Local Dimming in Automotive Displays

Logan Cummins
TI training – Summary

The automotive display market has historically lagged behind the consumer display industry in contrast ratio, black levels, resolution, curvature, and form-factors due to the automotive specifications and environmental conditions. Automakers are trying to differentiate their infotainment HMI displays and catch up to consumer demands to match the technological advances seen in the displays within personal electronics. The promise of OLED displays filling the performance void within automotive displays has been continuously delayed by numerous design and fabrication challenges, such as lifetime, cost, and peak brightness concerns. Local dimming has shown the potential to improve contrast ratio near OLED levels while also providing power savings over traditional backlight methods. This presentation will discuss the local dimming architectures, system level design considerations, and implementation challenges. Key design questions such as number of zones, LED parameters, and direct vs. scan drive topologies will be addressed.

What you’ll learn: In this presentation you’ll learn about the market trends, typical customer design challenges, and what types of designs TI has for local dimming.

Course details: Analog and System Level Design

Training level: Intermediate
Outline

• Display & Backlighting Overview
  • OLED
  • TFT LCD
• Local Dimming
  • Architecture
  • System Definition
  • Implementation Considerations
• Portfolio & Reference Designs
• Design Example
Evolution of Automotive Display

Yesterday

- PM LCD
- LCD-TN
- LCD-VA
- Resistive touch

Today

- LTPS LCD
- LCD-IPS
- Interactive
- On-cell touch

Tomorrow

- AMOLED
- Full Array Local Dimming
- Augmented Reality
- In-cell touch
- Gesturing

SOP 19-22

SOP 23+
Automotive Display Challenges & Requirements

Automotive Display Requirements:

• High brightness
  – >1000 nits
• Contrast ratio
  – 1000:1 to 1,000,000:1
• Wide temperature ranges
  – Less than 85C
• Long lifetimes and production support
• Low power consumption

Implementation & Design Challenges:

• System Power consumption
  – Backlight 80-90% system consumption
  – High peak brightness for daylight
• EMI Compliance
## Display & Backlight Architectures

<table>
<thead>
<tr>
<th>Display Category</th>
<th>Backlight Type</th>
<th>LED Type</th>
<th>Purpose</th>
<th>Driving Method</th>
<th>Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLED</td>
<td>Pixel Drive</td>
<td>AM OLED</td>
<td>Display</td>
<td></td>
<td>Millions</td>
</tr>
<tr>
<td>Micro LED Display</td>
<td></td>
<td>AM Micro LED</td>
<td></td>
<td>TFT</td>
<td>Millions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AM Mini LED (TFT gate structure)</td>
<td></td>
<td></td>
<td>Thousands</td>
</tr>
<tr>
<td>LCD Display</td>
<td>Local Dimming</td>
<td>PM Mini LED</td>
<td>Backlighting</td>
<td>Multi-channel Low Side</td>
<td>Hundreds / Thousands</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normal Size LED</td>
<td></td>
<td></td>
<td>Hundreds</td>
</tr>
<tr>
<td></td>
<td>Edge Lit</td>
<td></td>
<td></td>
<td>Low Sides + Boosted Voltage</td>
<td>One</td>
</tr>
</tbody>
</table>
Display Technology LCD TFT Technology

Source: Meko
Display Technology OLED/Micro-LED

Source: Meko
OLED in Automotive Displays

• Solves many of the LCD design challenges
  • High contrast ratio
    • >100,000:1-1,000,000:1
  • Much wider color gamuts
  • Incredibly thin form factors
  • Fraction of power usage
  • Allows for curved displays

• Disadvantages / Head-Winds
  • Lifetime
  • Luminance too low
  • Ambient reflections
    • Absorbed by polarizers in traditional displays

![AMOLED display forecast for automotive (000s)](image)
Local Dimming Concept

- In Local Dimming backlight, LEDs under the LCD panel are divided into many small zones.
- Using content-adaptive backlight control, the brightness of each zone is adjusted according to different display content.
- A local dimming backlight allows the display to have “darker blacks” and “brighter whites”.
- Bridges gap to achieve OLED characteristics
Local Dimming Prototypes & Demos

Tianma at SID 2018:
• 12.3” LTPS LCD Panel
• Native contrast: 2000:1
• Local dimming zones: 96
• 135,000:1 contrast ratio (dynamic mode)
  • Peak brightness: 2,500 nits
  • All white mode: 600 nits

Source: Meko
Local Dimming Prototypes & Demos

Innolux at CES 2018:
- 10.1” Active Matrix Mini-LED backlight
  - TFT addressed matrix
- Resolution: 1540x720
- Luminance: 700 nits (peak: 1500 nits)
- Contrast Ratio: 1,000,000:1
- Local dimming zones: 6720
- LED size: 1mm
- Pitch: 2 mm
- PPI 168.3 px/in (66 px/cm)

Source: Innolux
Local Dimming Architecture

- The system contains: System Board, TCON, LCD Panel, LED Backlight Unit, LED Driver
- Timing Controller (TCON) processes the video stream signal and the backlight control signal to realize the local dimming control for the display.
  - Generates zone histogram levels for each zone
- Multi-channel linear LED driver is normally used to drive the backlight, depends on the number of zones, several devices need to be connected in cascading mode.
Direct-Lit Local Dimming

- In more traditional 2D Full Array Local dimming backlight all the LEDs are driven at the same time in a parallel configuration. This means they can also all be driven up to 100% duty, however, this requires the device to have a current sink for each zone.
Direct-Lit Backlight w/ Multiplexing

• Image below shows LEDs in 2D (x & y) grid behind the LED display as in normal direct-lit backlight architecture. In the time multiplexed version of 2D full array local dimming the LEDs are driven sequentially in groups. This results in fewer ICs required to drive the LEDs but also results in lower average current for each LED since it is only on for a portion of the time (25% of the time in the 4:1 multiplexing example below).
Local Dimming System Definition

LED Count, Zones, & Pitch
Local Dimming System Definition Light Spread Function

- Light spread function
  - Relative illuminance from panel at a given pixel or x,y location emitted from single LED
Local Dimming System Definition **LSF w/o Diffuser**

**Light Spread Function (LSF)**

- Relative Illuminance
- X-Distance or Pixels

**LCD Panel / BLU**

- LC Panel
- Air Gap
- Substrate/PCB
- LED
Local Dimming System Definition **LSF with Diffuser**

![Diagram of Local Dimming System]

- **Relative Illuminance**
- **X-Distance / Pixels**
- **LC Panel**
- **Polarizer**
- **Air Gap**
- **Substrate/PCB**

**Light Spread Function (LSF)**
Local Dimming System Definition *LSF and Module Height*

**Light Spread Function (LSF)**

- **Relative Illuminance**
- **X-Distance / Pixels**

**Diagram:**
- **LC Panel**
- **Polarizer**
- **Air Gap**
- **Substrate/PCB**

**LCD Panel / BLU**
Local Dimming System Definition **Pitch**

Pitch – Distance between two LEDs
- Based on number of LEDs & display size
Local Dimming System Definition **Pitch**

**Pitch** – Distance between two LEDs
- Based on number of LEDs & display size
Local Dimming System Definition LSF to Pitch Relationship

Full Width Half Maximum – width at half peak value of LSF FWHM/Pitch Ratio
- Relationship between the LED spread/coverage and its distance to next zone/LED
- Studies claim that 1.5 FWHM/Pitch ratio is sufficient for uniformity
**Local Dimming System Definition**

**Module**

**Thickness & Uniformity**

FWHM-to-Pitch: 1

FWHM-to-Pitch: 1.5

Local Dimming System Definition Halo Effect

- Halo effect is the mura-effect where black/dark pixels are non-ideally illuminated
  - Light leakage
    - 1-5% transmissivity
  - Zone overlap
- Automotive HMI images have aggressive black to white transitions and could be more susceptible to halo artifacts than TV applications
Local Dimming System Definition Halo Effect

• Avoiding halo effect
  – Number of zones & locality
    • More zones better match image, thus light up less surrounding black pixels
  – Dimming algorithm
  – Native contrast ratio
    • Panel’s intrinsic ability to block the light leakage
      – Study[1] reported below counts for indistinguishable halo levels:
        5000:1 ratio need 200 zones
        2000:1 ratio need 3000+ zones

[1]: High dynamic range liquid crystal displays with a mini-LED backlight
Local Dimming System Definition

Contrast Ratio & Black Levels

- Image quality not only defined by contrast ratio, but also share of black pixels / black levels
- Share of black pixel
  - Black pixel defined by 0.01 rel. luminance

<table>
<thead>
<tr>
<th>Number of LEDs</th>
<th>Share of black Pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>0%</td>
</tr>
<tr>
<td>319</td>
<td>1.02%</td>
</tr>
<tr>
<td>1334</td>
<td>6.36%</td>
</tr>
<tr>
<td>2400</td>
<td>9.54%</td>
</tr>
<tr>
<td>5400</td>
<td>14.15%</td>
</tr>
<tr>
<td>OLED</td>
<td>29.65%</td>
</tr>
</tbody>
</table>

Display Image

OLED
29.7% black px

96 zones
0% black px

319 zones
1% black px

2400 zones
9.5% black px

96, 319, 2400 Zones (top to bottom)

Local Dimming System Definition

Contrast Ratio & Power Savings

*FWHM/Pitch: 1.5
*Native Contrast Ratio: 1000:1

Local Dimming System Definition

- Brightness
  - LED Luminance
  - LEDs / Current

- Power Savings
  - LED Current

- Contrast Ratio, & Black Levels
  - Native Contrast Ratio
  - Halo

- Zone Count
  - Algorithm
  - LEDs / Zone

- Local Dimming
  - Light Spread
  - Locality

- Thermals
  - Polarizer

- Uniformity
  - Light Guide
  - Air Gap
  - Thickness
LED Count, Zones, & Pitch

Zone Count
- LED Drivers
- LEDs
Local Dimming Implementation Considerations
Local Dimming Implementation Considerations

• Local Dimming Components
  – Backlight LEDs
  – Backlight IC & Drive Topology
  – Control
    • TCON
    • MCU
LED Characteristics & Selection Parameters

- Thermal dissipation
- Packaging
- Cost
- Luminous Intensity
- Current vs. Luminous Int.
- Forward voltage vs Current
- Peak current
- Forward voltage
- Continuous current
- Viewing angle
- Light distribution
- Color/Temperature

Die Size / Technology
Efficiency
Operating Characteristics
Other Characteristics

Other Characteristics
- Cost
- Viewing angle
- Light distribution
- Color/Temperature
LED Characteristics & Selection

**LED Type & Tech.**

### Conventional LED
- Discrete package
- >500um – 1mm+ size
- Mature technology
- Used in traditional edge lit backlight units

### Mini-LED
- Flip chip/COB
- Direct die on PCB/Substrate
- >200um – 750um size
- Easier, more mature fabrication than micro-LED
  - >80% yield
- Leverages existing processes/equip. used for conventional LED
- Estimated 35M BU units in 2025[^1]

### Micro-LED
- <100um size
- Immature technology
- Lower yield

[^1]: Mini-LED for Displays 2018
LED Characteristics & Selection Zone Configuration

- LED Series & parallel configuration (xSxP)
  - Series LEDs (xSxP)
    - Multiple discrete LEDs or multi-package/die
  - Parallel strings (xSxP)

- System parameters
  - LED Bias Voltage
    - \( V_{LED} = LED_{Series} \times V_{Forward} \)
  - LED Current Consumption
    - \( I_{LED_{Peak}} = \frac{I_{Low\,Side}}{\#\,Strings} \)
    - \( I_{LED_{Avg}} = \frac{I_{Low\,Side}}{\#\,Strings \times \#\,HS} \times PWM\% \)

Example: 5S4P (Edge-Lit : 1 zone)

Example: Local Dimming Zone

1S1P  2S1P  2S2P
LED Driver Requirements

• High channel counts
  – 12 to 48 ch. low side drivers

• Low side peak current
  – 30-50mA

• Breakdown voltage
  – 6-10V+

• Scalable control
  – Serial SPI interface
  – Daisy chain
Local Dimming Drive Topologies

**Direct Drive**
- Dedicated low side driver for each zone

**Advantages**
- Higher current per zone
- Simpler layout

**Disadvantages**
- High BOM count/cost

**LED Considerations**
- Can use smaller die / current rating LED

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**Scanning / Multi-Plexing / Matrix**
- Time-multiplex multiple LEDs attached to a low side driver

**LED Considerations**
- Higher peak currents
- Optical efficiency losses

**Advantages**
- Less LED drivers needed

**Disadvantages**:  
- Thermals (if integrated)  
- Ghost effect  
- TCON capability
Direct vs. Scanning / Multiplexing

- Direct drive
  - Dedicated low side for each zone
  - PWM used for individual zone dimming

Example: 24 LEDs @ 60 mA Average

- LED0
- LED1
- LED22
- LED23
Direct vs. Scanning / Multiplexing

- **Scanning**
  - Use high sides to only drive LED for a partial frame
  - \( \text{Zones} = \# \text{Low Sides} \times \# \text{High Sides} \)

![Diagram of LED circuit](image)
Scanning Ghost Effect

When HS1 is off, High Voltage in LED anode node capacitor makes LED falsely on

Low voltage at the current sink pin from previous group can cause LED to emit when next HS is turned on

Scan has Ghost Effect concern, more special circuits need to be taken to remove Ghost Effect
Scanning Ghost Effect

- **Pre-charge circuitry**
  - Reverse bias LEDs during phase transition ensures parasitic capacitance is drained

- **Bleed resistor**
  - Create discharge path for parasitic charge to flow through

- When HS is off, creates an RC circuit
  - Dead-time to allow discharge beneath forward voltage of parallel LED
Direct vs. Scanning PCB & Routing

Direct Drive
- Simple Routing
- Could use 2 Layers
- Drivers on back of board

Scanning
- More Complex Routing
- Has to use 4 Layer
Direct vs. Scanning Optical Efficiency

- LED Selection
  - Luminosity vs. Current & Current vs. Forward Voltage curves aren’t linear
  - Luminous Intensity / # HS = Equivalent Luminous Intensity of Muxed LED
- Desired average 10mA per channel

<table>
<thead>
<tr>
<th>Config.</th>
<th>Theoretical Current</th>
<th>Luminous Intensity</th>
<th>Equivalent Lum. Int. (multiplexed)</th>
<th>Actual Current (pk)</th>
<th>Forward Voltage</th>
<th>Actual Power (per LED)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>10 mA</td>
<td>0.75</td>
<td>0.75</td>
<td>10 mA</td>
<td>5.7 V</td>
<td>57 mW</td>
</tr>
<tr>
<td>2x HS</td>
<td>20 mA</td>
<td>1.3</td>
<td>0.65</td>
<td>25 mA</td>
<td>6.1 V</td>
<td>77 mW</td>
</tr>
<tr>
<td>4x HS</td>
<td>40 mA</td>
<td>2.2</td>
<td>0.55</td>
<td>60 mA</td>
<td>6.7 V</td>
<td>100 mW</td>
</tr>
</tbody>
</table>

![Graph]
**Direct vs. Scanning Integrated vs. Discrete**

Why not an all-in-one LED driver with integrated high sides and high current capacity?

- **Direct Drive**
  - 1x power / chip
  - Less PCB thermal peak

- **4x Scan w/ Integrated Scan**
  - 4-5x power / chip
  - Higher PCB thermal peak
## Direct vs. Scanning Summary

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Direct</th>
<th>Discrete Scanning</th>
<th>Integrated Scanning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability/Maturity</td>
<td>Available/Mature</td>
<td>Need verified</td>
<td>Needs development</td>
</tr>
<tr>
<td>Zone Count / Dr.</td>
<td>24 – 48 ch</td>
<td>(24 – 48 ch) * #HS</td>
<td>24 ch * #HS (TBD)</td>
</tr>
<tr>
<td>LS Current Capability</td>
<td>30-50mA</td>
<td>30-50mA</td>
<td>60-120mA (TBD)</td>
</tr>
<tr>
<td>Zone Current</td>
<td>High</td>
<td>Low</td>
<td>Low/Mid</td>
</tr>
<tr>
<td>Thermals</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>BOM Size</td>
<td>High</td>
<td>Mid</td>
<td>Low</td>
</tr>
<tr>
<td>IC Cost</td>
<td>High</td>
<td>Mid/Low</td>
<td>Mid/High</td>
</tr>
<tr>
<td>System Cost</td>
<td>Mid</td>
<td>Mid/High</td>
<td>Mid/High</td>
</tr>
<tr>
<td>Ghost Effect</td>
<td>No</td>
<td>Maybe/Yes</td>
<td>Maybe</td>
</tr>
<tr>
<td>Layout / PCB</td>
<td>2-layers / Simple</td>
<td>4 layers / Complex</td>
<td>4 layers / Complex</td>
</tr>
<tr>
<td>Zone Control</td>
<td>TCON supported</td>
<td>No TCON (needs MCU)</td>
<td>TBD</td>
</tr>
</tbody>
</table>
Timing & Control Video to Zone Control

- Every zone needs a histogram calculated from the pixel content within zone
- HDR displays in consumer market
  - Processor and ETOF protocol
- Automotive options
  - Specialized TCON for local dimming with zone histogram calculation
  - Local FPGA/processor
- Challenge:
  - Discrete multiplexing not compatible with current TCONs
    - Need MCU to buffer data and control signals
Serial Data Write & LED Driver Programming

- Each low side has register to write PWM value
  - TLC5955
    - 48 channels 16 bits each
    - 768 total bits
  - TLC6C5724-Q1
    - 24 ch. with 12 bits each
    - 288 total bits
- LED drivers can be cascaded
  - Ex. 10x TLC5955
    - 10*768 bits = 7680 bits
    - 10 MHz SPI → ~0.8 ms write time
- You can write data to registers during previous frame
  - Needs to be less than panel refresh rate
    - 60 Hz → 16ms
LED Biasing & Power

• Automotive battery transients
  – Warm crank transient during start/stop condition drops battery voltage down to 3-4V

• LED bias voltage rail
  – LED forward voltage + headroom
    • LED series/parallel configuration
    • LED current/temperature voltage drift

• Adaptive Headroom – VLED Adjust
  – Sense LED temp for dynamic voltage adjustment
TI Local Dimming Portfolio & Designs
Local Dimming Portfolio

**TLC5941-Q1**
- Const. Current Sink
- 17V breakdown Voltage
- Vcc = 3 ~ 5.5V, Serial I/F
- Cont. <60mA/ch (16 ch)
- 6 bit Ind. Dot Correction
- 12 bit Int. Ind. PWM
- OT, LED Open

**TLC6C5716/24-Q1**
- Const. Current Sink
- 7V breakdown Voltage
- Vcc = 3 ~ 5.5V, Serial I/F
- Cont. <50mA/ch (24/16 ch)
- 7 bit Dot Correction, 8 bit BC
- 12/10/8 bit Int. Ind. PWM
- Full Diagnostic & Protection
- Deactivated LED Fault Detection

**TLC5955**
- 48 CH Const. Current Sink
- 10V breakdown Voltage
- Vcc = 3 ~ 5.5V, Serial I/F
- 32mA/CH current
- 16 bit Int. Ind. PWM
- Diagnostic & Protection
### Features
- Operating Range from 4V to 40V
- Localized dimming control of 144 LEDs
- Adjusts backlight brightness based on ambient light level
- Output current adjustment
  - 7-Bit Dot Correction for each channel
  - 8-Bit Control for each output group
- Individual channel PWM dimming
  - 12-Bit, 10-Bit, or 8-Bit adjustment modes

### Benefits
- Lowers system power & extends life of backlight and LCD
- Higher contrast ratio for darker blacks and brighter whites
- Up to 4MHz data-shift clock frequency, 8MHz GCLK frequency
- Protection & Diagnostics
  - LED-Open, LED-Short, Short-to-GND, Adj Pin Short, Thermal Warning & Shutdown

### Applications
- Automotive Displays

### Tools & Resources
- **TIDA-020001 Folder**
- **Design Guide**
- **Design Files:** Schematics, BOM, Gerbers, Software, etc.
- **Device Datasheets:**
  - LM74700-Q1
  - TLC6C5716-Q1
  - TLC6C5724-Q1
  - TPS22918-Q1
  - OPT3001-Q1
  - LMT87-Q1
Board  (Materials here)
TIDA-020012 Pixelized Dome Light Reference Design for Interior Lighting

Features

• Operating Range from 4V to 40V
• Localized dimming control of 150 LEDs
• 3 TLC6C5724-Q1 24-ch low side LED drivers
  • Every 2 ch. tied together
  • 36 total low sides w/ 100mA capability
• LED matrix
  • 30 LS x 5 HS for 150 ch.

Applications

• Automotive Lighting
• Automotive Displays

Tools & Resources

• TIDA-020012 Folder
• Design Guide
• Design Files: Schematics, BOM, Gerbers, Software, etc.

• Device Datasheets:
  – TLC6C5724-Q1
TIDA-020012

- 5*30 LED Matrix
Conclusion

• LCD TFT lacks in image quality consumers expect
  – Contrast ratio
  – Light leakage

• Local dimming performance proportional to number of zones
  – Halo effect

• Trade-off between local dimming price and image quality improvement
**TLC6C5724-Q1**

**Applications**
- Automotive Cluster Indicators
- Automotive HVAC Panel Backlighting
- Automotive Local Dimming Display
- Automotive Ambient Lighting

**Features**
- AEC-Q100 Qualified for Automotive Applications
- 24 Channel Outputs
  - Constant current up to 50mA, set via external resistor
  - Breakdown voltage up to 8V
- **Constant Current**
  - 7-bit, 128-step Dot correction for each channel
  - 8-bit, 256-step Brightness Control for each color group
- **PWM Dimming**
  - Configurable Grayscale Mode: 12-bit, 10-bit, 8-bit
- **Diagnostic & Protection**
  - LED Open Detection
  - LED Short Detection
  - Output Short to GND Detection
  - Adjacent-Pin Short Detection
  - Pre-Thermal Warning, Thermal Shutdown
  - IREF Resistor Open and Short Detection and Protection
  - GCLK Error Detection
  - LOD_LSD Circuit Self Test
- **Serial Data Interface**
- **Programmable Output Slew Rate**
- **Output Channel Group Delay**
- **Thermal Effective Package**
  - 38 HTSSOP (PowerPAD)

**Benefits**
- Constant current provide good LED brightness uniformity
- Full LED diagnostics features improves system reliability and safety
- Individual PWM dimming and DOT correction benefits RGB LED color mixing
- Programmable slew rate control optimizes the system EMI performance
- Output group delay reduce the peak load of front power stage

**Key Parameter Overview**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vcc Operating Voltage</td>
<td>3 ~ 5.5</td>
</tr>
<tr>
<td>Output voltage maximum rating</td>
<td>8</td>
</tr>
<tr>
<td>Full range output current</td>
<td>50</td>
</tr>
</tbody>
</table>
TLC5955
48ch, 16bit PWM LED Driver w/ 7x48bit DC, 3x7bit BC, 3bit MC & LOD/LSD

Features

• 48 Outputs with 7bit DC for each output
• 16bit PWM Constant-Current with 3x7bit Brightness Control and 3bit Max Current Control for 32mA, no external RlREF resister
• IC Supply Voltage Range: 3.0 – 5.5V
• LED Voltage Range: 10V
• Precise Constant Current Regulation:
  Channel-to-Channel: ± 2% (typ)
  Device-to-Device: ± 2% (typ)
• Low Headroom Voltage: 0.25V@19mA
• LED Open/Short Detection
• Power Save Mode: 7uA consumption
• HTSSOP 56 Package (DCA) / VQFN 56 Package (RTQ)
• Operating Junction Temperature Range: -40 C to +85C

Benefits

• Best to drive 16 RGB LED with uniformity
• Reducing microprocessor load, more smooth grayscale performance, achieving high quality video output
• 3V and 5V logic interface, drives multiple of LED lamps in series
• Improves LED display image with uniform brightness
• Reduces system power consumption
• Reduces maintenance cost

Applications

• LED Video Displays
• Cinema Video Displays
• LED Illuminations

Typical Application circuit (Multiple Daisy chained TLC5955s)