APPLICATION NOTE

ANO013 | Single Wire ICLEDs from an EMC perspective

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1. INTRODUCTION

The ICLEDs are RGB LEDs with an integrated controller that can be dimmed via PWM signals. The IC provides the power for the three different color chips and is perfect for color mixing solutions, making it easy to create both static and dynamic lighting effects for a wide range of applications. Thanks to the integrated controller in each ICLED, complex circuits with challenging PCB layouts are a thing of the past. An MCU sends the information of an entire chain of ICLEDs only to the first ICLED in the circuit. This information is passed on to the following ICLEDs via daisy-chain connection, so that all subsequent components do not require an additional connection to the microcontroller. This makes ICLEDs attractive for many different applications such as smart lighting, gaming peripherals, decorative lighting or industrial control systems. They are used as single signal LEDs, as LED strings or as matrices.

What initially sounds simple and attractive can present challenges, especially from an EMC perspective. In this application note, the EMC performance of single wire ICLEDs is analyzed and design considerations are made for a successful design without EMC problems.

2. TEST BOARDS AND FUNCTION OF THE ICLEDS

Single Wire ICLEDs (SW ICLEDs) are presented below and the implementation on test boards for evaluating the EMC performance is discussed.

2.1 Single Wire ICLEDs

The ICLEDs facilitate the use of RGB LEDs thanks to their simple circuitry and fast data transmission. Würth Elektronik's portfolio includes six different models with different protocols (24-bit, 48-bit Single Wire (SW) and Dual Wire (DW)). The 24-bit SW ICLEDs are the most widely used on the market, which is why the ICLEDs with PN 1315050930002 are used in this application note. They offer a simple and reliable way of showing more than 16 million (256^3) different colors and only require one data line.

The typical application circuit for SW ICLEDs is shown in Figure 1. The ICLEDs use the same power supply in parallel, while the date line is connected in series through all LEDs. This makes circuit design simplier compared to analog RGB-LEDs.

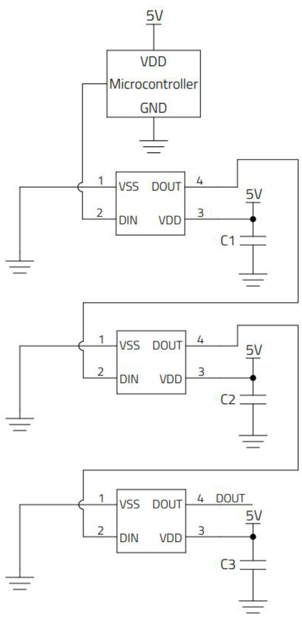

Figure 1: Typical application circuit of SW ICLEDs.

Typically, the ICLEDs use a supply voltage of V_{DD} = 5 V and consumes a maximum current of 43.5 mA (max. 13.5 mA per color/LED chip). This means a maximum power consumption of 240 mW per ICLED. For the data signal, a high pulse must be in the range of $0.7 \cdot V_{DD}$ to VDD, while the low input voltage must be less than $0.3 \cdot V_{DD}$. Further information on the ICLEDs and their data sheets can be found in Application Note ANO009.

2.1.1 Data transmission

The total transmission of 24 bits for this type of SW ICLED is split into 8 bits per color, which determines the intensity of each LED chip. With 256 light levels for each color, this results in 256^3 different colors. However, communication with only one data line requires a special bit protocol, which is realized by pulse width modulated (PWM) signals with high and low pulses of defined lengths to send a digital 1 or a digital 0. This means that the 1 and the 0 bits for the ICLED bits are not a standard bit as in SPI communication where 1 equals high and 0 equals low. An example for the bit timings for the 1312020030000 ICLED are depicted in Table 1 and a corresponding voltage-time-diagram can be observed in Figure 2.

Properties	Symbol	Value			Unit
		Min.	Typ.	Max	
Bit Period	T	0.9	1.2	1.5	µs
Bit 0 High Pulse	T0H	0.15	0.3	0.45	µs
Bit 0 Low Pulse	T0L	0.75	0.9	1.05	µs
Bit 1 High Pulse	T1H	0.75	0.9	1.05	µs
Bit 1 Low Pulse	T1L	0.15	0.3	0.45	µs
Reset Pulse	Treset	200			µs

Table 1: Bit timings of the single wire communication protocol for the 1312020030000 ICLED.

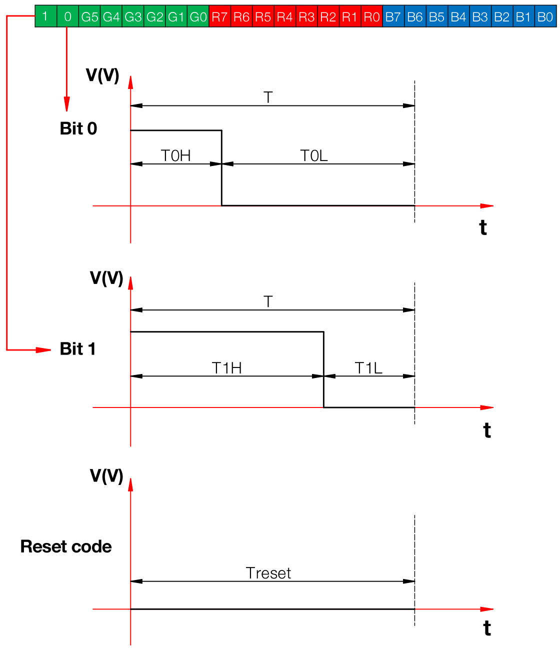

Figure 2: Graphical representation of the single wire communication protocol.

The bits are sent via a daisy-chain as one package for all ICLEDs (Figure 3): Each ICLED takes out 24 bits from the data stream which makes individual color control possible.

2.2 Test boards

The PCBs used for the EMC tests are based on an application of a LED matrix. The measurements were performed when considering the MCU and ICLEDs as one system (MCU and LED matrix on the same board) and when looking at a split system with the MCU and ICLEDs connected via 1 m cable between the boards.

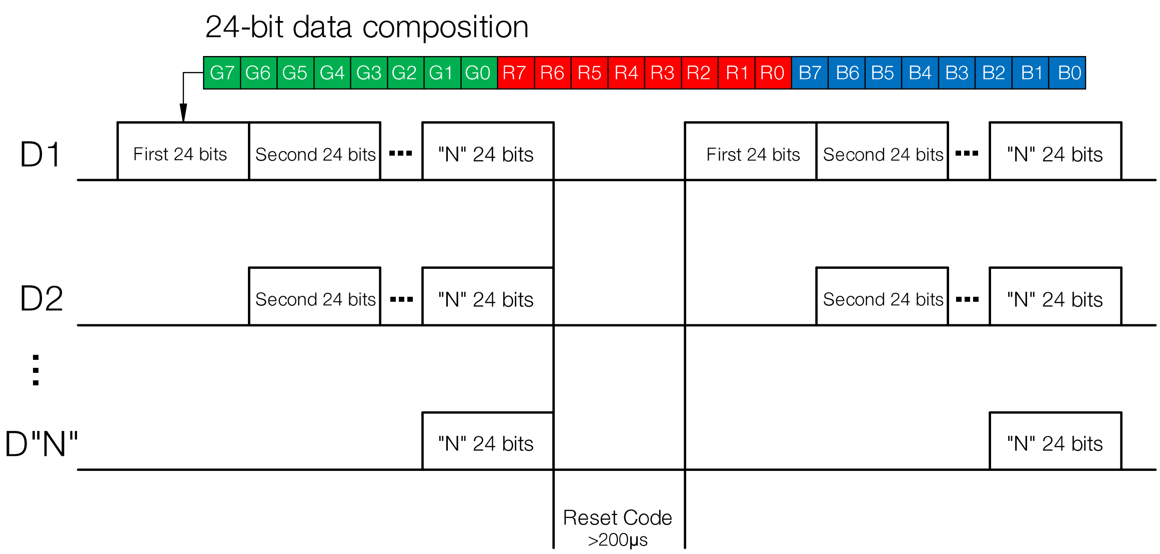

Figure 3: Graphical representation of the single wire communication protocol.

The MCU is an Espressif ESP-WROOM-32UE (red) Module. To address the ICLEDs the COPI/MOSI Pin of the SPI is used.

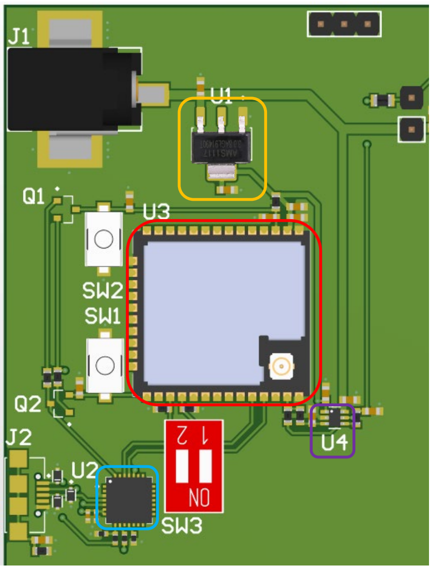

Figure 4: PCB Layout of the MCU circuit.

The entire board is powered via the DC power jack with 5 V for the ICLEDs. To supply the MCU with 3.3 V the LDO (AMS1117-3.3, orange) is used.
The controller is programmed through the Micro-USB connection. The conversion from USB to UART is handled by the CP2102N-A02-GQFN28 (blue). It is possible to switch between four programs using the dip switch next to the MCU.

With a 3.3 V supply voltage the microcontroller can only output the same voltage as the high signal over the data line. However as discussed, the ICLEDs requires a high signal of at least $0.7 \cdot V_{DD} = 3.5$ V, hence a level shifter (TXS0101DCKR, purple) is employed to convert the data signal to 5 V.

For the ICLEDs, a 7x10 ICLED matrix was used with various measures implemented to improve the EMC performance. Each ICLED has the recommended 100 nF decoupling capacitor at the V_{DD} pin. The entire PCB with MCU and ICLED has a size of 260x136 mm. In many applications, such matrices can be even larger.

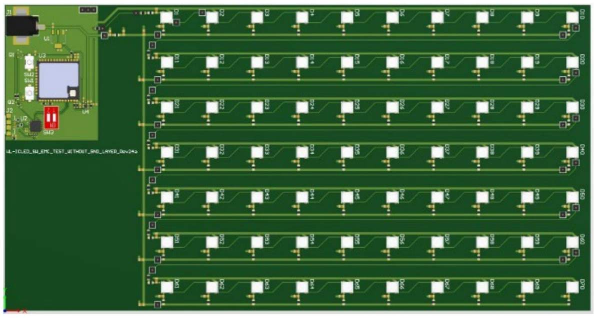

Figure 5: Layout of the ICLED Matrix without GND-Plane.

For the MCU and ICLEDs as one system the following designs were tested:

- Using a PCB with a GND-Plane.
- PCB without a GND-Plane.
- PCB without a GND-Plane but added ferrites in each data line.

For the split system, the PCB with GND plane was used for the IC-LED matrix, and the following measures were also applied:

- Shielding the cable between LED and MCU PCBs.
- Filtering the data cable and input line of MCU-PCB.

In the initial design for the PCB without GND-plane, the decoupling capacitors had a different ground path than the ICLEDs. As a result, the advantages of decoupling are not utilized because, as shown in Figure 6, the current loop is not reduced. It can be seen that the current drawn by ICLED D9 has to go around the entire string to return to the decoupling capacitor, which does not lead to the reduction intended with the decoupling capacitor.

An adjustment therefore had to be made to reduce this loop and take the advantage of the decoupling capacitor. At each ICLED, a wire was placed from the GND connection of the decoupling capacitor to the main GND trace, which connects the V_{SS} pins of the ICLEDs (See Figure 8). This reduces the current loop for D9 as shown in Figure 7 and the advantages of the decoupling capacitor are realized.

2.3 Software

The software for the ESP32 MCU comes from Würth Elektronik's library for the Espressif Systems MCUs, which is based on the existing library for Adafruit Feather M0. The program uses R = G = B = 170 out of 255 intensities for the test. This corresponds with a bitstream of 10101010 for each color and shows the color white. Here the bitstream for the ICLEDs is repeated every 1 ms. While it is sufficient for applications to send the information once to an ICLED, it is better for the EMC testing to have a continuous communication and thus to test the emission and immunity continuously. When the ICLED is used to indicate rapid color changes or as a real time signal LED, the data is sent continuously. In addition, it is easier to detect errors as all ICLEDs have the same color and therefore there is no visual interference.

Figure 8: Correction with a wire on each decoupling capacitor

2.4 Signal measurement in the time domain and expected emissions

2.4.1 Data signal

The square wave signal used to control the single wire ICLEDs in this EMC analysis is generated directly by a CMOS output of the ESP32 MCU. The transmitted signal to send a digital bit 0 and a digital bit 1 to control the ICLEDs are shown in Figure 9.

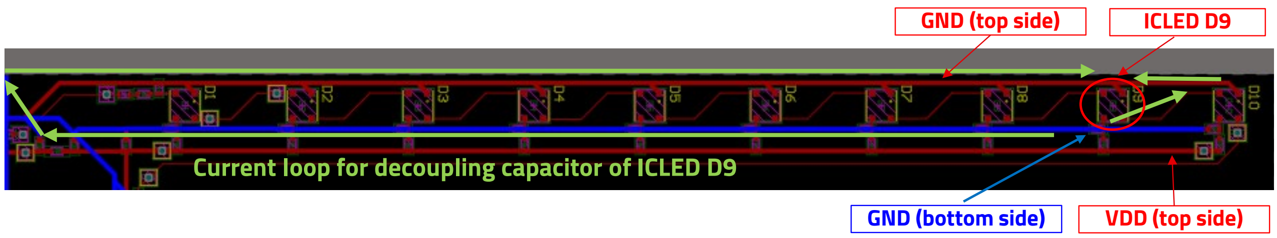

Figure 6: Current loop for the decoupling capacitor of ICLED D9 (green - top).

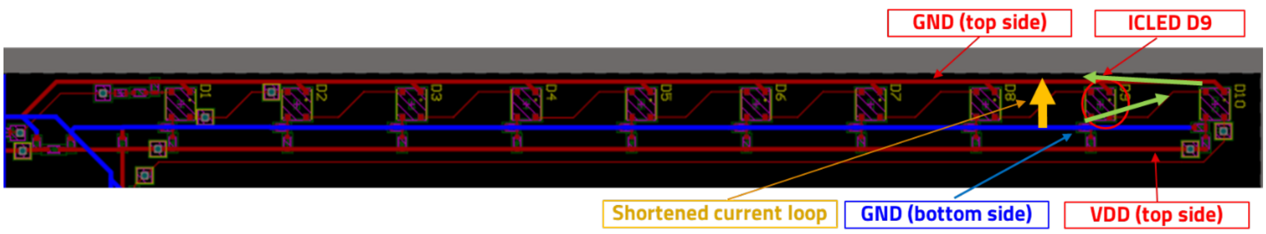

Figure 7: Reduced current loop for the data output of ICLED D9 with a wire at the decoupling capacitor – with the modification the loop gets as small as possible.

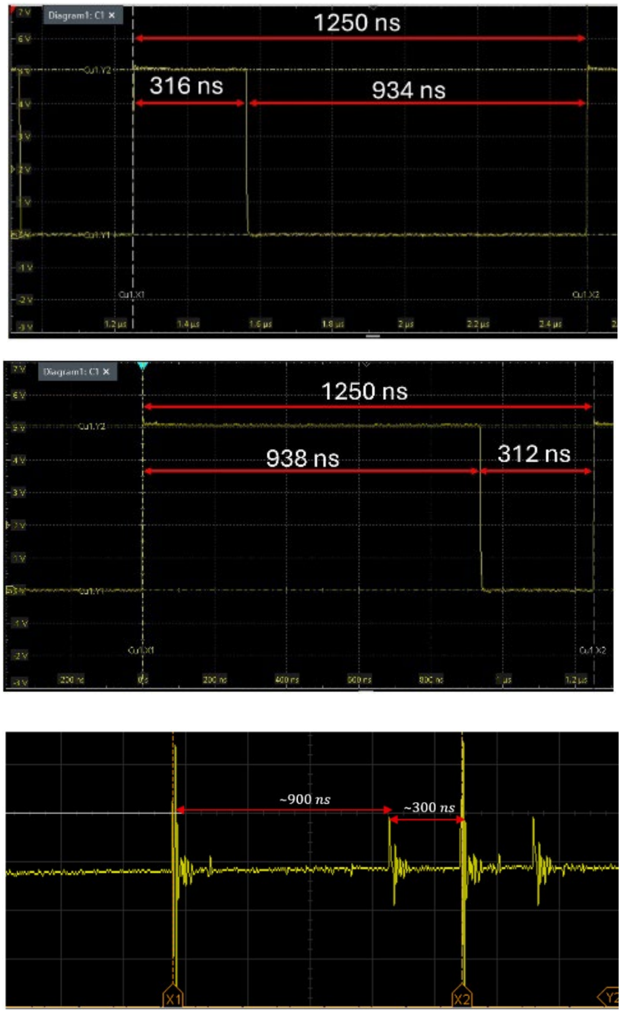

Figure 9: Measured voltage for digital bit 0 (top) and digital bit 1 (bottom) to control the ICLED.

In order to obtain a signal that comes close to the ideal rectangular signal, harmonics would have be superimposed in phase up to an infinite frequency range. The resulting spectrum of such a signal initially decreases at approximately −20 dB per decade. The rise and fall times of the signal delimit the point where the attenuation increases to about –40 dB per decade. Consequently, the signal is bandwidth-limited as shown in Figure 10.

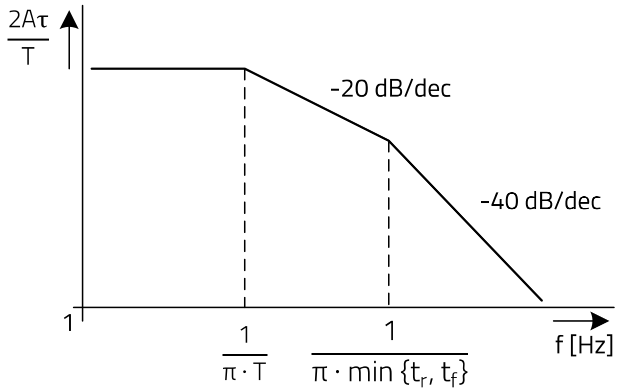

Figure 10: Envelope of the spectral analysis of a rectangular signal.

The harmonics can be observed at multiples of (1)

$$\frac{1}{T} = \frac{1}{1250\ \text{ns}} = 800\ \text{kHz} \tag{1}$$

The frequency points at which the envelope curve changes its slope can be calculated accordingly:

$$f_1 = \frac{1}{\pi \cdot T} = 255\ \text{kHz} \tag{2}$$

and

$$f_2 = \frac{1}{\pi \cdot t_r} = \frac{1}{\pi \cdot 2{,}1\ \text{ns}} = 152\ \text{MHz} \tag{3}$$

(where the rise time of the electrical signal is measured at t_r = 2.1 ns whereas the fall time measured at t_f = 3.5 ns). Despite this simplified representation, in which the shift of the discrete spectral amplitudes by coupling mechanisms and various signal rise and fall times were not taken into account, it is easy to see that the signal transmitted via all data lines has harmonics of up to several hundred MHz.

Measurements on the 5 V power line show transients that are time-correlated with the data transmissions, thereby also generating high-frequency spectral components (see Figure 11).

Figure 11: Voltage spikes due to an ICLED digital bit 1 measured on the 5 V trace line.

With a rise time of the voltage spikes of t_r = 21 ns, the important second cut-off frequency, as shown in the diagram in Figure 12, is f = 15 MHz.

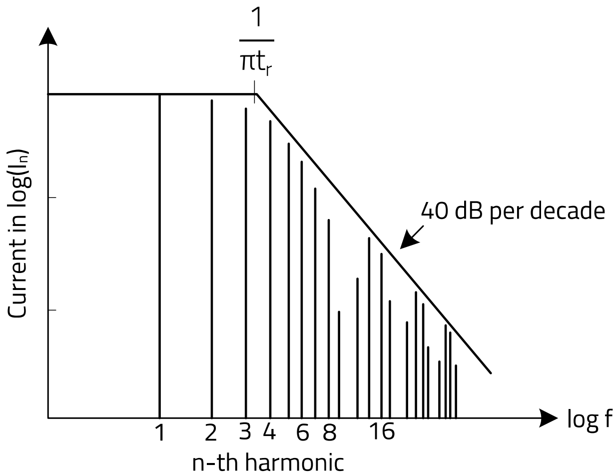

Figure 12: Graphical representation of the spectrum for the voltage peaks.

Both properties described lead to conducted and radiated emissions, whereby legal limits can be exceeded and must be dealt with.

3. EMC PERFORMANCE OF THE TEST BOARDS

This section compares the EMC performance of the test boards when the MCU and the LEDs are located on the same PCB. The focus here is on the test board with a GND plane and without a GND plane. The EMC performance of the device was dramatically reduced by removing the GND plane, and only partially compensated by using ferrites on the data line.

3.1 Emission testing

When starting the analysis from a theoretical point of view, it can be assumed that the EMC performance of the board without the GND plane will be much worse compared to the one with a GND plane. The reason for this is the increased loop of the data line. At frequencies above 1 MHz the return current of the signal runs below the data trace (path of lowest impedance), because the inductive component of the impedance predominates.

This behavior is like current compensation in a common-mode choke, where opposite currents cancel out magnetic fields, reducing emissions. If a design with a GND plane is chosen, the loops of the data currents are as small as possible, minimizing common-mode noise and ensuring the best performance in emissions.

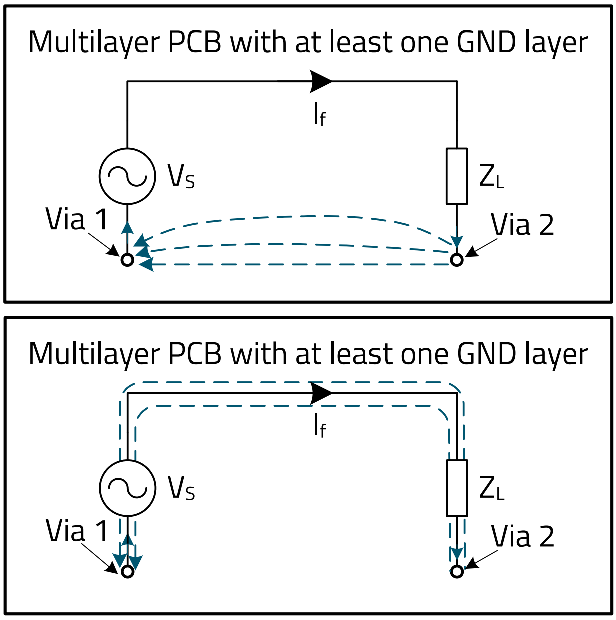

Figure 13: Return current at low frequencies (top) and high frequencies (bottom).

Additionally, the high frequency magnetic field of the loops contains the frequencies demonstrated in chapter 2.4. These frequencies are now coupled into all traces in the loop by the magnetic field – which leads to massive common mode issues.

The measurement result of the radiated emissions testing in Figure 14 shows, that the theoretical presumption becomes reality when the GND plane is changed to a return trace with a larger loop. The low emissions of the test board when using a continuous GND plane on the entire board increase by 30 dB when the plane is replaced by return traces. If the frequency spectrum of the data trace is reduced by adding SMD ferrites (742792711) between the data output and input pins of the LEDs in the string, the test board can pass the radiated emissions test, but the margin to the class B is critical.

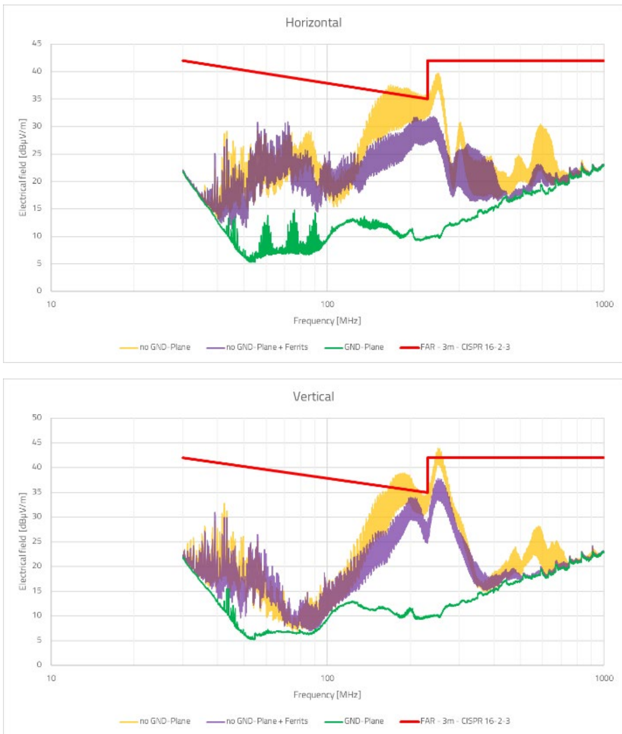

Figure 14: EMC test results radiated emissions - MCU and ICLEDs on the same board.

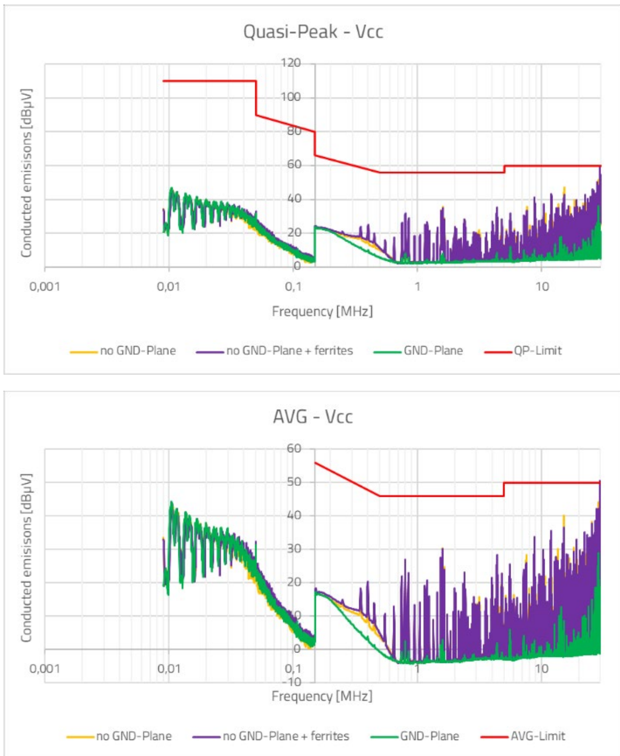

Figure 15: EMC test results conducted emissions - MCU and ICLEDs on the same board.

The conducted emissions are tested at the DC-Input of the ICLED test board. The limit values for AC mains are showed in the results graph. If the emissions of the DC port are below this limit values, it can be assumed, that a complete setup with the test board and an EMC compliant AC/DC power supply unit will also pass the test, even if the EMC attenuation of the power supply unit is weak.

For this test, an external electrolytic capacitor at the DC-Input is required to compensate for the high inductance of the LISN and stabilize the regulators integrated in the ICLEDs controllers. As the results of V_{CC} and GND are the same, only the results for the V_{CC}-Line are shown in Figure 15.

The results of the conducted emissions show that only the board with a GND plane has a margin of at least 10 dB to the limit. As an AC/DC power supply is normally used in such applications, these results are not so critical. However, depending on the attenuation of the power supply from the secondary to the primary side and the setup of an application with the ICLEDs, this result could lead to problems due to noise coupling from the LED panel through the power supply. From an emission point of view, a PCB design with a GND plane is preferable to achieve low radiated and conducted emissions.

3.2 Immunity testing

As explained in the emissions section of this chapter, the performance of a design with GND plane is preferable. The loops, which have a negative impact on the emissions, can also affect the immunity performance of the test boards.

3.2.1 Performance Criteria

Before the Immunity test can be performed, the performance criteria of the device under test (DUT) need to be defined.

Performance Criteria:	DUT Performance
A	The LEDs are not changing colors during the test, no change in brightness or any communication issues are allowed.
B	During the test the performance may be temporarily disturbed, but will return after the test without operator intervention. The performance degradation may be a change in color, data communication or a change in brightness.

Table 2: Performance criteria during immunity testing.

The following pictures are showing disturbances of an ICLED panel during an immunity test:

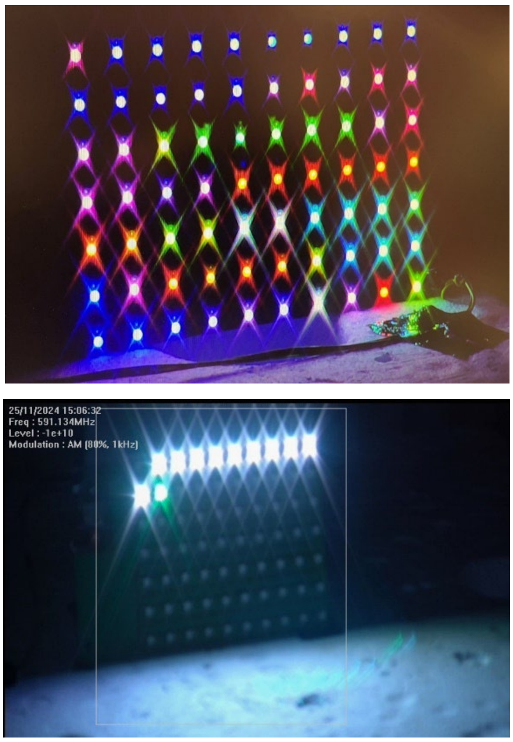

Figure 16: Disturbance of an ICLED panel during immunity testing.

Figure 16 shows a disturbance of the LED panels color (top) and an interrupt in the LED chain (bottom). During immunity testing only single LEDs in the middle of the string were disturbed sometimes.

The DUT was monitored by a camera and by laboratory personnel – no optical analysis tool was used to monitor the DUT during the immunity test. The laboratory staff's subjective perception of the detection of changes in luminosity and color constancy limits the performance analysis during the test to a certain extent. However, through careful setup, high-performance camera technology and careful observation, it can be assumed that the parameters relevant to the assessment of the performance criteria have been sufficiently monitored to ensure a reliable assessment.

3.2.2 Modified immunity tests

ICLEDs applications typically have an enclosure, so direct ESD discharges to the electronic circuit should not be possible. For this reason, ESD discharges are only tested on the horizontal coupling plane to simulate the discharge on a metallic enclosure in an LED application. This discharge on the housing of the application can couple into the circuit of the application if the housing is only partially closed. The designer of the LED application must ensure protection against direct discharges into the electronic circuit of the application.

The burst test is performed with the capacitive coupling clamp at the input of the test board. A battery with a DC/DC converter is used as the power supply. In an LED application, the burst is injected into the AC side of the power supply unit and then coupled into the LED circuit on the secondary side. A direct injection into the DC Line of the LED circuit is not to be expected, as the circuit is only connected to the dedicated power supply.

3.2.3 Immunity Test results

Table 3 below shows the results of the immunity tests for the boards with MCU an ICLEDs on the same board.

The test board with GND plane or without plane and with ferrites in the data lines passes the radiated immunity test at the maximum possible test level of the EMC test system. The performance in criterion A is reduced to a test level of 20 V/m when using the test board without GND plane and other EMC measures.

The maximum test level for the radiated immunity test is shown in the following figure:

- 80 MHz to 180 MHz: 20 V/m.
- 180 MHz to 500 MHz: 40 V/m.
- 500 MHz to 1 GHz: 30 V/m.
- 1 GHz to 6 GHz: 10 V/m.

All boards pass the conducted immunity test at 20 V/m. During the test, the noise is injected in common mode on the 5 V_{DC} input of the test boards.

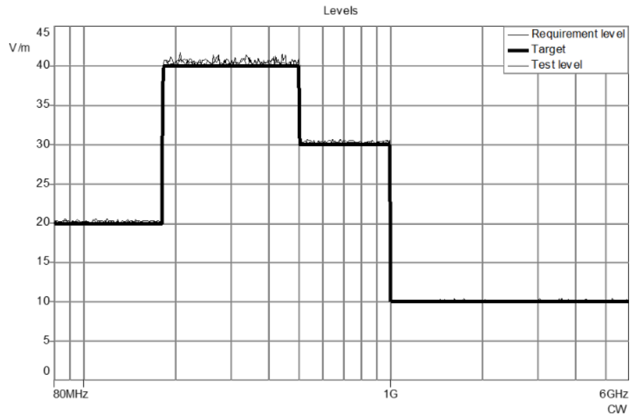

Figure 17: Maximum field strength that was tested during immunity testing.

During the fast transients and ESD test different performance levels can be observed. The test board with a GND plane has the best performance - during the burst (5 kV) and ESD (30 kV) tests with very high test levels, no disturbance was detected. The test board without a GND plane and EMC measures performs worse and only passes the burst test in criterion A at 1 kV and the ESD test at 6 kV. This can cause malfunctions in an ICLED application. A solution could be a software measure – by periodically resending the LED commands in the application.

	Continuous disturbance									Transient disturbance							
	61000-4-3						61000-4-6			61000-4-4 (CCC tested)						61000-4-2	
	80 MHz to 1 GHz				1 GHz to 6 GHz		CDN tested			5 kHz and 100 kHz tested						Test level [kV] HCP	
Measures	3 V/m	10 V/m	20 V/m	Max. level	3 V/m	10 V/m	3 V	10 V	20 V	200 V	500 V	1 kV	2 kV	3 kV	5 kV	Crit. A	Crit. B
GND plane, 100 nF @ V_{IN} of every LED reduced loop																30 kV	
No GND plane, 100 nF @ V_{IN} of every LED reduced loop																6 kV	30 kV
No GND plane, 100 nF @ V_{IN} of every LED reduced loop + ferrites in data line																10 kV	30 kV

Table 3: Immunity performance of the test board – MCU and ICLEDs on the same board. Gray color – passing the test in performance criteria A; Green color – passing the test in performance criteria B.

Single disturbances caused by transient pulses can be overwritten, so malfunctions only happen while the transient occurs. If the ferrites are added to the test board without the GND plane, the performance increases slightly to 2 kV burst immunity and 6 kV ESD immunity in performance criterion A.

4. SPLITTING LED-PANEL AND MICROPROCESSOR

If the LED panel and the MCU need to be separated in an application, additional challenges may arise. In some applications, the LED matrix or a decorative LED strip can be located outside the MCU-PCB and the supply and data connection is routed via a cable.

4.1 Setup

As already analysed in chapter 3, the EMC performance is best with a GND plane. To test a system with two boards, both PCBs are provided with a continuous GND plane and connected to 5 V, GND and the data line via a cable. The cable between the two PCBs is 1 m long.

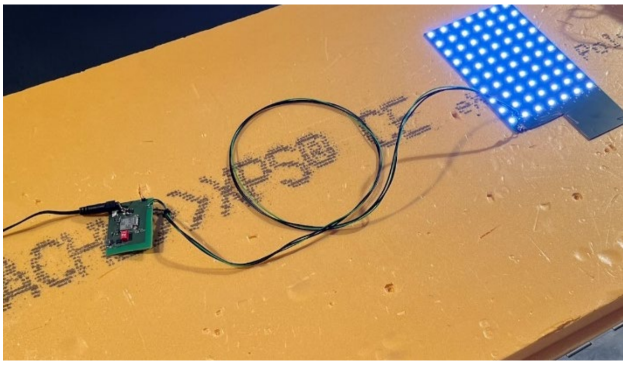

Figure 18: ICLEDs test setup with two PCBs during the conducted immunity test.

The design of the LED matrix and the MCU PCB is identical to the test board design with MCU and LED string on the same board.

4.2 Emission test results

Figure 19 compares the radiated emissions of the system with two boards (see Figure 18) and the system on one board with and without GND plane and without EMC measures. The emissions increase strongly if the MCU and LED string are not on the same PCB – the emissions are up to 20 dB above the limit and are significantly worse than with the PCB without GND plane and measures. Only the horizontal emissions are shown, as they are higher than the those in vertical polarization.

Figure 19: EMC test results radiated emissions - MCU and ICLEDs on the same board (green and yellow) and setup with two boards (blue).

Not only do the radiated emissions increase if the MCU and LEDs are not on the same PCB, the conducted emission also increase between 10 dB and 20 dB.

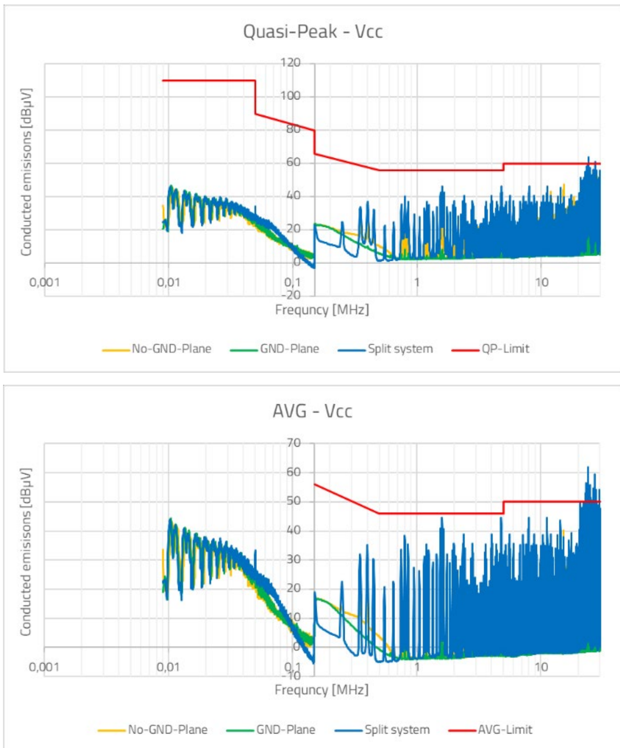

Figure 20: EMC test results conducted emissions - MCU and ICLEDs on the same board (green and red) and setup with two boards (blue).

4.3 Optimizing the performance of the split design

Ideally, the MCU and LEDs should not be used on separate circuit boards. If the application requires separation of the MCU and the ICLED matrix, EMC measures should be taken. These options are discussed in this chapter.

Shielded cable: The cable between the two devices is shielded according to Figure 21. The shield is connected directly to the GND plane on both boards. The cable shield serves as a return line for the digital signals and reduces the loop to a minimum (see Figure 21). The connection of the shield to the GND planes should be as large as possible – no pigtail connection!

Implementation of a filter (Figure 22): A CMC with a wide impedance curve (744237152) with a 4.7 µF MLCC (885012209048) on the cable side is introduced at the power input of the MCU board. The signal output pin on the MCU is filtered against the GND plane using a Pi filter with a PCB ferrite (74279265) and two 220 pF MLCCs (885012006010). A 220 pF MLCC is placed at the data input pin on the LED matrix board. The signal integrity of the data bus must be considered, as the filter on the data line reduces the harmonics in the spectrum of the square-wave signal and therefore reduces the rise and fall times of the data signal.

Figure 21: Cable between MCU-PCB and LED-Panel shielded with aluminium foil.

To ensure signal integrity, a general guideline suggests that the fifth harmonic of the frequency spectrum corresponding to the shorter (i.e., faster) of the rise or fall time should be preserved and remain unaffected when applying signal filtering.

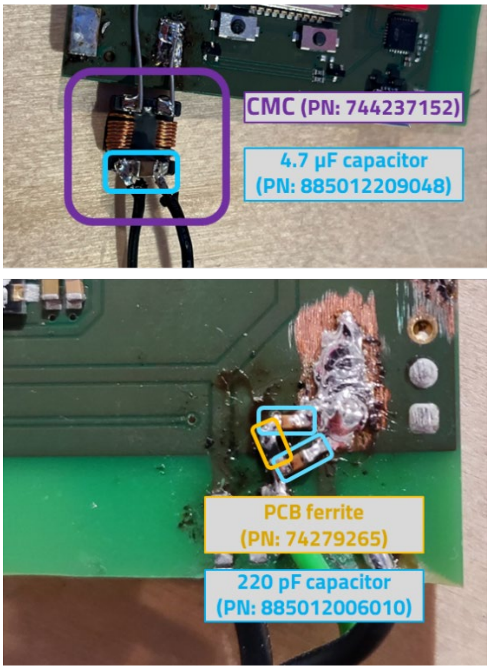

Figure 22: Optimization of the MCU-PCB with input filter (top) and Pi-filter on the data line (bottom).

4.3.1 Shielded cable – Emissions

Figure 23 and Figure 24 show that the emissions are significantly reduced when the connecting cable between the MCU and the LED board is shielded. The EMC performance of this setup is comparable to the emission results where ICLEDs and MCU are placed on the same board with GND plane.

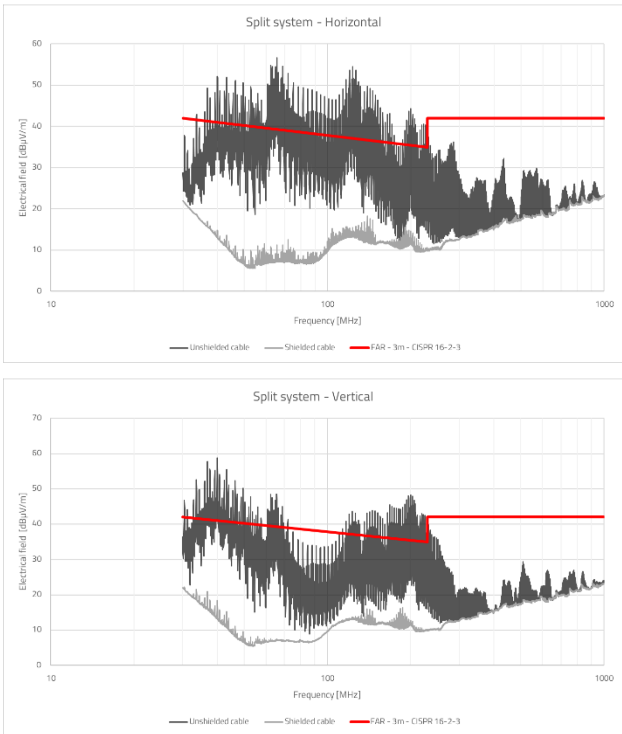

Figure 23: EMC test results radiated emissions - MCU and ICLEDs on different boards, with and without shielded cable.

Not only are the radiated emissions strongly reduced, the conducted emissions are also reduced and comparable to the single-board solution with a GND plane.

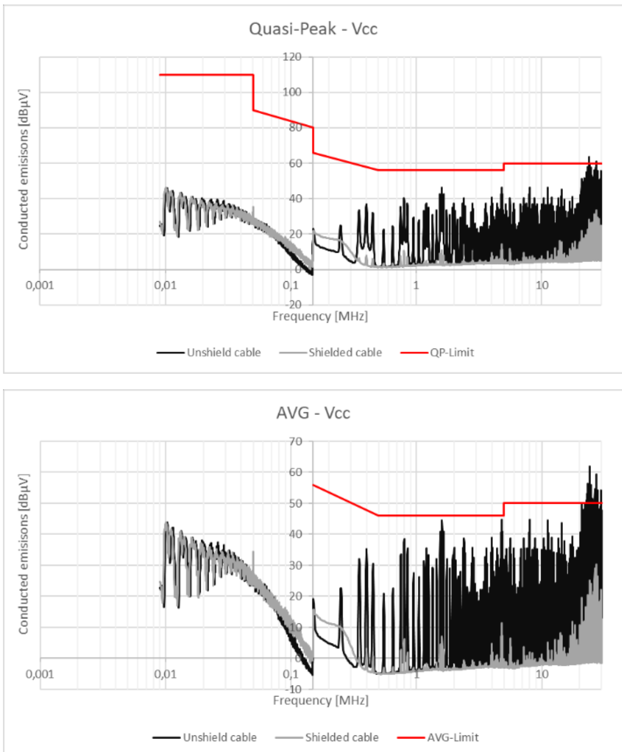

Figure 24: EMC test results conducted emissions - MCU and ICLEDs on different boards, with and without shielded cable.

4.3.2 Filter effect – Emissions

The filter also reduces the radiated emissions of the split system very well. The conducted emissions are reduced to below the class B limit, but the emissions are higher than in the setup with shielded cables.

Figure 25: EMC test results radiated emissions - MCU and ICLEDs on different boards, with and without filter and unshielded cable.

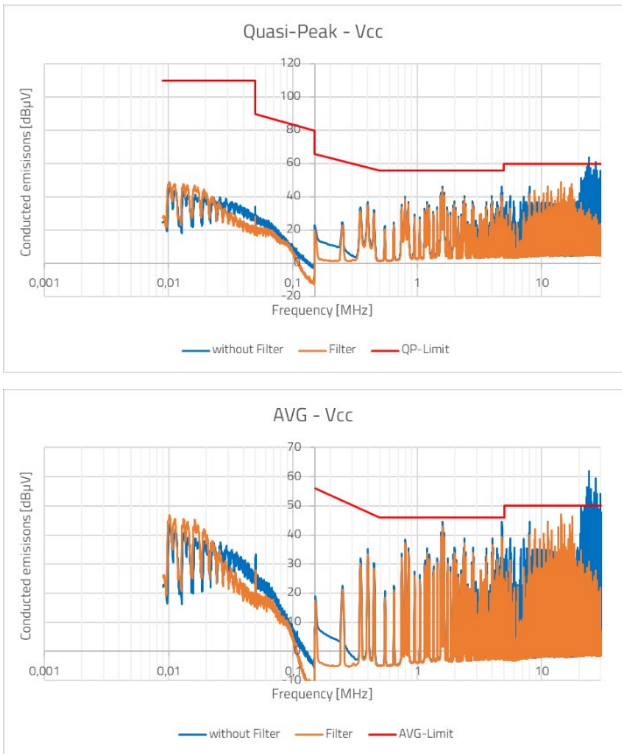

Figure 26: EMC test results conducted emissions - MCU and ICLEDs on different boards, with and without filter and unshielded cable.

4.3.3 Immunity of the setup with two boards

Table 4 shows the immunity performance when the MCU is on a separate PCB. The burst immunity of the unshielded device and the filtered device is poor, and the boards are disturbed at the lowest test level of 200 V. The performance increases for criteria A to 2 kV when the cable is shielded. The performance during the immunity test of the unshielded cable is generally very poor, and the conducted and radiated immunity tests also fail, and the ESD test level without performance loss is very low at only 1 kV. The shielded connection performs best in immunity tests – the performance is not as good as when the components are on the same board with GND plane, but the performance is good enough to pass all immunity tests in a possible application with increased test levels. The unshielded connection with a filter can pass the immunity test for a domestic level. While the performance in the radiated immunity is good, the device passes the conducted immunity at domestic levels and the burst test can only be passed in criterion B.

	Continuous disturbance									Transient disturbance							
	61000-4-3						61000-4-6			61000-4-4 (CCC tested)						61000-4-2	
	80 MHz to 1 GHz				1 GHz to 6 GHz		CDN tested			5 kHz and 100 kHz tested						Test level [kV] HCP	
Measures	3 V/m	10 V/m	20 V/m	Max. lvl	3 V/m	10 V/m	3 V	10 V	20 V	200 V	500 V	1 kV	2 kV	3 kV	5 kV	Crit. A	Crit. B
1 m cable between LEDs and µP	Gray	green	blue	blue	blue	blue	green	blue	blue	green	blue	blue	blue	blue	blue	1 kV	2 kV
Shielded signal cable: V_{CC} & Signal; shield = GND	blue	blue	blue	Gray	blue	Gray	blue	blue	Gray	blue	blue	blue	Gray	blue	green	15 kV	30 kV
Filter	blue	blue	blue	Gray	blue	Gray	Gray	green	blue	green	blue	blue	blue	blue	blue	15 kV	30 kV

Table 4: Immunity performance of the setup with two boards. Gray – passing the test in performance criterion A; green – passing the test in performance criterion B:

5. CONCLUSION

The EMC performance of the ICLEDs was investigated in detail in chapters 3 and 4 of this application note. Based on the test results, the following design recommendations can be made.

5.1 Microprocessor and LEDs on the same PCB

If the MCU and LEDs are located on the same PCB, very good performance of the ICLEDs from an EMC point of view can be achieved if a PCB with a continuous GND-Plane is used. The GND vias to the caps and pins should be placed according to the known design considerations. This approach ensures strong EMC performance in both emissions and immunity.

It is not recommended to use a design without a GND plane as the emissions will significantly increase. Even if the immunity performance meets the requirements for domestic applications and the emissions can be reduced by using ferrites in the data line, a design with a GND plane is preferable.

5.2 Microprocessor and LEDs on different PCBs

If the MCU is located on a different PCB than the ICLEDs, a shielded cable connection between the two boards is preferable. Both PCBs should have a GND plane. If a shielded cable cannot be used, a filter can be implemented but considering the reduced immunity performance compared to the shielded cable option. Instead of a shielded cable, a flex PCB with VCC and signal on the top and GND plane on the bottom layer can also be used. A cable connection without any measures between MCU-PCB and LED-PCB should not be used from an EMC point of view, because the emissions and immunity requirements will not be met.

5.3 General design recommendations

The results and conclusions of the presented EMC tests can be partially transferred to all asymmetrical communication buses at PCB-Level like, I²C, SPI, UART and many others. The two most important conclusions from an EMC point of view to avoid problems are:

- An asymmetrical PCB-BUS should not be routed in a cable.
- An asymmetrical PCB-BUS should be routed on a GND plane without splits to ensure adequate return paths.

Even if all buses have their special features, these two general rules always apply! If a design does not adhere to these rules, EMC problems will occur and complicated workarounds and measures (which may also be costly or technically cumbersome) will be required.

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