ghosting. You can see that the pre-discharge circuit works well. When enabled, we do not see ghosting anymore.

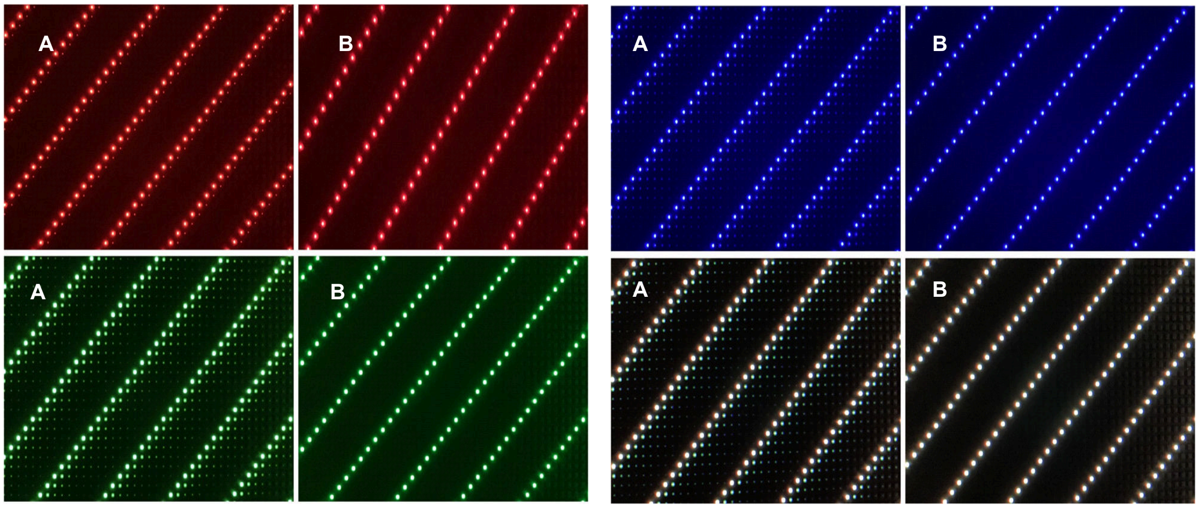


Figure 3-8. Downside Ghosting Comparison

A. With downside ghosting
B. Without downside ghosting

3.1.2 Upside Ghosting

Actually, the root cause analysis of upside ghosting is similar to what has been discussed in the downside ghosting session. The main cause of upside ghosting is the buildup charge in the parasitic capacitance on SW_n when transitioning between scan lines, the parasitic capacitance is charged through the LED causing this to light up when this must not be. Figure 3-9, Figure 3-10 and Figure 3-11 describe the root cause analysis of upside ghosting.

So, in P1 operation, when only wants to light up LED_{02}, the driver turns ON SW_0. And at this moment, the yellow parasitic capacitor on Scan Line 0 is discharged to 0, through these current paths in red dotted line.

During P1 operation, SW_0 is ON, LED_{02} lights up.

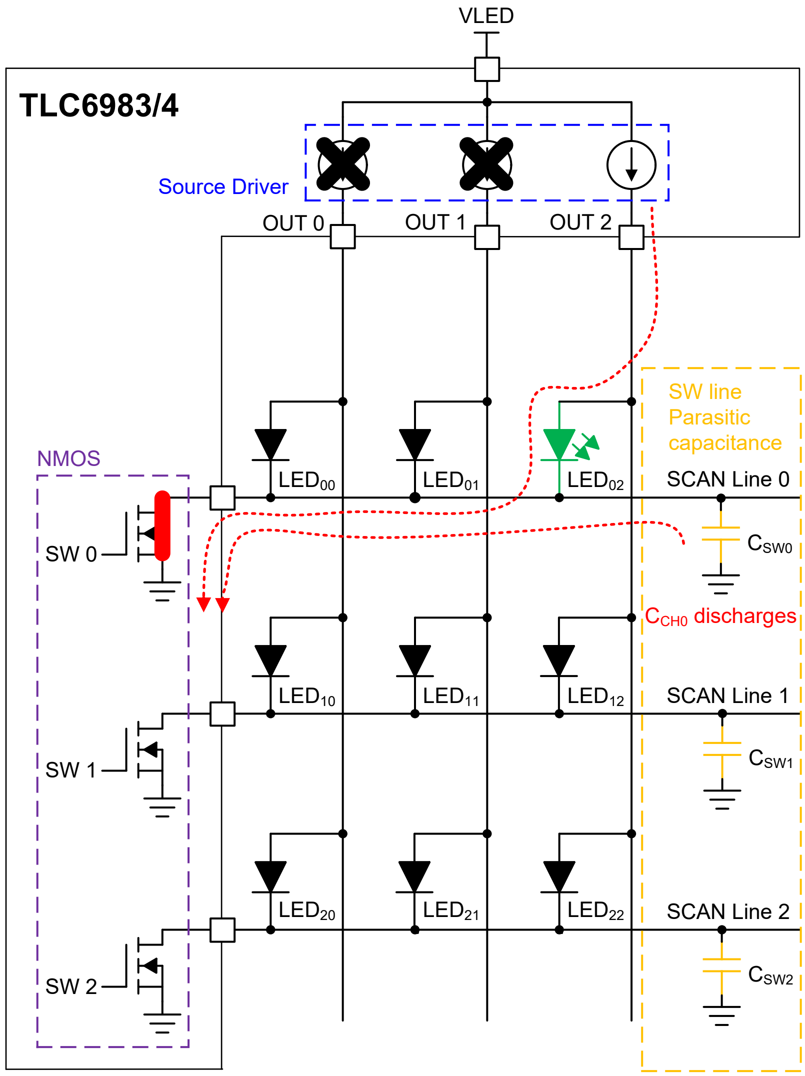


Figure 3-9. Upside ghosting - P1 Operation

Next, in P2 operation, when only wants to light up LED_{11}, the driver turns on SW_1 and the yellow parasitic capacitor on Scan Line 1 is discharged to 0, through these current paths in red dotted line. However, at this moment, the yellow parasitic capacitor on Scan Line 0 is also charged, through the current path in blue dotted line. So, LED_{01} is slightly light up even SCAN line 0 is closed. Because the parasitic capacitor on SCAN line 0 has been discharged previously, and LED_{01} is light up through the current path in blue dotted line. So, LED_{01} is calling upside ghosting.

During P2 operation, SW_1 is ON, LED_{11} lights up, LED_{01} slightly lights up.

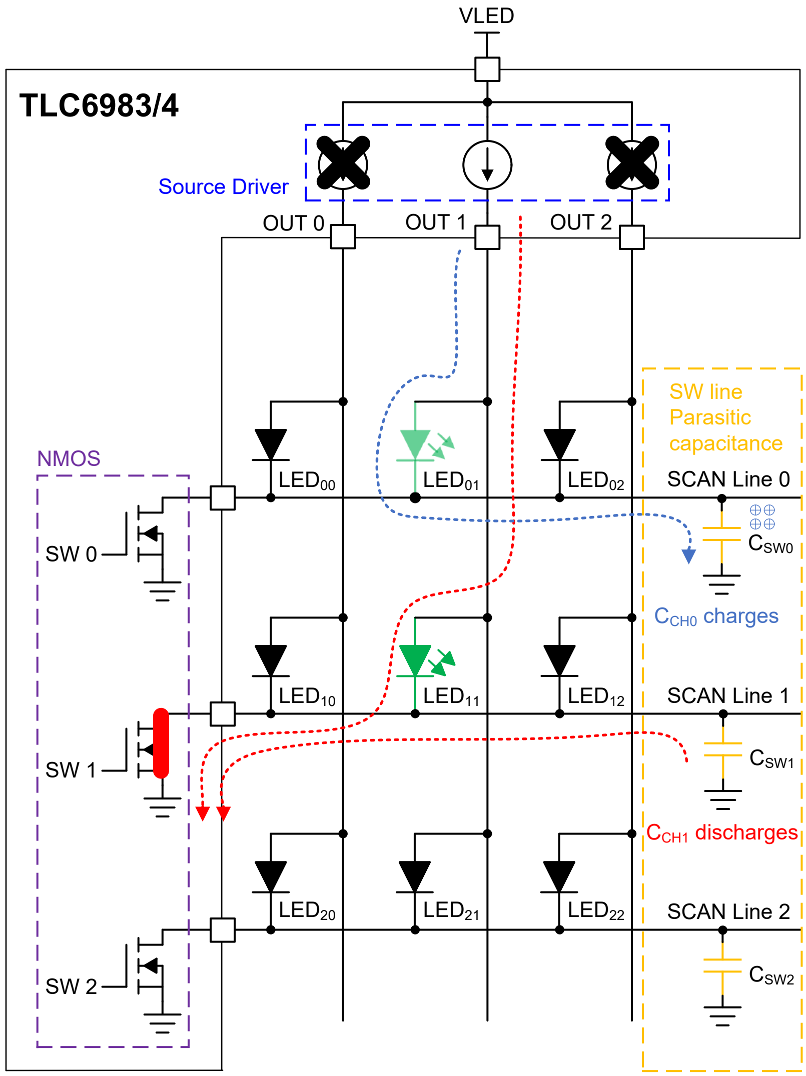


Figure 3-10. Upside ghosting - P2 Operation

Similarly, in P3 operation, when only wanting to light up LED_{20}, we can see that LED_{10} is slightly lit up and LED_{00} is even so slightly lit up, through the current paths in blue and orange dotted line, respectively. The reason is the same as previously due to the scan line parasitic capacitors.

The reason that LED_{10} and LED_{00} have different brightness is because the corresponding scan line parasitic capacitors accumulate different charges before the LED being faulty lighted up (different quantities of charge flow through the LED to charge the corresponding scan line parasitic capacitor).

During P3 operation, SW_2 is ON, LED_{20} lights up, LED_{10} slightly lights up, LED_{00} ever so slightly lights up.

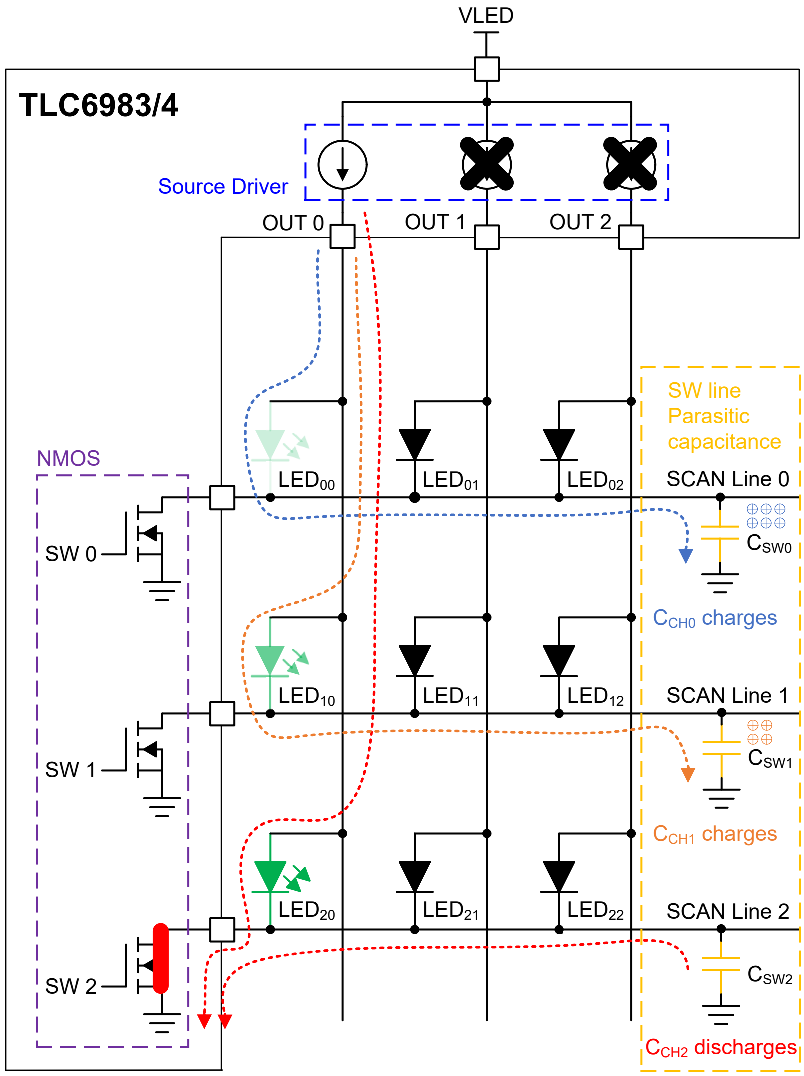


Figure 3-11. Upside ghosting - P3 Operation

So, how to solve this issue? The upside ghosting is because of discharges on SCAN line parasitic capacitors. So, if we can stop or weaken the discharge process, then we can solve this issue.

As shown in Figure 3-12, TLC698x uses scan line clamp circuits to pull up the line voltage to a high value (Vclamp) during the line switch time to maintain no current flow to the previous scan line, thus eliminating upside ghosting.

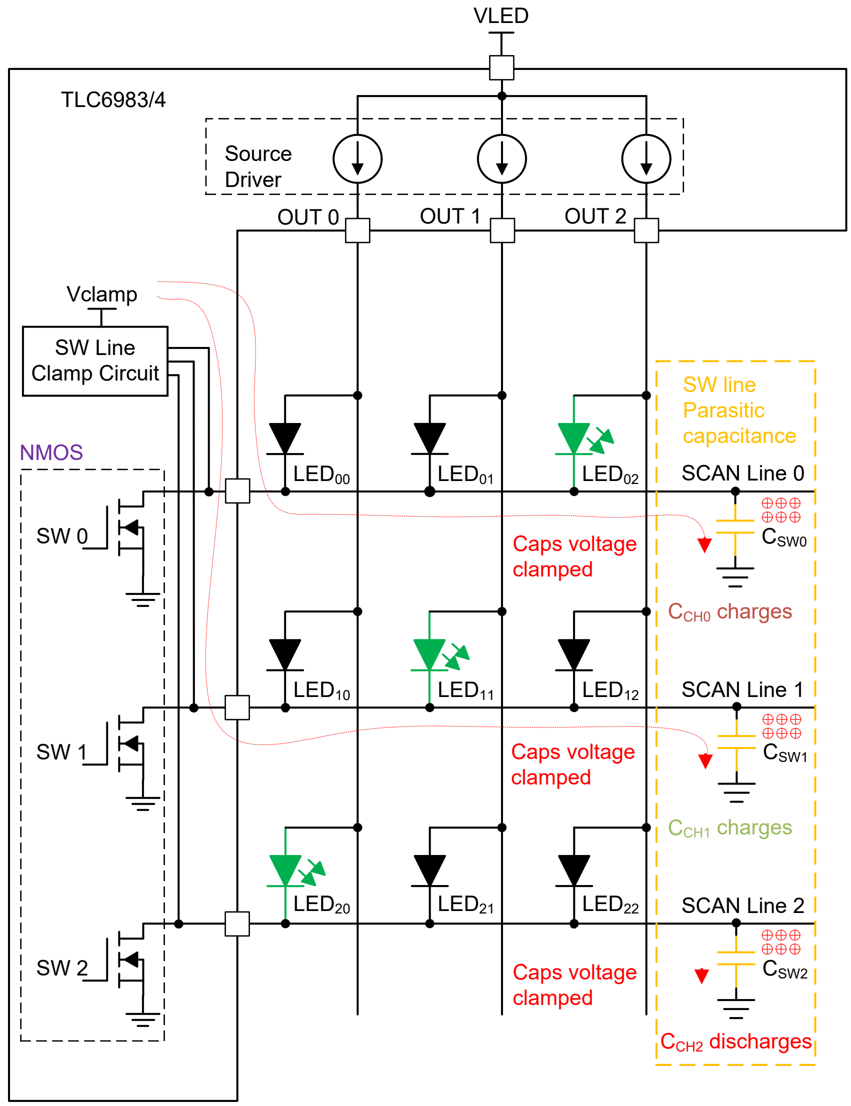


Figure 3-12. Upside Ghost Effect Elimination by SW Line Clamp Circuit

Figure 3-13 shows the comparison demo with or without upside ghosting. We can see that the clamp circuit works very well. With this being enabled, we do not see ghosting anymore.

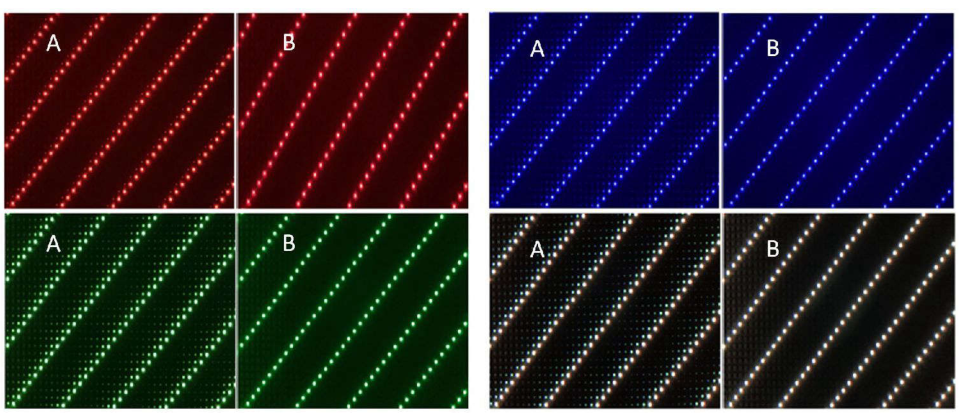


Figure 3-13. Comparison Demo With or Without Upside Ghosting

A. With upside ghosting
B. Without upside ghosting

3.2 Coupling Issue

Coupling means mutual interference between LED driver output channels for LEDs on the same lines and within the same sub-block. This is primarily attributed to the parasitic capacitors on channels and scan lines, as well as parasitic capacitors across LEDs. This issue is even more pronounced in high contrast ratio image. In other words, high-brightness areas of the image are near the low brightness areas of the image. Such as bright object in dark background, and object shadows in a bright environment.

There are 2 common kinds of coupling, brighter coupling and darker coupling, as the demos shown in Figure 3-14 and Figure 3-15. Brighter Coupling means high brightness area makes low brightness area brighter and the opposite for darker coupling. We can see that area A and B are supposed to behave like D area. However, area A and B are affected by C area.

In Figure 3-14, high-brightness area makes low-brightness area brighter. The bright horizontal guidelines in area C couple the corresponding lines in areas A and B to be brighter than the other lines, such as those in area D.

In Figure 3-15, low-brightness area makes high-brightness area darker. The dark area C couples areas A and B to be darker than the other lines, such as those in area D.

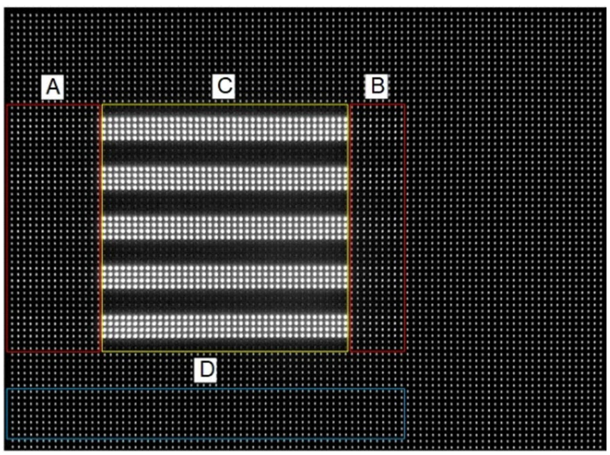


Figure 3-14. Brighter Coupling

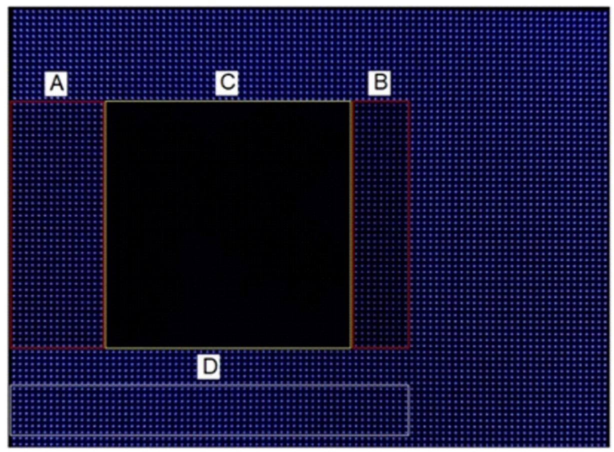


Figure 3-15. Darker Coupling

3.2.1 Brighter Coupling

Figure 3-16 shows the root cause Analysis of the brighter coupling. The left sub-figure shows the whole capacitor modeling of matrix LED display. Apart from parasitic capacitors on channels and scan lines, this modeling also considers parasitic capacitors across the LED, which is crucial to analyze the coupling issue.

The middle sub-figure shows the analysis when LED_{01} is turned ON. LED_{01} ON means channel OUT_1 and SW_0 are chosen. As shown in the green shadow block, this is called the chosen line. For the rest of the lines shown in the red shadow block, this is called unchosen lines.

The chosen line is connected to ground and the unchosen lines are floating. In addition, since channel OUT_0 is closed, the anode of LED_{00} is also floating.

For further equivalence, simplify the capacitor modeling of all unchosen lines to 3 capacitors shown in the upper right sub-figure. The 2 capacitor C_{a_N-1} and C_{b_N-1} in blue represent LED's parasitic capacitors. The capacitor C_{sw_N-1} in yellow represents SCAN lines' parasitic capacitors.

Since the fact that the parasitic capacitor of SCAN line is much less than that of LED, this can further simplify the modeling as shown in the lower right sub-figure. With this simplified modeling, now the root cause of brighter coupling becomes clearer. When the LED_{01} is lit up as the current path in red dotted line, the voltage on the anode of LED_{01} is increased a delta. The voltage across the capacitor can not suddenly change. So, the voltage on the anode LED_{00} is coupled to increase another delta. This makes the LED_{00} slightly light up, as shown in the current path in blue dotted line.

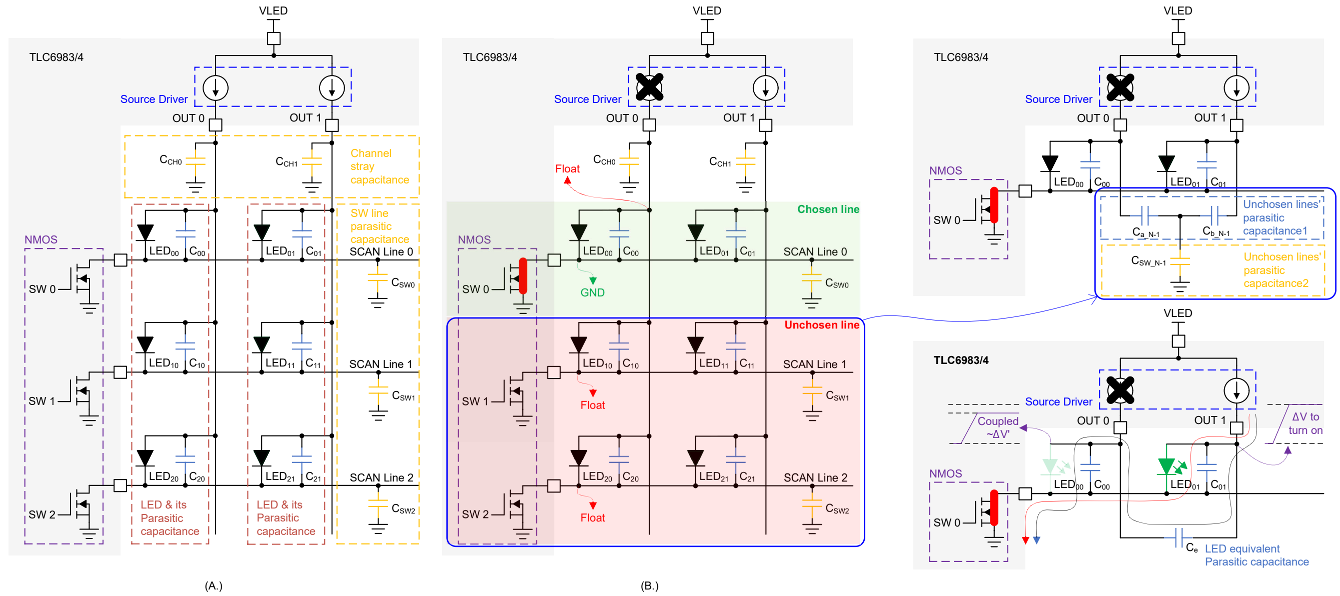


Figure 3-16. Root Cause Analysis of Brighter Ghosting

A. Whole capacitor modeling of matrix LED display

B. SW_0 and OUT_1 are chosen

Figure 3-17 shows a brighter coupling simulation example in spice. From the simulation results, we can see that OUT_0 (blue cure) is coupled by OUT_1(green curve) and ramps from 0 to around 2.6V. That's larger than the LED forward voltage and can make this light up. The peak current through the LED_0 is around 400uA.

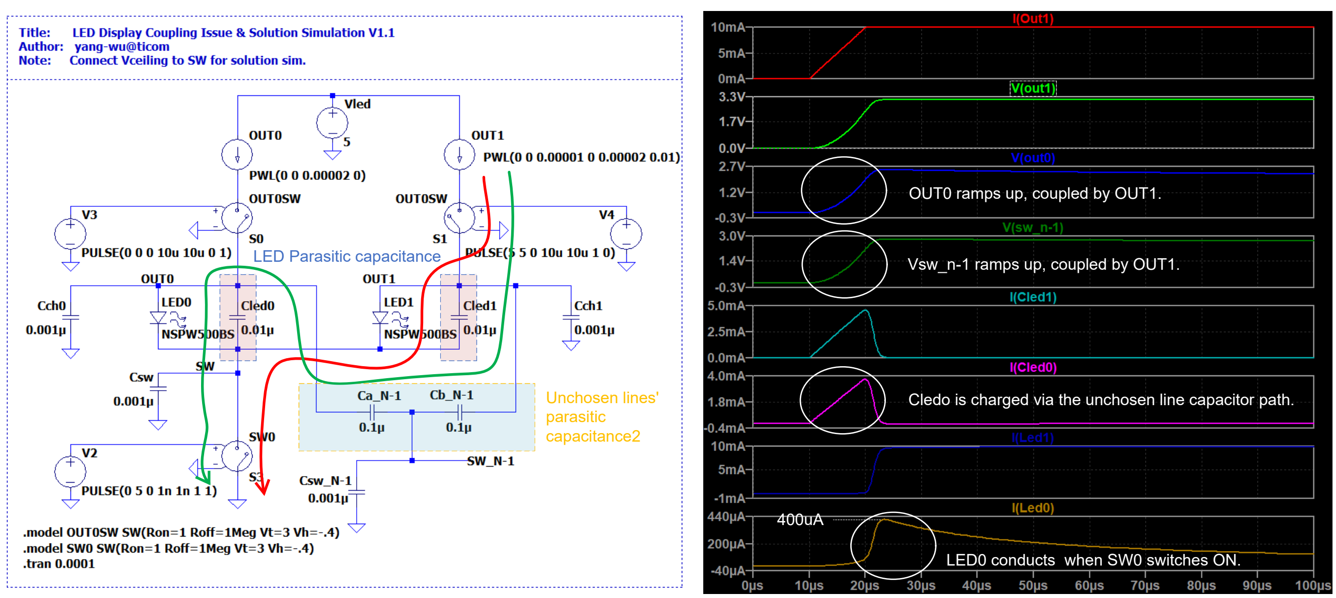


Figure 3-17. Brighter Coupling Simulation

So, how to solve the brighter coupling issue? From the previous modeling, the unchosen lines are floating, which means the unchosen lines are easily to be affected by variable voltage. Supposing we can make voltage on the unchosen lines be a certain level, what happens? In fact, this is the design shown in Figure 3-18. This can make the unchosen lines voltage be upper clamped to a fixed voltage to isolate the Switch ON and Switch OFF channels, as the SW line ceiling circuit block shown. Now we can see that the voltage on anode of LED_{00} is keeping constant and not coupled.

TLC698x can set the line ceiling voltage (upper line clamp voltage) that clamps the maximum voltage level on scan lines to maintain voltage across the unwanted LED is smaller than the LED forward voltage. thus, eliminating the brighter coupling issue.

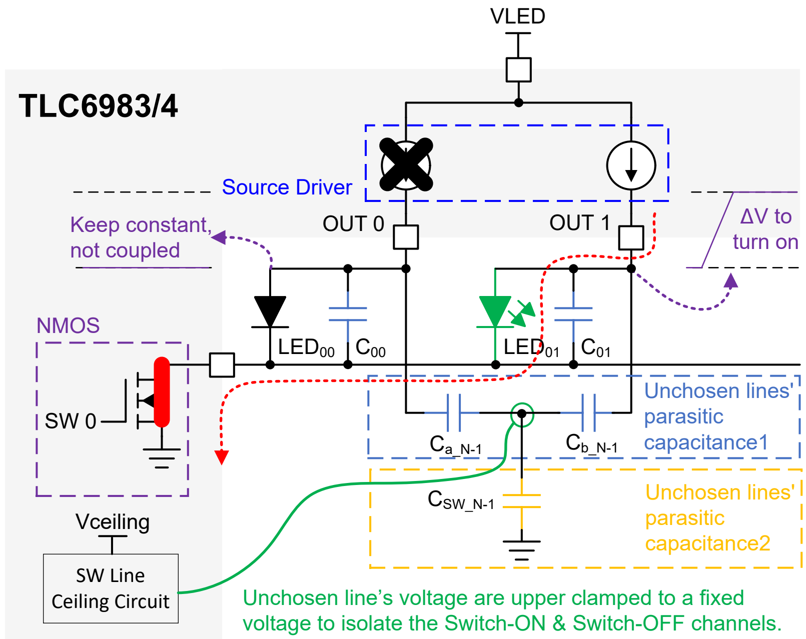


Figure 3-18. Brighter Coupling Elimination by SW Line Ceiling Circuit

Line ceiling is different from SW line clamp that we have discussed in previous sections for upside ghosting. To distinguish, we also call line ceiling as upper line clamp, and SW line clamp as lower line clamp, shown in Figure 3-19.

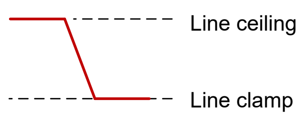


Figure 3-19. Line Ceiling and Line Clamp

A. Upper line ceiling for de-brighter coupling
B. Lower line clamp for de-upside ghosting

Figure 3-20 shows the line ceiling simulation example in spice. From the simulation results, we can see that the clamping method works and LED_0 is not coupled to light up.

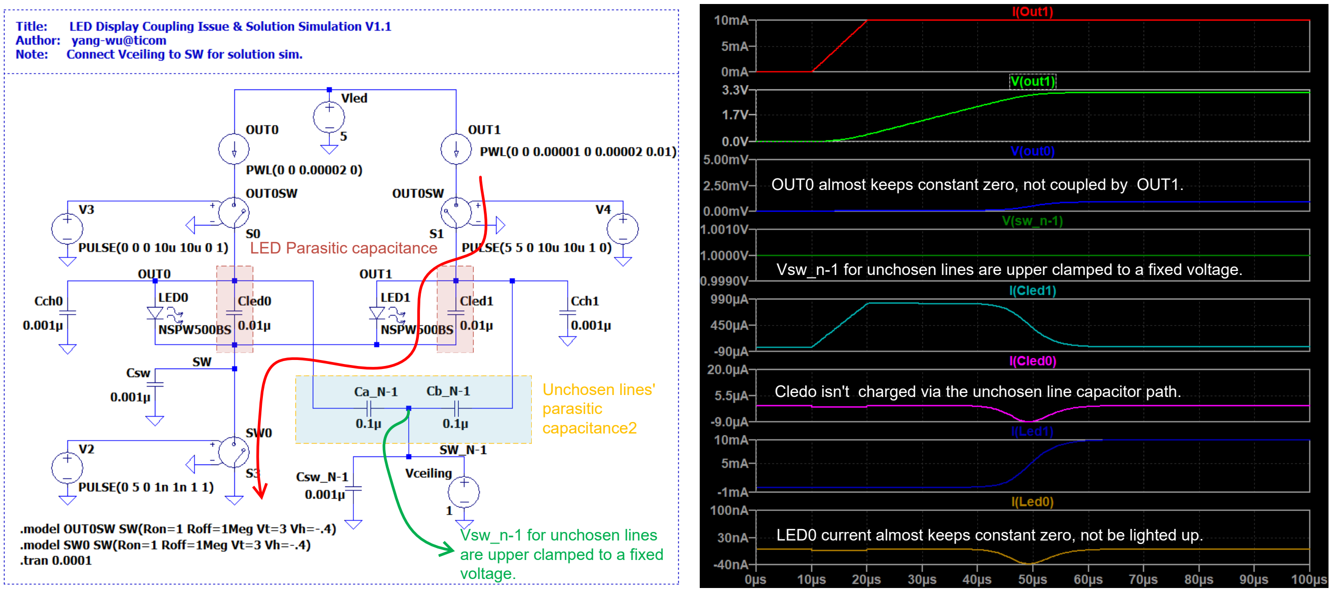


Figure 3-20. Line Ceiling Simulation

Figure 3-21 and Figure 3-22 show the comparison demo with or without brighter coupling. The bright horizontal grid lines in area C couples the corresponding lines in areas A and B to be brighter than the other lines (such as area D). The dark area A an B are coupled by the high grayscale area C to be brighter. With this being enabled, we don't see coupling anymore.

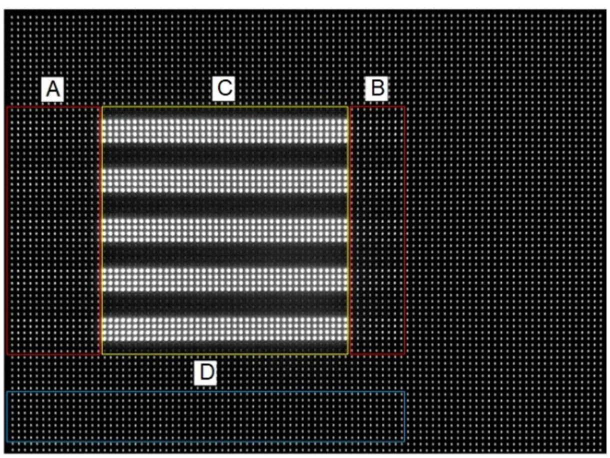


Figure 3-21. With Brighter Coupling

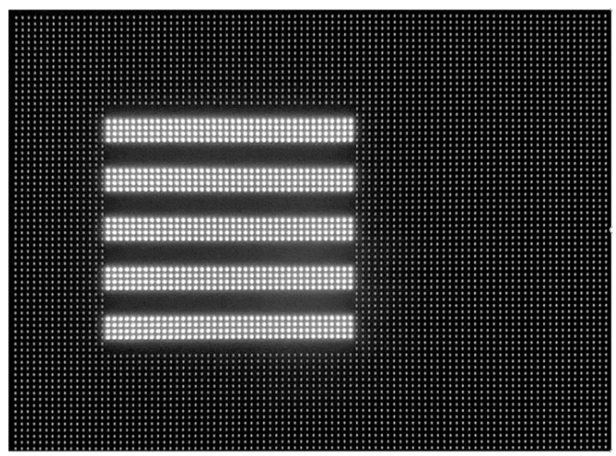


Figure 3-22. Without Brighter Coupling

3.2.2 Darker Coupling

Brighter coupling has been discussed in previous session. Darker coupling is easier.

Essentially, darker coupling is the opposite of the brighter coupling. Hence, the root cause is actually the same. Figure 3-23 shows the root cause analysis of the darker coupling. The electric charges from OUT_1 is supposed to fully go to LED_{01} (and the parasitic capacitor C_{01}) as the current path shown in red dotted line, but shared by LED_{00} (and the parasitic capacitor C_{00}) as the current path shown in blue dotted line. So, LED_{01} looks darker than usual.

Though darker coupling has the same root cause with brighter coupling, designs are different to solve those issues. The designs are shown in Figure 3-24 and Figure 3-25.

LED_{01} is normally lit up as the current path shown in red dotted line. However, LED_{01} also sets a dummy rising one-shot on OUT_0 which produces a fake one-time switch-ON for darker coupling compensation. The parasitic capacitor of LED_{00} is charged during the short fake switch-ON time. However, the LED is not lit up during this charge process (called dummy rising one-shot).

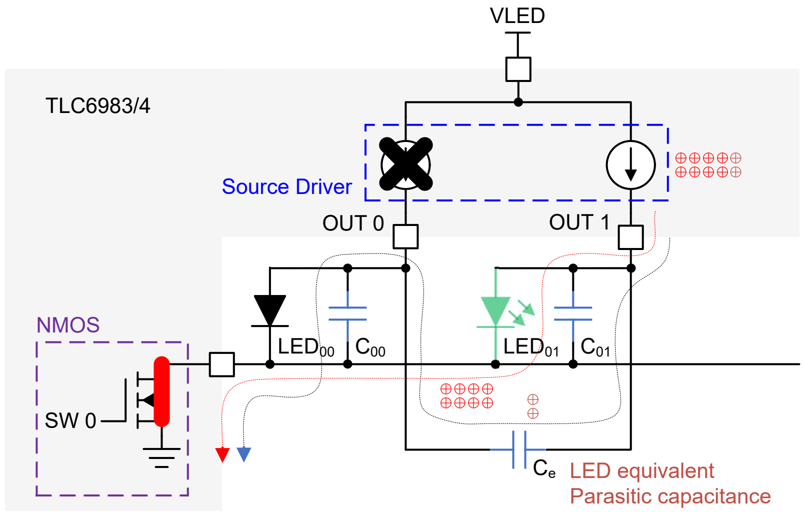


Figure 3-23. Root Cause Analysis of Darker Coupling

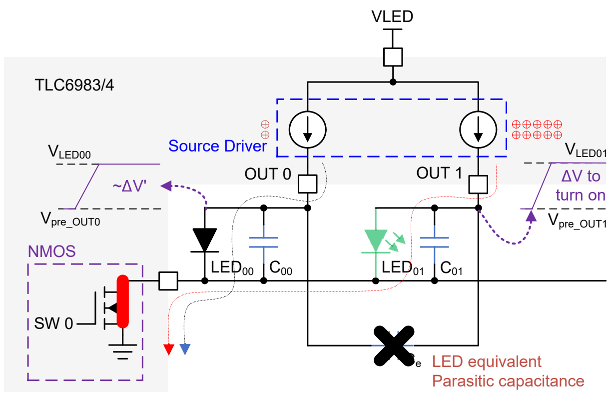


Figure 3-24. Analysis of Darker Coupling Elimination

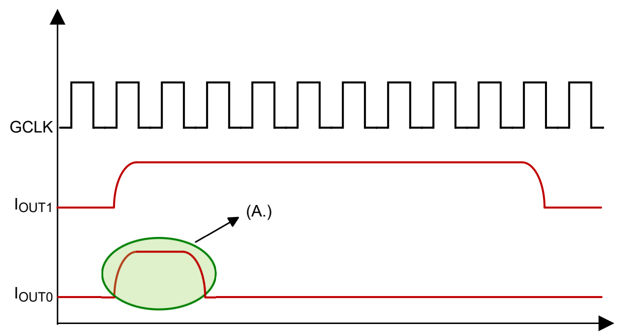


Figure 3-25. Darker Coupling Elimination by Dummy Rising One-shot

A. Set a dummy rising one-shot on OUT0 that produce a fake one-time switch-ON for darker coupling compensation. The short fake switch-ON time charges LED parasitic capacitor but doesn't really light up LED, that's why calling dummy shot.
B. With darker coupling
C. Without darker coupling

The line ceiling is used to eliminate brighter coupling and dummy rising one-shot is used to eliminate darker coupling. Why can't only use either one to solve both issues? Actually, line ceiling can't fully solve darker coupling due to depending on how strong the clamp circuit is. Dummy rising one-shot can not solve brighter issue and makes the issue worse since unchosen lines are floating.

Figure 3-26 shows the comparison demo with or without darker coupling. You can see that the line ceiling circuit works very well. When enabled, we do not see coupling anymore.

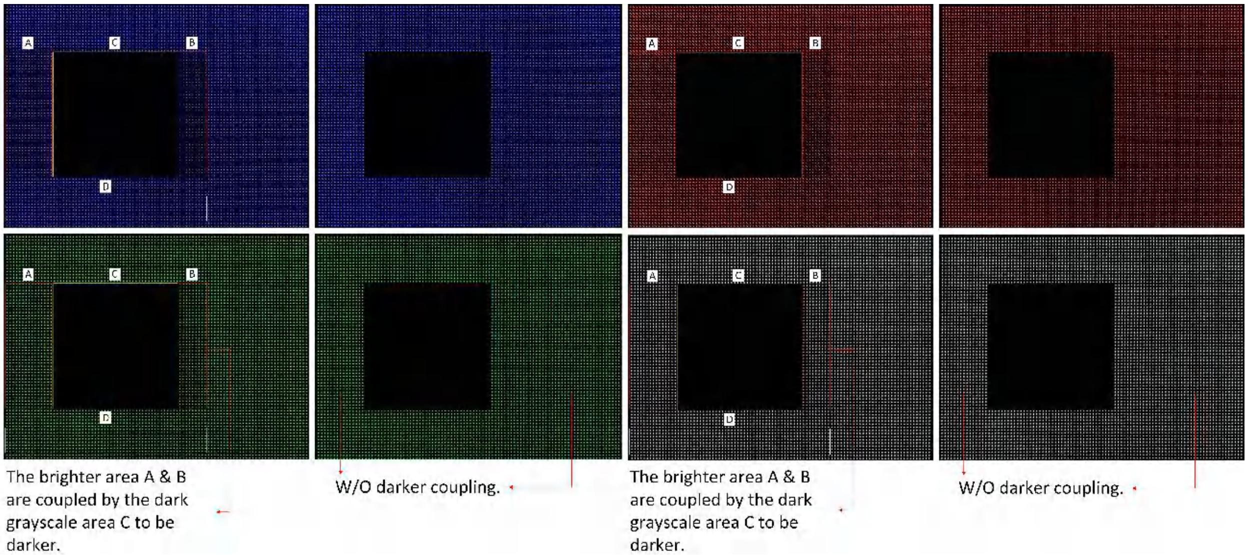


Figure 3-26. Comparison Demo With or Without Darker Coupling

3.3 Low Grayscale Non-Uniformity Issue

The display performance of low grayscale images is also important to NPP LED display. Display performance means the ability to perform rich color-depth images under conditions of low brightness and low grayscale level. Why does this need to be in low brightness? Because of the characteristics of human eyes.

Based on Weber law, human eyes' perception of natural brightness is non-linear, which means human eye is very sensitive to low brightness change, but not to high brightness change, as the curve shown in Figure 3-27.

For indoor NPP LED display applications, display brightness is not very high for the comfort of human eyes viewing. So, a low-brightness and rich color-depth image display capability is crucial. And low grayscale non-uniformity is a common issue that can be observed.

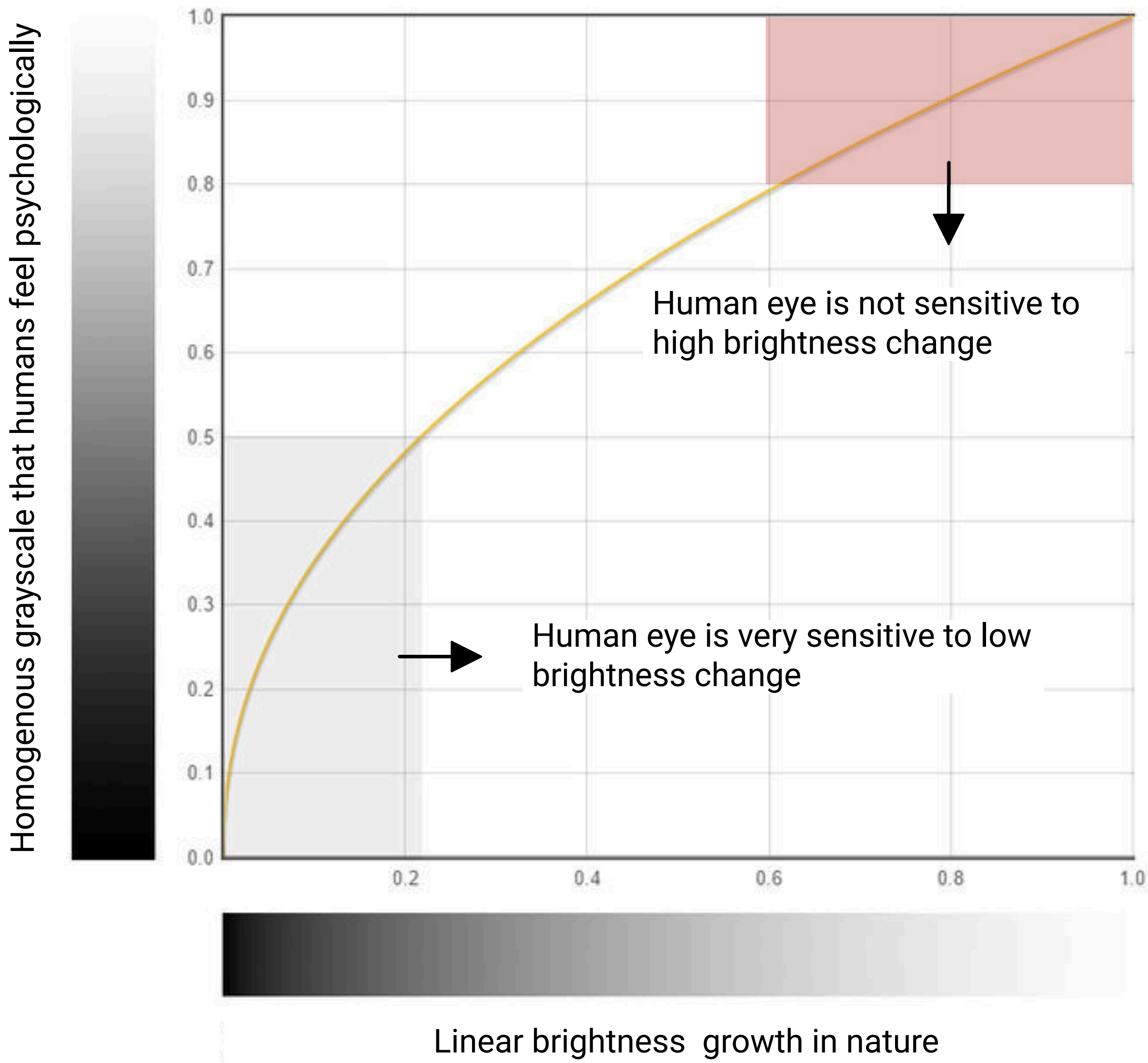


Figure 3-27. Human Eye Perception of Natural Brightness

Low grayscale non-uniformity refers to LED pixel brightness vary to each other (uneven). The effect is easier to be observed by human eyes when the image is in low brightness and low grayscale conditions.

There are 2 kinds of low grayscale non-uniformity effect shown in Figure 3-28 and Figure 3-29. Device-to-Device (D2D) brightness non-uniformity makes the screen looks dirty. Pixel-to-Pixel (P2P) brightness non-uniformity makes the screen looks blurry.

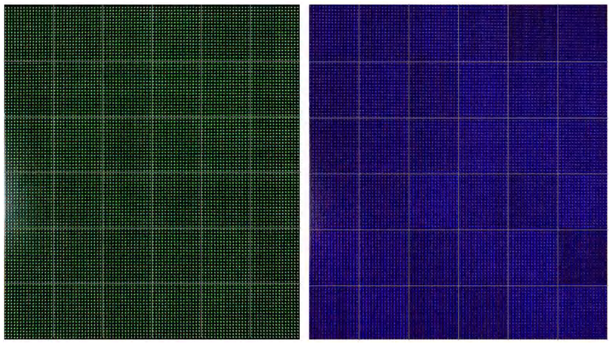


Figure 3-28. Device-to-Device (D2D) Low Grayscale Non-Uniformity Effect

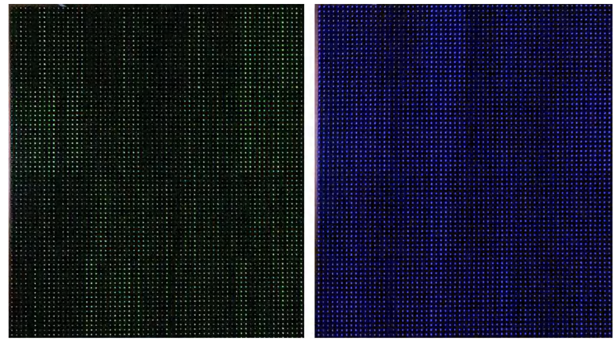


Figure 3-29. Pixel-to-Pixel (P2P) Low Grayscale Non-Uniformity Effect

Device-to-Device low grayscale non-uniformity is because LED driver's constant-current sources have device-to-device variation, making driving current be different, shown in Figure 3-30.

Pixel-to-Pixel low grayscale non-uniformity is because of LED pixel-to-pixel variation on production, performance discreteness and channel to channel layout difference. The non-uniformity makes LED brightness different even with the same driving current. LED production and performance discreteness are shown in Figure 3-31, please refer to *Variability in LED Production and the Impact on Performance* for more information.

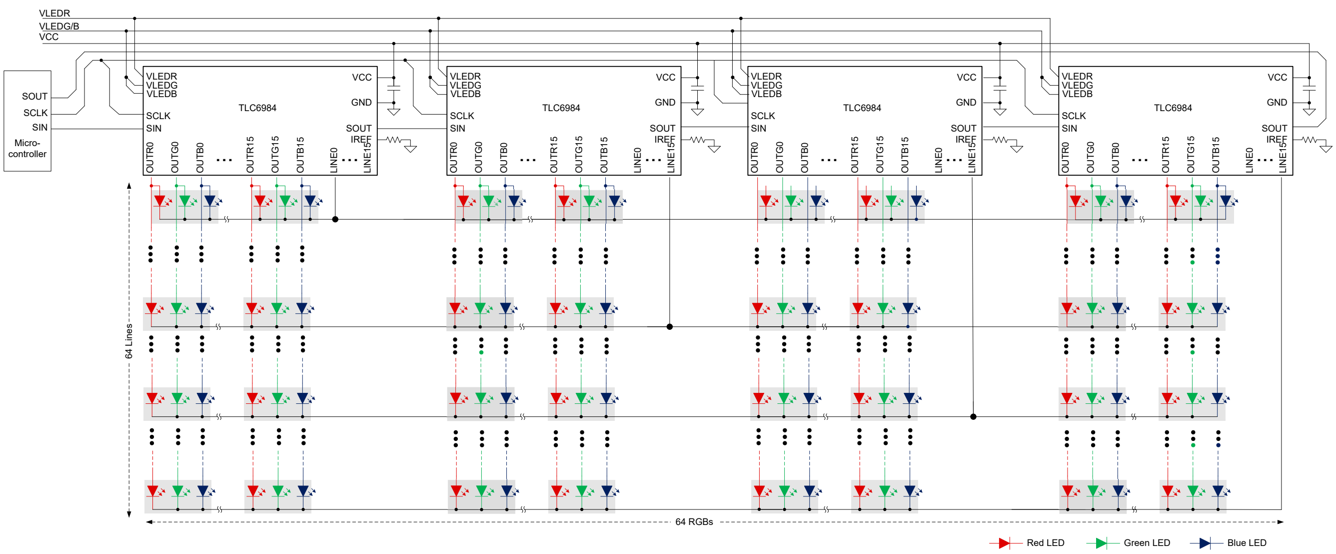


Figure 3-30. Device to Device Variation of LED Drivers Constant-Current Sources

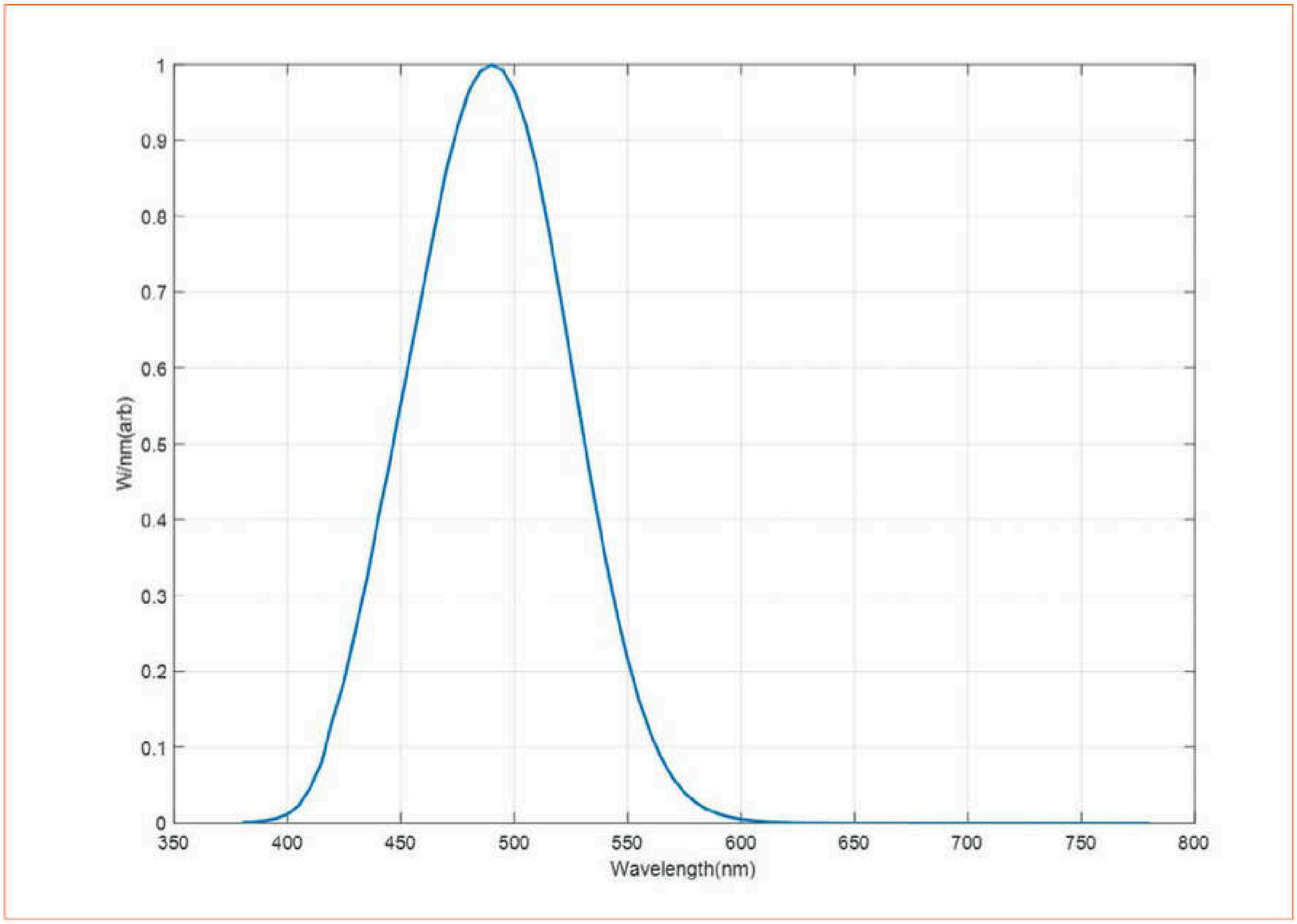


Figure 3-31. Variability in LED Production and Performance Discreteness

For most NPP display products with brightness higher than 600 nits, the low grayscale non-uniformity won't be as bad as shown previously or even can't be observed. For low brightness (48 nit) application (such as LED cinema screen), with relatively very low driving current (about 200/300uA), low grayscale non-uniformity can be a challenge, since current source error increases a lot in very low current. Fortunately, TI's LED display driver TLC698x has very low D2D variation at typical ±0.5% and maximum ±2%.

So, how to solve the low grayscale non-uniformity issue?

Figure 3-32 shows the Dynamic Spectrum-Pulse Width Modulation (DS-PWM) algorithm of TLC698x. A whole frame is split to several sub-periods. In each sub-period, all SCAN lines are lighted up in turn. To achieve ultra-low brightness, LED driver must have the ability to output a very short current pulse (1 GCLK time). However, due to LED's parasitic capacitance, such one pulse or even several pulses can not turn on the LEDs. If GCLK frequency is getting higher, turning on LEDs is more difficult.

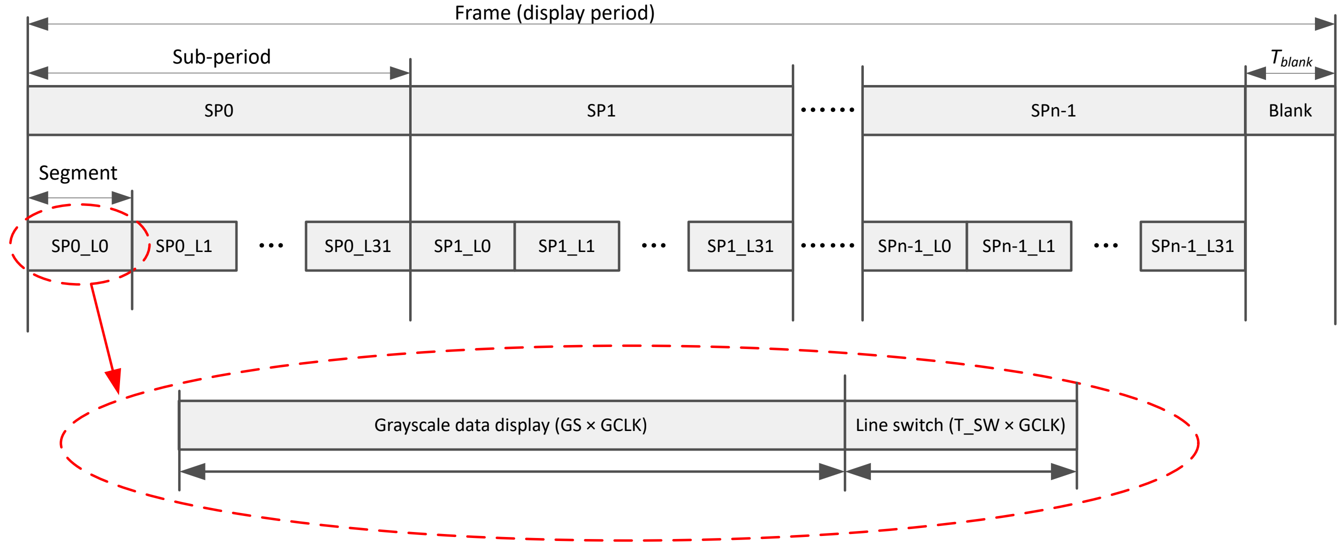


Figure 3-32. DS-PWM Algorithm of TLC698x

As mentioned previously, the reason that people observe non-uniformity is human eyes are very sensitive to low brightness change, which means the brightness can improve a little bit, this can cheat eyes and make the image look like uniform.

So, the way to solve low grayscale non-uniformity issue is shown in Figure 3-33. Normally, the LED current is shown in red pulses. TLC698x has low grayscale enhancement function to compensate the charge loss from the parasitic capacitor of the LEDs and solve non-uniformity issue by extending the turn-on time in each sub-period for all GS data, as shown in the green shadow block. Note that this function does not exceed the upper limit of the grayscale. So, this is global compensation for all grayscale, not only local compensation for low grayscale.

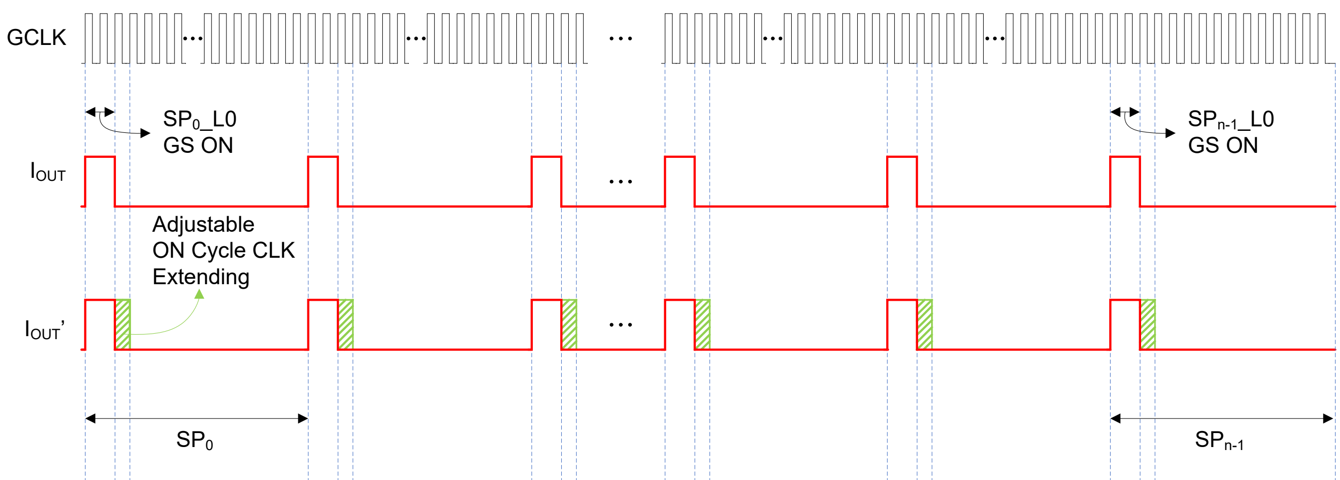


Figure 3-33. Low Grayscale Non-Uniformity by ON Cycle Clock Extending

Figure 3-34 and Figure 3-35 show the comparison demo with or without low grayscale non-uniformity. The ON cycle clock extending algorithm works very well. When enabled, the display effect is improved.

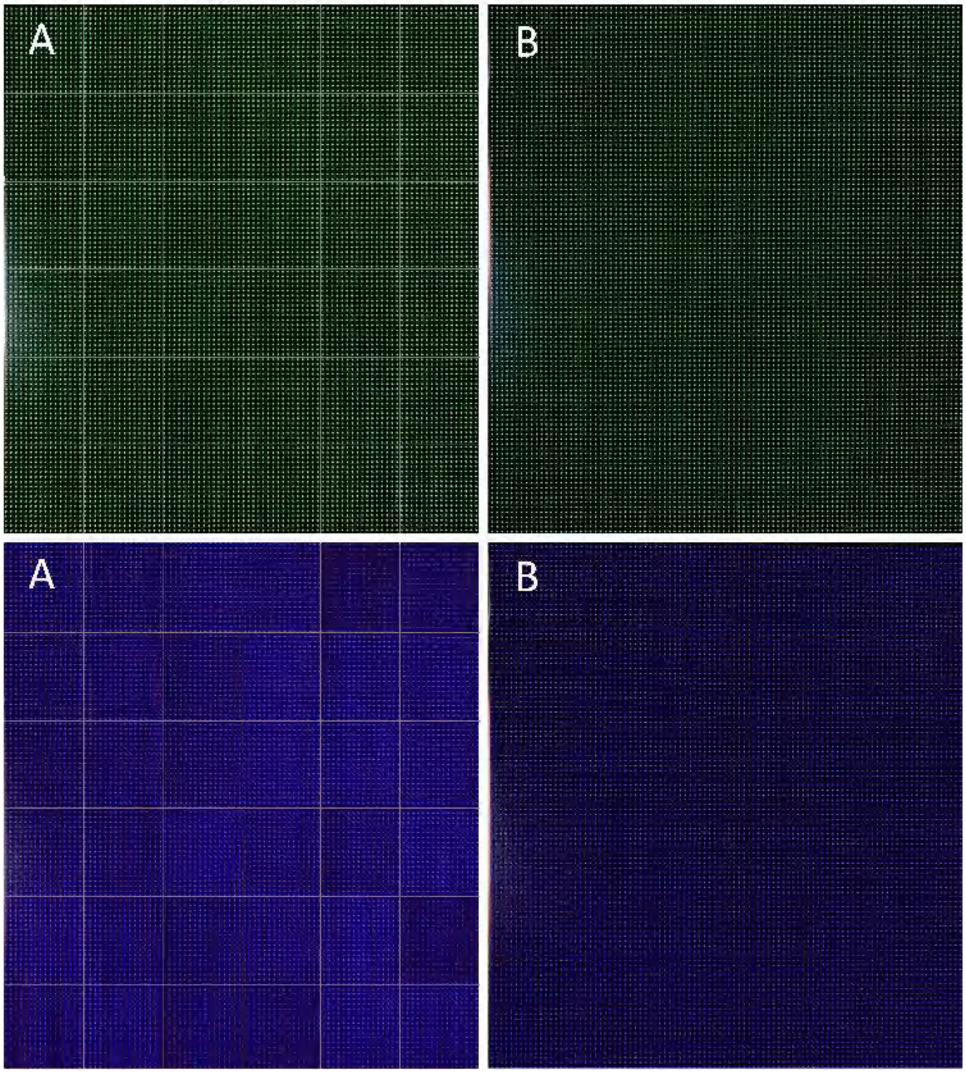


Figure 3-34. Comparison Demo with or without D2D Low Grayscale Non-Uniformity

A. With D2D low grayscale non-uniformity
B. Without D2D low grayscale non-uniformity
C. With P2P low grayscale non-uniformity
D. Without P2P low grayscale non-uniformity

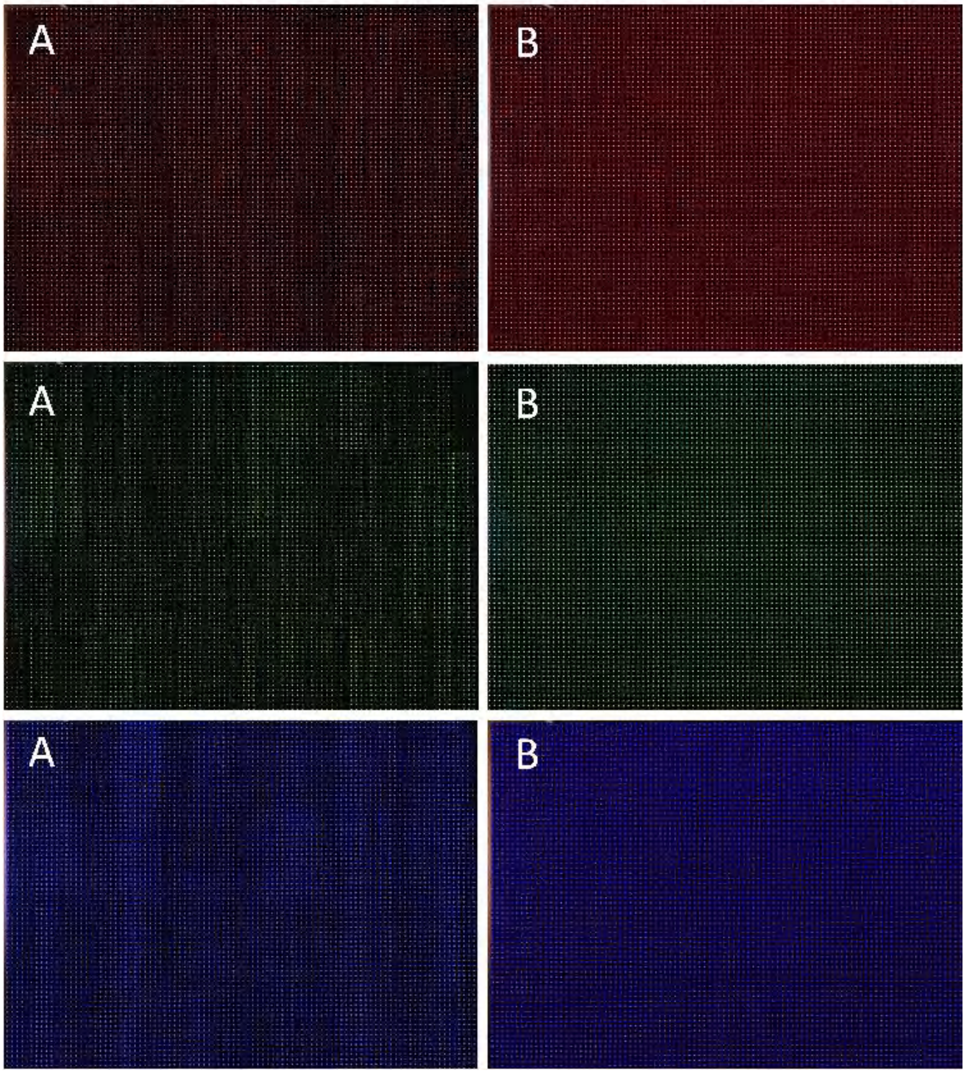


Figure 3-35. Comparison Demo with or without P2P Low Grayscale Non-Uniformity

4 Summary

This application note firstly brings a thorough understanding of display technology, LED driver topology, matrix LED display driver architecture and system. Then the document goes deeper into root causes and designs of several typical LED display challenges, from IC circuits and algorithm perspectives, based on TI's latest Common Cathode Matrix LED Display Driver TLC6983 and TLC6984, which is helpful for engineers to understand and use matrix LED display driver properly.

5 References

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3. Intel, *What Is Refresh Rate and Why Is It Important*
4. Vox, *LED green screen for virtual production*
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6. Samsung, *LED commercial display*
7. Texas Instruments, *Animated automotive flexible rear light*
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