LED-based signage and matrix displays are bringing new dimensions of versatility and eye-pleasing visual effects to a growing number of outdoor and indoor applications. Recent advances in LED technology have even made it difficult to distinguish still images on their high-quality displays from traditional printed or painted billboards. In this tutorial, Texas Instruments takes a detailed look at the essential technical principles of LED display systems and the engineering considerations required to design them using arrays of discrete LED lamps.

LED driving basics
First we will compare the various LED driving circuitries to determine the best method.

Connecting a voltage source
It is well known that an LED lamp (or diode) starts turning ON with enough forward voltage (VF). When ON its forward current emits light. From this basic knowledge, one can come up with the first option in Figure 1a but it will not work. Because an LED current is an exponential function of its voltage bias (equation 1), light intensity from the LED lamp is very sensitive to the voltage. In most cases the high current condition turns the normally long-lived LED into a very expensive flash bulb.

\[ I_{LED} = I_S \left( e^{(V_F - R_S \times I_{LED})/V_T} - 1 \right) \]  
(eq 1)

Here’s why Figure 1a will not work. In equation 1, \( I_S \), \( R_S \) is a constant, depending on the LED product, and whether \( V_T \) is the thermal voltage. Assuming a series resistance \( R_S \) is ideal and zero, only 0.1V of \( V_F \) change makes 47 times difference in \( I_{LED} \).

\[ \frac{I_S \left( e^{(V_F + 0.1)/V_T} - 1 \right)}{I_S \left( e^{(V_F)/V_T} - 1 \right)} \approx \frac{e^{(V_F + 0.1)/V_T}}{e^{(V_F)/V_T}} = e^{0.1/V_T} \approx 46.8 \]  
(eq 2)

For example, a target LED current value 20 mA jumps up to 1A with only 0.1V difference of its bias current. Even taking into account a realistic \( R_S \) value, a real LED device still shows 10 to 20 times difference with a 0.1V bias difference.
Figure 1 Comparing three LED driver circuits

Voltage source with current limit resistor
Now let’s examine Figure 1b. A current limit resistor $R_{\text{LIMIT}}$ is added to protect an LED lamp. Because of the limit resistor, the lamp does not blow up. Still, it is not great at controlling LED light intensity in video display applications. An LED curve and a load curve by $R_{\text{LIMIT}}$ determine its LED current value. As shown in red or blue annotations, this LED and resistor has variations of forward voltage and resistance from manufacturing errors. These error factors change the LED current (green) at non-negligible levels.

Constant current source
Figure 1c employs a constant current circuitry instead of resistors. This constant current driver circuit regulates an LED current directly at the target value. The LED conducts a certain value, no matter how much $V_F$ variation the LED lamp has from its manufacturing process. Because the light intensity of an LED lamp is strongly tied to charges crossing its PN junction, this constant current driver method is ideal to get uniform light output from LED lamps.

Furthermore, it is well known that an integrated circuit (IC) provides good matching circuit pairs. This is another benefit of selecting a constant-current method. Figure 2 shows a basic output stage structure of LED drivers. Many LED driver ICs in the market have a reference current setting terminal IREF, and this reference current is constant-current-mirrored to its output terminals.

Figure 2 A basic LED driver IC output configuration

Figure 2 illustrates the results of this discussion, a basic output circuitry configuration of LED drivers.

Driving in color
Thus far, we have been able to determine how to drive an individual LED lamp. The next step is to achieve full color light output for video display systems. By combining varying shades of light’s three primary colors, red, green and blue (RGB), any color can be generated. A familiar example is a color selection tool on a personal computer (PC).
Gray scale control by digital or analog
A PC’s operating system blends three colors in 256 steps (8 binary bits each) or more to display a full color pixel. For the LED display system, the same concept of step color intensity control is needed. The goal is to achieve step control, or gray scale control in LED driver design.

Your first decision should be whether to use digital or analog control. As explained earlier, the total charge count crossing a PN junction determines light intensity, so both digital and analog methods can control the light intensity. Figure 3 illustrates 50 percent gray scale control in digital and analog methods. In a total 256-step example, this 50 percent indicates a 128 gray scale target.

![Figure 3 Fifty percent intensity control in digital and analog](image)

LED current and color change
At this point, the effects of current change on the wavelength value of LED light output needs to be considered. A changing wavelength means changing color to the human eye. Figure 4 shows a green color LED lamp example. Usually, 510 nm widely represents green in the industry. Thus, most LED lamp manufacturers design a lamp to have 510 nm at maximum-rated current of LED lamp products. In Figure 4, the wavelength reaches 510 nm as the LED current rises. The best way to get green color is to always drive a lamp as close to its maximum rated current as possible. This explains why using digital control is better than analog control.

Another benefit of choosing digital control is the ease of implementing the control on LED driver ICs as a digital circuit block. For a gray scale control over a 256 step range, digital control costs less than analog control.

![Figure 4 A green LED current vs. wavelength example](image)
This ON/OFF digital control is known as a pulse-width modulation (PWM) control, or PWM dimming. Now PWM control switches are added to Figure 2.

**How to form a matrix or 2D image**
RGB LED lamps are tiled to form a 2-dimensional (2D) image.

*Structure of display systems*

![Figure 5 LED display system consists of module / panel / display](image)

RGB LED lamps are arranged to form a square-shaped base structure, or module. It usually consists of one PCB with a pixel array of 16×16 to 64×64, depending on applications. Multiple modules are combined to form a mechanical and system structure, or panel. LED display system vendors usually provide panels. Each panel has a mechanical frame to hold multiple modules. It contains one or more control units to provide a power distribution, data interface and processor. At a display system building site, such as stadium screens or road side billboards, multiple panels are installed to form a final display. At the construction site, all the data and power cables from each panel are routed to central control units.

*Pixel pitch*
One LED display system comprises a huge number of LED lamps and a large power supply. Optimizing LED lamp density is a key item to consider when designing a system. This density of LED lamps is discussed as a distance of each pixel, or *pixel pitch*. If the pixel pitch is too tight, it won’t improve image output quality once it is finer than the human eye can detect, and adds to the cost. The human eye can distinguish two individual light sources when these two points form 1/60 of one arc degree (= one minute of arc).

![Figure 6 The ability of the human eye to detect resolution](image)
**Figure 6** illustrates how the human eye distinguishes pixel pitch $D_{PP1}$ is calculated in equation 3 where $L$ is a viewing distance.

$$D_{PP1} \approx 2 \times L \times \sin\left(\frac{1}{60} \times \frac{1}{2}\right) = L \times 0.29e^{-3}$$  

(eq 3)

In best practice, DPP1 is considered overkill in that roughly three times of $D_{PP1}$ is good enough for a good quality video system. $D_{PP}$ is the guideline in equation 4.

$$D_{PP} = D_{PP1} \times 3 \approx L \times 1e^{-3}$$  

(eq 4)

An easy way to remember equation 4 is this:

Required Pixel Pitch in millimeter (mm) = "Viewing distance in meter"(m)

For example, a system with a viewing distance of 5 m requires 5 mm of pixel pitch to achieve good resolution. Another visual example is shown in **Figure 7**, which illustrates how too low of a pixel pitch degrades the output image quality. The 12.5 mm pixel pitch image (top) looks rough, and is not discernable at close distance. However, the image starts to make sense when viewing it at arm's length, which is similar to viewing the 5 mm pixel-pitch image (bottom). This is a good example of the relationship between the viewing distance and pixel pitch.

![Figure 7 Comparison between different pixel pitch and viewing distance](image)

*Static drive and time multiplexing drive*

From **Figure 2**, the cathode side of LED lamps is driven by LED driver ICs common in today’s market. Here, drive circuitry for the anode side of LED lamps is reviewed. With the benefit of employing constant-current drive at the cathode side, the anode side is expected to supply just
enough voltage. Still, an important decision is needed: how to drive the anode side!

**Figure 8** compares static and time-multiplexing anode drive systems. The static anode drive configuration is very straightforward: one LED driver IC drives one LED. When designing a system with a huge number of pixels, the static anode drive requires a huge number of LED driver ICs. In contrast, the time-multiplexing anode drive system uses fewer LED driver ICs by sharing one IC with multiple LED lamps. A tradeoff with the time-multiplexing drive is that output LED light intensity is reduced due to time-sharing.

In outdoor display systems, very strong LED output is required to overcome the brightness of the sun in order to deliver the image to the human eye. In such outdoor systems, the static anode drive is preferable. On the other hand, in indoor systems, the time-multiplexing anode drive is a good method to reduce system building cost.

Since time-multiplexing has become the most commonly-used technique in today's applications, we'll use it for the applications we discuss in the remainder of this document.

![Figure 8 Static and time-multiplexing anode drive](image)

**How to create movie/video images**

Earlier we discussed how to display a still image. If we keep changing that still image, we can turn it into a movie or video.

**Frame rate/frame refresh rate**

Old analog TV systems used to show 24 different still images in one second, for a frame rate of 24. When an analog TV camera views another analog TV screen, it creates a zebra mix comprising video images and black bands (**Figure 9**). This is caused by the synchronized TV camera and TV screen scanning rate. The same problem occurs when a camera taking a shot of an LED screen uses the time-multiplexing anode drive. Examples include a TV camera capturing an image of a concert stage with an LED display enlarging a performer on the back wall, or a TV camera viewing a stadium score/display panel at a sport event. To avoid this issue, LED displays today need to operate faster than camera systems, especially in a professional use LED display market.
To meet this faster operation requirement, many LED display systems repeatedly show the same image within one frame period, known as the frame refresh rate. **Figure 10** shows the relationship of the frame rate and refresh rate. There are only two frame images: A and B. Each frame repeats “image x” twice. Thus, this example is \( \text{"Frame Refresh Rate"} = 2 \times \text{"Frame Rate"} \).

In a common LED display system, a frame rate is in the range of 50 Hz to 120 Hz, and a frame refresh rate is in the range of 50 Hz to 2 kHz.

**ON/OFF control driver or PWM control driver**

To meet system requirements of frame rate and refresh rates, a decision needs to be made between two ways to implement the logic circuit. First is the ON/OFF control driver, and the second is the PWM control driver.

**Figure 11a** shows a system with an ON/OFF control IC, which has an ON/OFF register that corresponds with each bit to its output. A logic high of the register bit turns ON the corresponding output; a logic low turns it OFF.

**Figure 11b** shows a system with a PWM control IC, which has a gray scale reference clock input terminal that references the clock counter. Plus the IC has a set of registers that hold gray scale logic code. PWM comparators compare and generate PWM output patterns from the counter and gray scale (GS) register.

For both types of driver ICs, two operations are performed in parallel:
The constant current driver block drives its LED lamp array based on inputs from the current display cycle data. Meanwhile, the data for the next display cycle is received into the shift register.

**Figure 11** LED display with ON/OFF control IC and with PWM control IC

**Summary**
Beginning with a driver circuit for a single LED lamp, a complete LED driver IC structure is derived by reviewing details of the LED lamp physical characteristics; physical layout and structure of display system; and static and time-multiplexing control.

**Part 2** addresses data transfer between an image processing controller and LED driver ICs with examples provided. LED display driver IC-related features and topics will also be examined.

**Reference**
For more information about designing LED signage, visit Texas Instrument’s [LED Signage Solutions home page](https://www.ti.com/led-signage-solutions).

**Related articles:**
• How-to design LED signage and LED matrix displays, Part 2
• Use an LED matrix horizontally
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