Master Thesis

SMART LIGHTING NETWORK TECHNOLOGIES

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Graz, May 2017

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Signature

STATUTORY DECLARATION

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor Dr. Florian Hollomey for the continuous support, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my master thesis.

Besides my advisor, I would like to thank my fellow workmates for their hands-on support in building up the test setup and for the numerous entertaining hours we were working together.

ABSTRACT

This master thesis explores the technological fundamentals of lighting networks, represented by wired and wireless communication principles. Amongst the first considerations, linked to lighting control systems is the question of why to have it, therefore the first chapter focuses on the numerous advantages and possibilities which are provided by the use of smart lighting. Presence detection, brightness control loops or colour temperature adjustments are only some of the helpful enrichments users and facility managers benefit from.

To determine the further benefits of smart lighting systems, and far more important, to enable troubleshooting, a certain amount of background knowledge regarding signal transmission and wired networks is required.

The past five years have shown a significantly increasing demand for wireless lighting systems. As a result, a huge number of proprietarily as well as standardized technologies have entered the market leading to an uncontrolled growth. This thesis enlightens a selection of promising wireless technologies and the main leading wired lighting control protocol for professional lighting: DMX. The high frequency field bus DMX is an area, which has frequently caused communication issues. The relatively high sensitivity for disturbances increases the probability for issues on commissioning due to constantly changing environmental influences.

The aim of this thesis is to elaborate the impact of certain influences on the network, such as electromagnetic interferences or suboptimal electrical installation. A compact catalogue of executed tests and a summary of recommendations regarding installation, commissioning and the entire electrical surrounding of lighting networks is an appreciated outcome.

KURZFASSUNG

Vorliegende Arbeit untersucht die elektrotechnischen Grundlagen von Lichtsteuerungsnetzwerken, welche allgemein entweder kabelgebunden oder kabellos arbeiten. Eine der ersten Fragen die auftaucht betreffend komplexer Lichtsteuerungssysteme ist deren tatsächlichen Nutzen geschuldet, aus welchem Grund bereits eingangs auf die Vorteile eingegangen wird. Anwesenheitsdetektion, Helligkeitsregelung und Lichtfarbenveränderung sind nur einige der vielen Möglichkeiten welche ein solches System seinen Benutzern und Instandhaltern bringt.

Um die technischen Möglichkeiten voll ausschöpfen zu können und vor allem um auch eine Fehlersuche effizient durchführen zu können, ist ein gewisses Niveau an Grundlagenwissen zur Signalübertragung sowie Netzwerktechnik unabdingbar, welches im theoretischen Teil erarbeitet wird.

Durch die erfolgreiche Einbindung von Beleuchtung ins IoT haben vor allem kabellose Systeme einen wahren Wildwuchs an proprietären als auch standardisierten Verfahren erfahren. Aus diesem Grund beschäftigt sich diese Arbeit mit der Ausarbeitung der wichtigsten Fakten der vielversprechendsten kabellosen und einem langjährig etablierten kabelgebundenen System am Markt; DMX. Der für Lichtsteuerungen relativ hochfrequente DMX Feldbus ist durch den vermehrten Außeneinsatz nicht selten die Ursache für Kommunikationsprobleme. Die bekannte Anfälligkeit von weitreichenden Feldbussen auf Störungen durch parallele Lastkreise oder mangelhaften Potentialausgleich führt oftmals zu Reklamationen und damit verbundenen Kosten.

Das Ziel dieser Arbeit ist daher die Auswirkungen gewisser Einflüsse auf das Beleuchtungsnetzwerk zu untersuchen. Die bedeutendsten Faktoren sind hierbei elektromagnetische Einkopplungen und suboptimale Elektroinstallation. Das Ergebnis dieser Untersuchungen ist eine kompakte Beschreibung von Auswirkungen der EMV auf das Netzwerk, belegt durch Messungen an einem Testaufbau. Des Weiteren wurden daraus Empfehlungen zur Inbetriebnahme bzw. der Elektroinstallation in der Umgebung abgeleitet.

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1 INTRODUCTION

1.1 Initial situation

At the moment companies within the lighting industry are facing a big change as far as communication of devices and control of lights is concerned. Keywords like Smart Home, Intelligent Lighting and Smart Metering are omnipresent both in professional and private settings and everyone has heard one of these terms at least once. Especially in the consumer market new technologies are revealed almost monthly and customers, manufacturers as well as developers are hit by an avalanche of new standards, various incompatible versions, and proprietary systems.

In order to cover the positive achievements of smart lighting a few examples are given.

• Presence detection	Lights are dimmed or turned off completely if rooms are vacant
• Constant light	Output of the lighting system is regulated according to additional daylight
• CCT[1] adjustment	Correlated colour temperature (CCT) varies to support human well-being
• Light over time	Brightness and CCT follow a predefined profile over the course of the day
• Heat mapping	A colour coded footprint of the building shows where people spend time
• Energy monitoring	Analysis of energy consumption for lighting systems
• Motion trails	This function shows how people move through a space over time[2]

Due to that huge number of different technologies, it is difficult to ensure that salesmen are trained accordingly on each product. In fact, their limited knowledge leads to less and decreasing confidence in products they should sell. The result is a sales team that might miss great opportunities of starting new markets or convincing customers to invest more money in intelligent lighting solutions.

Sales are not the only point of interest, as there are still new technical challenges with long established systems already dominating the market for years, such as DALI and DMX. Especially electromagnetic interferences and earthing are becoming more important, as the number of grid loads increases daily and poor or faulty filtered devices are the rule rather than the exception.

[1] CCT = correlated colour temperature

[2] cf. enlighted (2017), online source [30.11.2017]

1.2 Problem setting

The words smart lighting are strongly tied to wireless systems although there are perfectly working wired solutions on the market. Both systems show individual main problems. Existing wired networks show good compatibility but struggle with electrical disturbances caused by huge grid loads and poor or faulty installation. New wireless technologies are, on the other hand, of limited compatibility and lots of them operate in the already well-filled 2.4 GHz ISM band.

The possibility to connect lights and smartphones via Bluetooth, WLAN or many more with the help of gateways enabled software companies to enter the lighting market without the need to produce hardware. Lighting companies, however, do have to deal with the hardware behind the technologies, therefore require a market overview of the most common technologies as well as the most promising projects for the future.

Issues with established wired systems are generally caused by more fundamental reasons. Such systems frequently fail due to inconsistent concepts of earthing, shielding, cable routing or poor lightning protection. A careful investigation of such malfunctions, thereby creating countermeasure concepts, would help to prevent future problems.

1.3 Objective

The first chapters are aimed to provide the reader the theoretical knowledge in order to understand the following practical parts dealing with fundamental concepts of wireless technologies and troubleshooting of wired systems.

The main part of this thesis will be an analysis and troubleshooting of a real case in which a DMX facade illumination system that partly failed and had to be restored in a sustainable way. This included the development of protective hardware to save the outdoor luminaires from lighting strikes.

To prove that the solution does inhibit future failures, a test setup will be implemented to investigate influences of various kinds of electrical disturbances. The results will be implemented in next redesigns of the luminaire series.

2 PARAMETERS AND LIMITATIONS OF WIRED NETWORKS

Wired bus systems use electrical signals for data and are generally represented by voltage signals. Such signals have an enormous amount of different parameters and characteristics. The most important ones will be covered on the following pages in order to get a better understanding of how wired networks work and which environmental influences they must resist.

2.1 Analog and digital signal transmission

2.1.1 Analog signals

An analog signal is a time-continuous and value-continuous signal representing a particular value at a specific point in time of a mathematical equation. Except omnipresent noise, analog signals are by definition infinitely precise, i.e. errors result out of quantifying an analog signal by measuring it and taking the readings of the instrument.

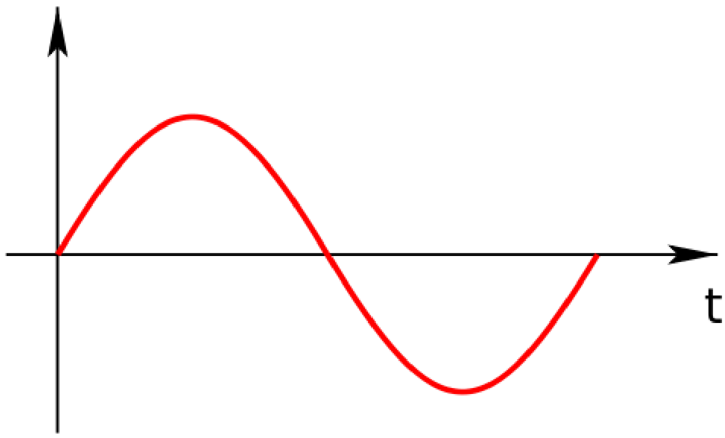

Figure 1: Time-continuous and value-continuous signal, Source: Werner (2008)

Due to the infinite number of possible values an analog signal can take on, one can no longer distinguish between the original and useful signal and additional noise. Thus, each signal conversion, amplification, and transmission diminishes the signal quality significantly. In extreme cases, the signal can be lost completely due to noise and disturbances without any possibility to restore the original signal.

Nevertheless, several countermeasures can be taken to avoid electrical noise being induced into the conductor and thereby added to the signal, such as shielding of wires, ensuring proper connections, twisting supply and return conductors. Thermal noise represents an exception to this statement, as it cannot be avoided at all.

2.1.2 Digital signals

Digital signals are value-discrete and time-discrete signals representing a signal that is, as far as its course of time is concerned, organised in equidistant time slots. In contrast to a time-continuous signal, its value stays the same for the entire timeframe. When the timeframe is over, it immediately jumps to the next level in order to hold the value for another timeframe. As a digital signal has a countable set of values, it is only finitely accurate. Combined with the quantized finite number of possible values, the sampled time slots create a matrix of possible states of the signal.

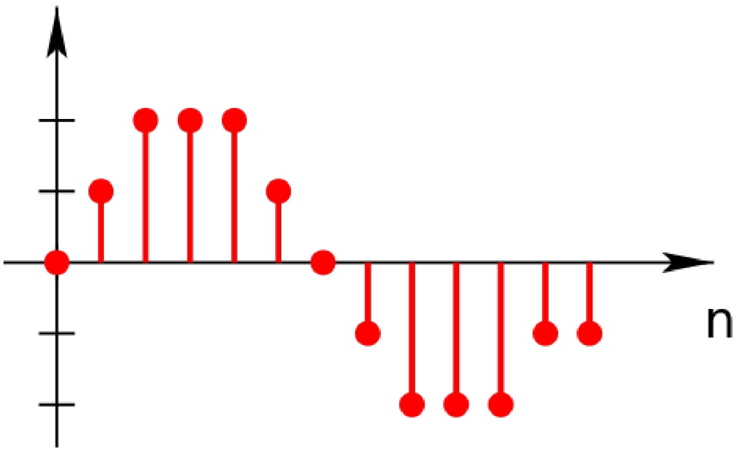

Figure 2: Time-discrete and value-discrete signal, Source: Werner (2008)

Digital signals generally do not suffer from noise because as long as there is a slight difference between certain possible states left, it can be restored to the original output quality. Circuits can be designed to detect whether the interfered digital signal is representing a high “1” or low “0”, and restore it to its original clear square wave.[3] A limit to the amount of information contained within a signal reveals the true value of digital signal transmission. Digital information can be duplicated, transmitted and processed as often as the application requires without even a slight modification of the information itself.

2.1.3 Analog-to-digital conversion

The conversion from analog to digital signals requires two fundamental steps to receive a proper output. The first step samples the analog signal to organise the signal in periodical time frames. Secondly quantisation is done by giving the digital signal a finite value representing the amplitude of the original analog signal.[4] These two steps underline the significance of the lost information during analog-digital conversion.

Nowadays, if analog-to-digital conversion is applied in the field of lighting, mostly digital signals are used to transmit data. Ten years ago things were different, as the 0-10 V analog dimming signal was the norm until it was replaced by digital wired and wireless lighting systems.

[3] cf. Beckert (2017), online source [7.6.2017]

[4] cf. Beckert (2017), online source [7.6.2017]

2.2 Signal frequency

Lighting networks generally operate with the help of digital serial connections, meaning that information is transmitted in a stacked manner over time, while addresses ensure that the intended receiver receives the correct telegram.

To transmit digital information, the amplitude changes between high and low thousands of times per second. The signal frequency defines not only the number of possible status changes per second, but also serves as an indicator of the maximum bandwidth of the network. Logically, frequency stands in direct relation to the timeframe a single bit requires within a telegram.

$F = \frac{1}{T}$	(2.1)	F/s^{-1} T/s	Frequency Bit time

Equation 1: Relation between bit time and frequency

Certain bus systems carry a clock signal on a separate conductor or modulate the information with a clock to combine both on a single wire.[5] Especially clocks at higher frequencies are sensitive to electrical disturbances as well as possible noise sources their selves. The higher the frequency gets, the higher the possibility of crosstalk occurring from and to other cables. Although it may seem like the frequency is causing issues, in reality such issues stem from a high slew rate of the amplitude.

2.2.1 Slew rate

The slew rate is a measurement representing the change in amplitude over time. High signal levels combined with short switching times cause large slew rates and, consequently, cause harmonic waves of higher order.

Square wave signals are unnatural signals due to their theoretically infinite edge steepness. In theory, an ideal square wave therefore causes harmonic waves of infinitely high frequency.

$SR = \frac{dU(t)}{dt}$	(2.2)	SR/Vs^{-1} U/V t/s	Slew rate Signal amplitude Rise time / fall time

Equation 2: Definition of slew rate

Lighting control protocols generally define boundaries for the signals slew rate in order to standardise the hardware interfaces of control gears and control devices.

[5] e.g. Manchester encoding

2.3 Signal transmission

In the context of lighting networks, different applications require certain types of signalling. There can either be an extremely fast network, where it is crucial to avoid any telegram losses caused by disturbances, or a low-cost fault tolerant system. Both cases are examples of real-world applications discussed below.

2.3.1 Single-ended signalling

The most common and cheapest method to transmit a signal from a sender to a receiver is the single-ended transmission. Single-ended signalling transmits information represented by a voltage or current signal which is referenced to a fixed potential.[6]

As single-ended signalling is considered the simplest solution to exchange information, requirements are kept simple as well. The electrical signal changes over time in relation to the reference or ground. One major advantage of single-ended signalling is it’s functioning with a single reference, which in turn enables other signal conductors to use the same reference, consequently saving costs and keeping circuits simple. However it is precisely this circumstance which brings the largest drawback. Typical usages for common references are motherboard circuits hosting multiple independent busses to communicate with certain IC’s[7].

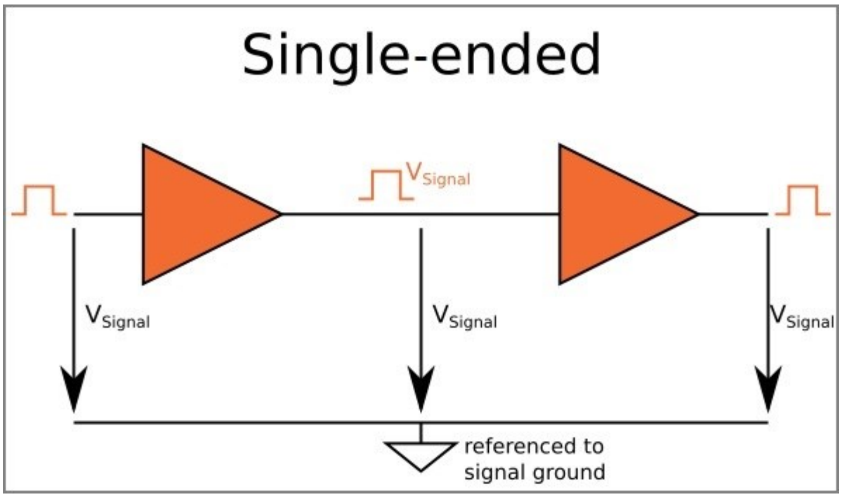

Figure 3: Single-ended signalling, Source: Pinkle (2016), online source [10.9.2017]

Advantages such as simple circuits and cost savings, as already mentioned, are countered by massive disadvantages, especially in applications with expected noisy environments. Therefore, this type of signal transmission is designed for applications in which only short distances need to be bridged, relatively low transmission frequency is used, and EMI[8] faults are very unlikely to appear.

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[6] cf. Pinkle (2016), online source [10.9.2017]

[7] IC = Integrated circuit

[8] EMI = Electromagnetic interference

2.3.2 Differential signalling

Regardless of whether it concerns analog or digital signals, the differential signalling is the technology to opt for if the application requires long transmission distances between the sender and receiver. At first glance, this technique might sound like an equivalent of unbalanced signalling, which obviously is not the case. The major difference is the reference voltage carried by the second conductor that is not fixed to the ground or any other potential. The reference signal could be considered a second signal that is identical to the main signal of opposing polarity. If the signal, as well as the reference, is transmitted through a twisted pair cable, interference is equally inducted on both wires.

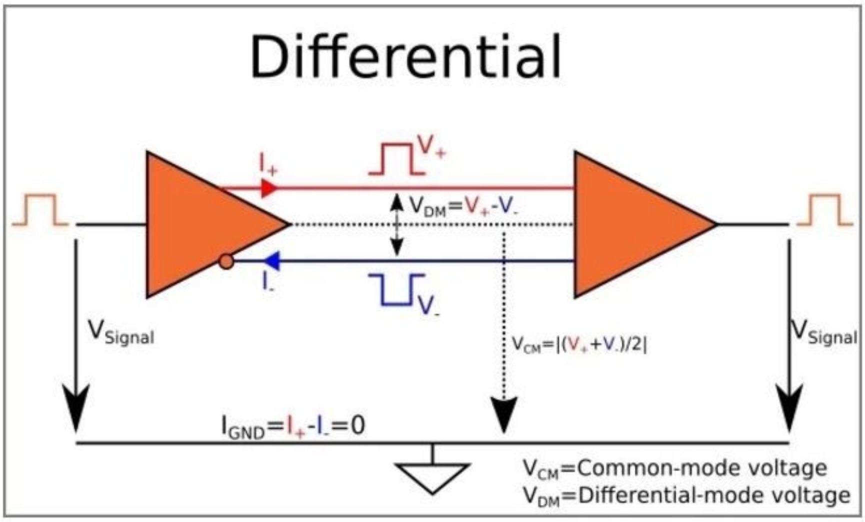

Figure 4: Differential signalling, Source: Pinkle (2016), online source [10.9.2017]

Assuming interference is induced on the transmission path, it will affect both the signal and the reference. The receiver subtracts the signal from the reference, thus calculating a useful signal again by subtracting the interference with itself on both lines. Unbalanced signals only have one wire going through the interference and are therefore not able to cancel the induced disturbances. Basically, the described transmission technique does not necessarily require a third conductor, although some applications carry one as a reference, which is usually referred to as floating. Another advantage is that not only the interference is eliminated but the signal amplitude is doubled by the substation process.[9]

$U_o = (U_i + U_n) - (-U_i + U_n) = 2\ U_i$	(2.3)	U_o/V U_i/V U_n/V	Output voltage Input voltage Interference voltage

Equation 3: Calculation of output voltage at differential signalling, Source: Sengpiel (2001), online source [1.8.2017]

It is of utmost importance to use proper cables. Otherwise, the noise induction would not be spread evenly across the conductors, and subtraction at the receiver end would not delete the disturbances correctly.

[9] cf. Sengpiel (2001), online source [1.8.2017]

Furthermore, the cable has to be terminated on both sides corresponding to the characteristic impedance of the cable. Otherwise reflexions may disturb or even eliminate the information signal.

Even though the fundamental advantage of differential signalling is a significantly better signal quality, the higher quantity of wires needed, as well as cumbersome transmitter and receiver circuits, lead to higher costs and network complexity.

As far as practical applications are concerned, especially in audio engineering and high-speed data networks, balanced signalling has become absolutely essential.

2.4 Noise and interferences

An interfering signal is the disturbance of a useful signal caused by either galvanic, inductive or capacitive coupling, or a combination of them. These different emission-coupling methods will be covered in detail.

Depending on the frequency, a further subdivision into line-conducted interference and radiated interference is made.

- Line-conducted interference: 0.1 to 30 MHz
- Radiated interference: 30 MHz and above[10]

Generally, interferences are caused by crosstalk from neighbouring wires and external electromagnetic influences. Noise and interferences worsen the useful signal quality and increase the risk of receiving a damaged or wrong telegram from the sender.

Direct coupling always appears if two or more circuits share a common impedance. For instance multiple electrical loads sharing the same supply cable or common grounds. The current of circuit I generates a voltage drop across the common impedance Z, thereby superimposing the useful signal of circuit II (see Figure 5).

[10] cf. Schwab/Kürner (2011), p. 26.

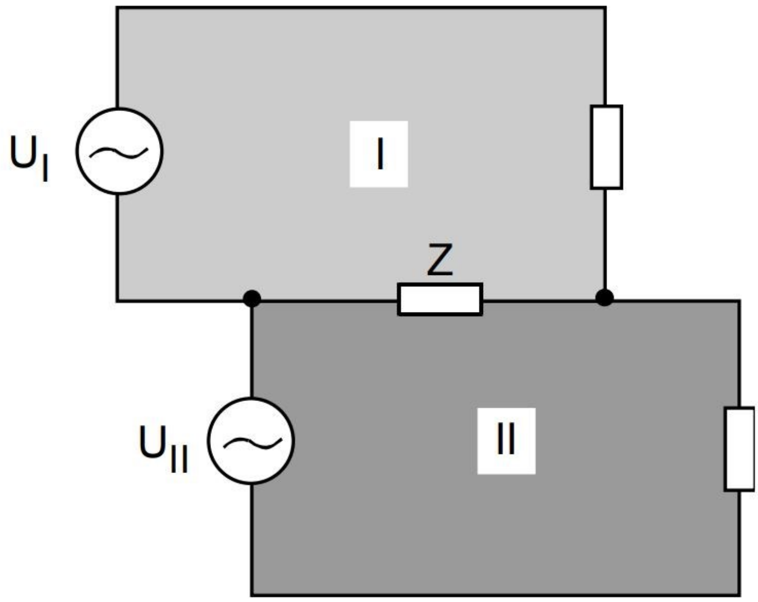

Figure 5: Example for direct coupling, Source: Schwab/Kürner (2011), p. 27.

Inductive coupling connects two individual conductor loops through the magnetic field as a result of electric current. Except using twisted pair cables, there is no real effective protection against magnetic interference, as the magnetic field penetrates nearly all kind of material and induces currents in neighbouring conductor loops. The only options are differential balanced lines and as much space between two loops as possible, since magnetic field strength decreases over distance exponentially.

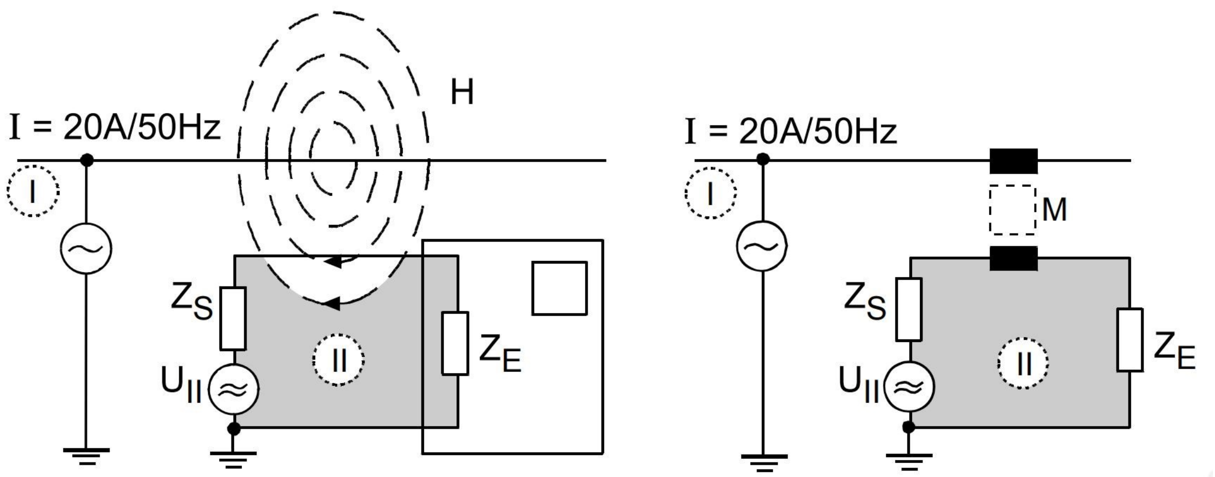

Figure 6: Example for inductive coupling, Source: Schwab/Kürner (2011), p. 28.

Capacitive coupling occurs when there are stray capacitances between a circuit and earth or ground. A different scenario would be a parasitic capacitance between two individual circuits. Due to the fact that the virtual corresponding electronic component is a capacitor, this coupling method is more relevant at higher frequencies as the impedance decreases the higher the frequency is. The figure below shows the influence of the power grid on a measurement circuit related to ground.

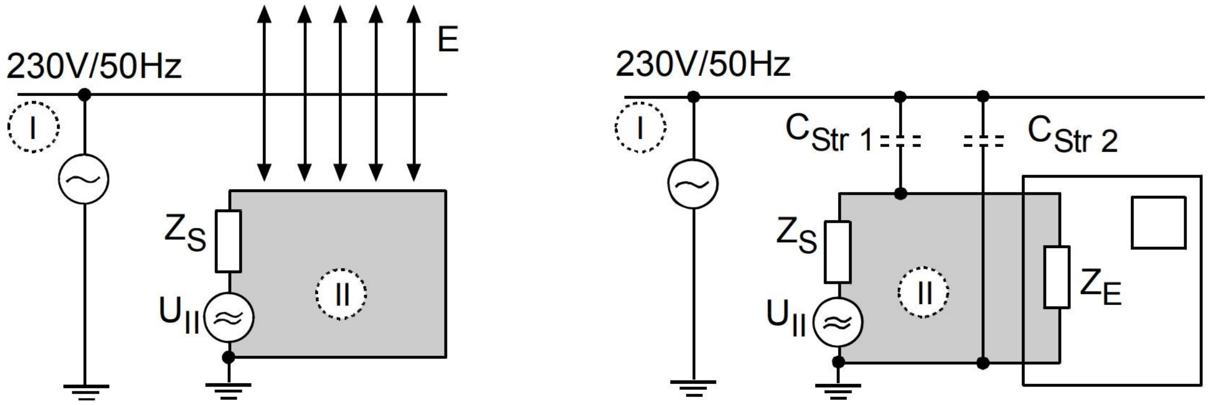

Figure 7: Example for capacitive coupling, Source: Schwab/Kürner (2011), p. 27.

Generally, there are two types of interferences as far as bus systems are concerned.

2.4.1 Differential mode interference

Magnetic stray fields of neighbouring wires or an electromagnetic polluted environment are inducing differential mode interference voltages. Such voltages generally share the same direction with the useful signal within the conductor, thus disrupting the useful signal.

Differential mode interferences affect both balanced and unbalanced circuits, whereas interference can be caused by direct or magnetic coupling. In practical applications, stray fields can have several origins within a lighting control network.[11]

These interfering signals stem from incorrect grounding, signal conversion, unbalance along the signal path or non-twisted wires in the case of differential signalling. Advantageously differential mode interferences are easier to handle as there are simple and cost-effective countermeasures, such as hardware redesign, improved cable routing or elimination of ground loops.[12]

2.4.2 Common mode interference

The common mode interferences, in contrast, are caused by parasitic stray capacitances, coupling the signal conductor to a second circuit, which very likely is a ground loop. Therefore, common mode interferences always appear between a circuit and ground, generating an interfering voltage with the same orientation on all conductors to the receiver.

Networks with large extensions will sooner or later face issues resulting from relative voltages between certain ground potentials along the network nodes. Such issues are typical indicators of a common mode interference.

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[11] cf. Schwab/Kürner (2011), p. 27.

[12] cf. ITWissen (2012), online source [20.8.2017]

Floating circuits avoid common mode interferences. However, the interference is theoretically present and even measurable between receiver and the ground. It does not influence data transmission, as no connection to the ground is given.

The theory mentioned above unfortunately only applies to lower frequencies, as stray capacitances play a more important role the higher the transmission frequency becomes. Assuming a high frequency is used for signal transmission, the stray capacitances impedance decreases significantly and enables common mode currents to flow on both the useful signal and the return signal part.

Even in floating circuits, common mode voltages can still lead to issues caused by a possible breakdown between grounded cases, housings and signals, normally causing irreversible damage to the circuit as a result.[13]

2.5 Data direction

Breaking down a telegram on a wire to its fundamentals shows that in the end it is just voltage signals travelling down the cable. This explanation might imply that there is always a direction of the electrons representing the telegram data. However, going increasingly further into the matter shows that the direction of current or voltage does not always correlate with the direction the information is intended to travel. The data direction defines the direction of information, irrespective of the electrical behaviour patterns seen on circuits.

Frequently mentioned terms in this context are “unidirectional” and “bidirectional”, meaning the information is able to either travel in one direction, i.e. from sender to receiver, or in both directions, i.e. the receiver is able to answer queries the sender requested.

2.6 Network topologies

The topology of a network defines the transportation routes of signals along the way to its intended receiver. It describes the resultant structure of all connected nodes as a whole, as well as the rules that apply to the paths between certain controllers.

A distinction is made between the physical and the logical topology:

- The physical topology describes the physical structure of a network, including wiring, placement of individual devices and connections between them.
- The logical topology defines how the network operates irrespective of its physical topology. Logical topology is the logical arrangement of nodes and connections on the physical network.

[13] cf. Schwab/Kürner (2011), p. 34.

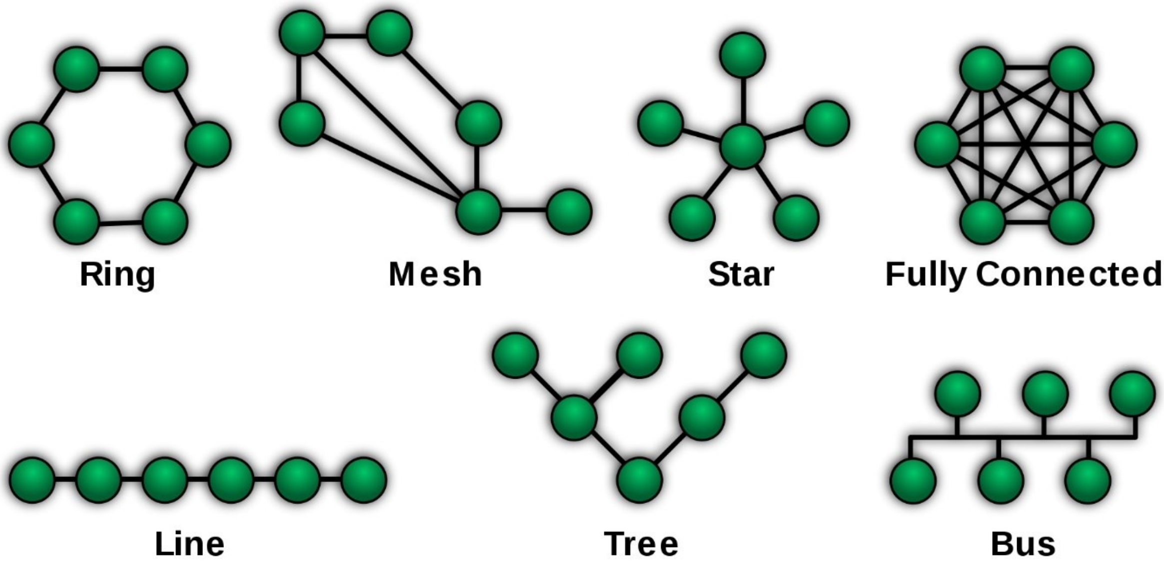

Figure 8: Network topologies, Source: kullabs.com, Website

2.6.1 Ring network

A Token-Ring is a practical example of a ring topology.[14] This topology enables data to circulate through each node within the ring. If one node has got pending data to transmit, it does so by taking the token and sending data to a certain network node participating in the ring network.

As far as office networks are concerned, the token ring as a system is nowadays considered more or less extinct. Ring topology is still commonly used in industrial contexts for high speed data transmission, in conjunction with minimum cycle time.[15]

As said above, the ring topology is generally considered a relatively fast way to communicate, as each node receives the opportunity to provide data to the data chain, which returns on a regular basis. The major disadvantage is that the entire bus becomes inoperative whenever a node stops working.

2.6.2 Star network

The star network topology is probably the most common topology when it comes to computer networks for one main reason: simplicity. It is easy to install even though each node is connected to the central concentrator separately. One would expect it to be easier to wire a bus topology, as only a single wire would have to be installed. However, if one node has to be rearranged or added, the entire network is affected and the wiring could become significantly more difficult. For both commercial and non-commercial use, the star topology in combination with twisted pair cabling is today’s standard for computer networks.

The central component to which nodes are connected can either be a hub or a switch depending on the network requirements specification. However, considering the given examples are based on Ethernet

[14] cf. Schemberg/Linten/Surendorf (2010), p. 46.

[15] cf. Schemberg/Linten/Surendorf (2010), p. 46.

networks it has to be mentioned, that there are various kinds of concentrators always depending on the technology used.

In the event of a node or line failure, there is no influence on the rest of the network. However, should the central hub fail, the entire network stops operating.

2.6.3 Bus network

The central connection cable and each node are connected via a short stub line, as the central cables basically connect the nodes with each other.

The first appearance of Ethernet, a widely used network specification, was in bus topology. Interestingly, one of its essential characteristics is the decentralization of the complete network, which started to play an increasingly important role when it comes to failure safety.[16]

Each node connected to the network receives the same information simultaneously with the other nodes. If lighting control networks are used in real-world settings, it is important to terminate both ends of the cables in order to avoid reflexions of the useful signal.
The absence of a central component managing the actions on the bus leads to the need for a protocol that ensures a proper handling of signals in the network. Master-slave networks are generally not affected by collisions[17]. However, multi-master systems require a method to give access to the network to all devices in order to avoid two nodes accidentally sending information at the same time.[18]

As each node receives each telegram, there is always an address contained in data packages. The intended recipient recognizes its address and processes the data, otherwise the telegram would be ignored, as there would be no need for the respective data inside.

2.6.4 Tree network

A tree topology usually consists of several individual star networks, which is why they are commonly used in large-scale networks, especially if individual networks of different topologies get interconnected.

2.6.5 Mesh network

The mesh topology represents the perfect redundant network, which is not a subject to any restrictions as far as interconnection of certain nodes is concerned. In its practical use, the origin of mash networks is generally an uncontrolled growth of an existing network resulting in a quite chaotic structure. One of the best examples for a mixed topology is the most fundamental network itself: the Internet. Contrary to appearances, the Internet is based on a well-conceived structure where a countless number of devices form the Internet into one massive network which contains all possible combinations of topology.

[16] cf. Schnabel (2017), online source [1.8.2017]

[17] collision = occurs if multiple nodes within a network simultaneously send data on a shared media

[18] cf. Schemberg/Linten/Surendorf (2010), p. 45.

A special case of mesh networks is the full-mesh network. It is in principle identical with the partial mash, except for each node being connected to all other nodes apart from partially connections.

One positive aspect of a full-mesh topology is that, as long as it only contains full function devices, it is completely fail-safe, meaning if a device or a connection fails, there is no impact on the remaining structure.[19]

2.6.6 Advantages and disadvantages of topologies

The following table summarizes the previous subsections by showing the most important advantages and disadvantages of each basic topology. Combinations of different topologies, however, simply share their properties, e.g. the tree combines the benefits and drawbacks of star and bus topologies.

Topology	Advantage	Disadvantage
Ring	Large network extension possible	Network outage if one node fails High wiring effort
Star	Simple structure Easily expandable	High wiring effort Network outage if central hub fails
Bus	Easy installation Low wiring effort at commissioning	Limited network extension Network outage if cable fails
Mesh	Unlimited network extension High failure safety	High administration effort Expensive wiring

Table 1: Advantages and disadvantages of basic topologies, Source: Elektronik Kompendium, Website

[19] cf. Schnabel (2017), online source [1.8.2017]

3 PRINCIPLES OF WIRELESS TRANSMISSION TECHNOLOGY

3.1 Transmission power

One of the most important influencing factors linked to wireless signal transmission is transmission power. It limits the maximum range of a device and gains more range as the transmission power is increased under stable conditions[20]. Therefore, in theory, the transmission power should be implemented as high as possible to ensure that the signal always reaches the receiver.

Contrary to the theoretical aims, limitations of practical applications force developers to limit the transmission power, as there are reasons such as costs, legal restrictions and circuit size limitations. In a practical scenario, transmission power is as low as possible and as high as absolutely necessary in order to establish a stable connection. On the one hand, it saves energy, on the other hand it reduces signal disturbances on other wireless systems caused by interferences. In short, the transmission power should be held as low as possible to ensure a stable connection between devices.

3.2 Signal dispersion and carrier frequency

Signal dispersion describes how electromagnetic waves spread. Depending on the applications for signal dispersion, there are several requirements to be met. Basically, there are two different uses nearly every real-world wireless network application can be assigned to.

- Long-range signal transmission
- Comprehensive coverage

Satellite TV is a descriptive example for long range transmission, as the respective satellites are in a geostationary orbit, which means that there is about 35,786 km to be bridged. An alternative to this is the cellular network, which aims to cover even the smallest town thereby limiting the range. Lighting networks generally focus on the second kind of application due to the higher amount of nodes within the network, which is equipped with routing functionality to extend the covered area by each participant.[21]

[20] cf. Krauße/Konrad (2014), p. 13.

[21] cf. Rembold (2017)

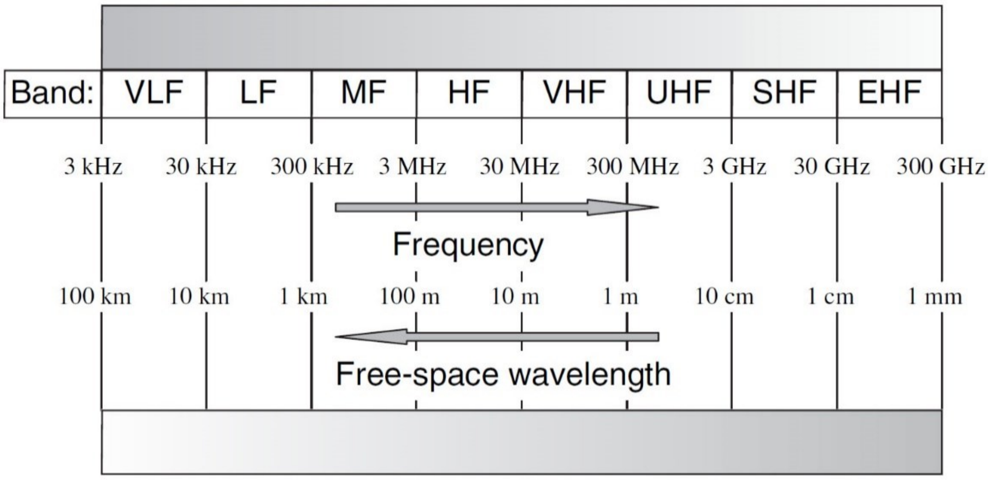

Figure 9: Relevant frequencies and their respective wavelengths, Source: Rembold (2017)

Wireless communication is subject to several influences that, in contrast, do not affect wired networks, where noise and interferences are generally of minor importance.

Electromagnetic waves are interacting with the environment, which combine the objects and the media in which they travel.[22] Depending on used technology and environmental impacts, certain influences on the signal are better or worse.

3.2.1 Wave behaviour

Electromagnetic waves behave similarly across the frequency spectrum. Interaction with an obstacle forces a wave to react in a certain way. Depending on the specific case, the effective reaction will differ, but will always conform to one of the following behaviour patterns:

[22] cf. Poole (2017), online source [27.10.2017]

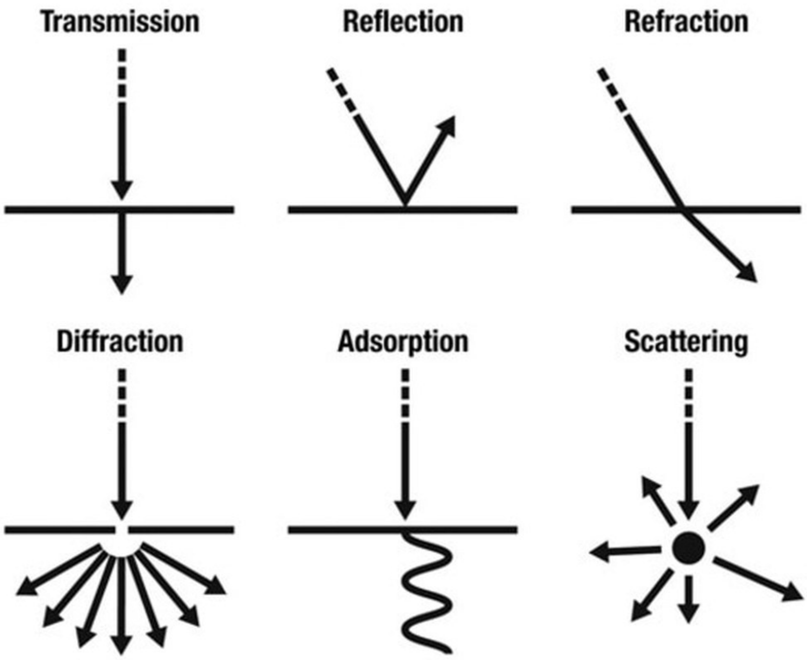

Figure 10: Wave behaviours, Source: NASA, Website

- Absorption

  When a wave hits a dielectric object, it is not able to penetrate it and therefore it gets damped; this is called absorption. It is the most important influence on a wave.

- Reflection

  If a wave does not get absorbed by a dielectric object, which is the case if the obstacles dimensions are far larger than the wavelength, it will be reflected. Thereby the wave power will be reduced but at the same time it will, depending on the surface structure, find a way into areas it would not reach in a direct line.[23]

  The angle of incidence when a wave hits a surface automatically defines the angle of reflection. Reflection always appears with absorption, as the wave loses power by its reflection. It serves as a very important effect in the lighting industry, such as with metal housings that only have small openings for the wave to leave the luminaire.

- Diffraction

  The diffraction effect on electromagnetic waves describes the fact that waves encountering an object tend to travel around it. The phenomenon that a receiver receives a signal, despite an obstacle within the direct line of sight to the transmitter, can be explained by diffraction.

  Huygens's principle stipulates that each point on a wave front can be considered a source of a secondary wave front. One, of course, has to consider that there is a shadowed area directly behind an obstacle, but referring to the mentioned principle, this space is rather small.

[23] cf. Krauße/Konrad (2014), p. 8.

Another phenomenon associated with diffraction shows that waves of lower frequencies tend to diffract significantly more than those of higher frequencies.

- Refraction

As electromagnetic waves encounter a transition line between two transmission media of different indexes of refraction, incidence angle and outgoing angle differ, which is referred to as refraction.

$n_2 * \sin\theta_2 = n_2 * \sin\theta_2$	(3.1)	$n_1/1$	Refractive index of medium 1
		θ_1/rad	Incidence angle
		$n_2/1$	Refractive index of medium 2
		θ_2/rad	Refraction angle

Equation 4: Snell's Law also known as law of refraction

- Transmission

When a wave reaches the end of a medium and continues into the next medium, transmission happens. The theory of transmission and its logical implication can be summed up under the term boundary behaviour. The velocity of a wave changes as it encounters a medium where the index of refraction differs. The energy conservation stipulates that the energy of the wave before and after encountering the interface has to be equal. However, since the velocity changes, this is impossible. Therefore, within the interface, the power has to be divided into one part of the wave that continues in the same direction or with a different angle and the second part which is reflected, however at a different velocity. The reflected wave has the exact difference of power.[24]

In sum, transmission can be stated as a special case of reflection and diffraction.

3.3 Antennas

To ensure a comprehensive coverage, antennas are of non-directional or sectoral character, thus radiation power mainly gets distributed across two axes, which limits the maximum antenna gain. Therefore, the concentration of radiation power remains, as it is the only possibility to increase gains of non-directional antennas. If there are mobile nodes, the gain decreases due to the fact that mobile nodes do not have a fixed position in space and directional antennas within these devices cannot be used.

Wireless lighting networks generally operate within strict guidelines to design. Low frequencies would require large antennas, which would no longer enable design-orientated luminaire designs.

3.4 Theoretical ranges

The Danish-American radio engineer Harald Trap Friis investigated the propagation characteristics of high-frequency electromagnetic signals. In 1946, he developed the following formula to create a context between

[24] cf. Poole (2017), online source [27.10.2017]

transmission power, reception power, damping, and system constants. The following equation is furthermore handling the path loss coefficient, which differs by environmental influences. Such influences, just to name a view, are typically terrain conditions, construction of buildings and air quality (temperature, atmospheric pressure, humidity and gas composition) transmission either with or without obstacles within the direct transmission line.[25]

$P_R = \frac{P_T * g_T * g_R * \lambda^2}{(4 * \pi * D)^n}$	(3.2)	P_R/W P_T/W $g_T/1$ $g_R/1$ λ/m D/m $n/1$	Transmission power Reception power Transmitter antenna gain Receiver antenna gain Wavelength Distance Path loss coefficient

Equation 5: Friis transmission equation

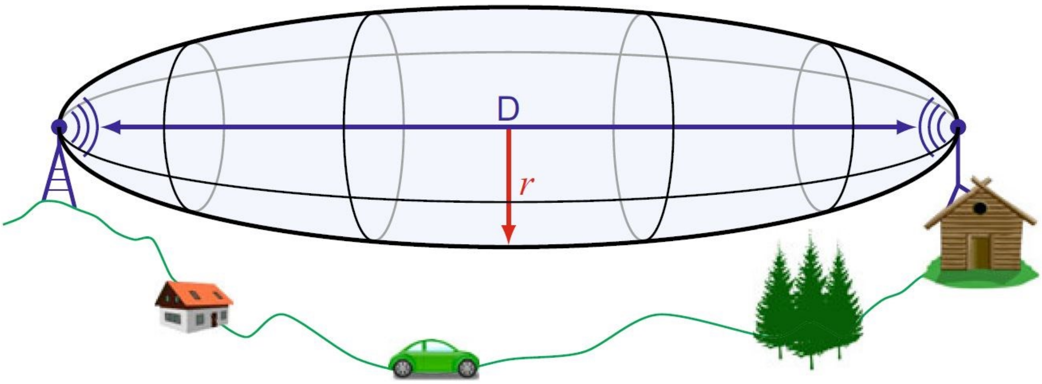

Figure 11: Fresnel zone, Source: Krauße/Konrad (2014), p. 9.

The Fresnel zone is named after the French engineer Augustine Jean Fresnel, who investigated the behaviour of light waves. It describes the space where the major proportion of energy is distributed, while its boundaries are set by the maximum of a half wavelength of path difference. The dimensions of this spheroid are given by the distance D between transmitter and receiver and the signals wavelength. The half-axis r is calculated as follows:

$r = 0.5 * \sqrt{\lambda * D}$	(3.3)	r/m λ/m D/m	Radius of Fresnel zone Wavelength Distance

[25] cf. Krauße/Konrad (2014), p. 9.

Equation 6: Fresnel zone radius calculation required to determine the most relevant space for wave propagation

Referring to equation 5, if $n = 2$ the term $(4 * \pi * D)^n$ describes a propagating radio wave with a constant power $P_T = const.$ over an unobstructed distance D within the so-called Fresnel zone between transmitter and receiver. This Fresnel zone is, as the upper figure (Figure 11) shows, formed by a virtual spheroid, whose ends are represented by antennas. The direct line between the antennas and furthermore the space around it is of special interest for electromagnetic waves, as obstacles within this spheroid would lead to disturbances of the signal propagation. Obstacles within the Fresnel zone are causing reflections, which in turn lead to a lower reception power arriving at the receiver antenna.[26]

[26] cf. Krauße/Konrad (2014), p. 9.

4 ISO/OSI REFERENCE MODEL

The basis for each network is the ISO[27] standardised OSI[28] reference model. This model represents the organisation of all network protocols in various layers. Enabling communication through diverse technical systems is its most important purpose, it serves as an international standard since the early 80's. It requires clearly defined interfaces between all layers and protocols and therefore allows a simple exchange of existing protocols without the need of changing the neighbouring directly affected interfaces.

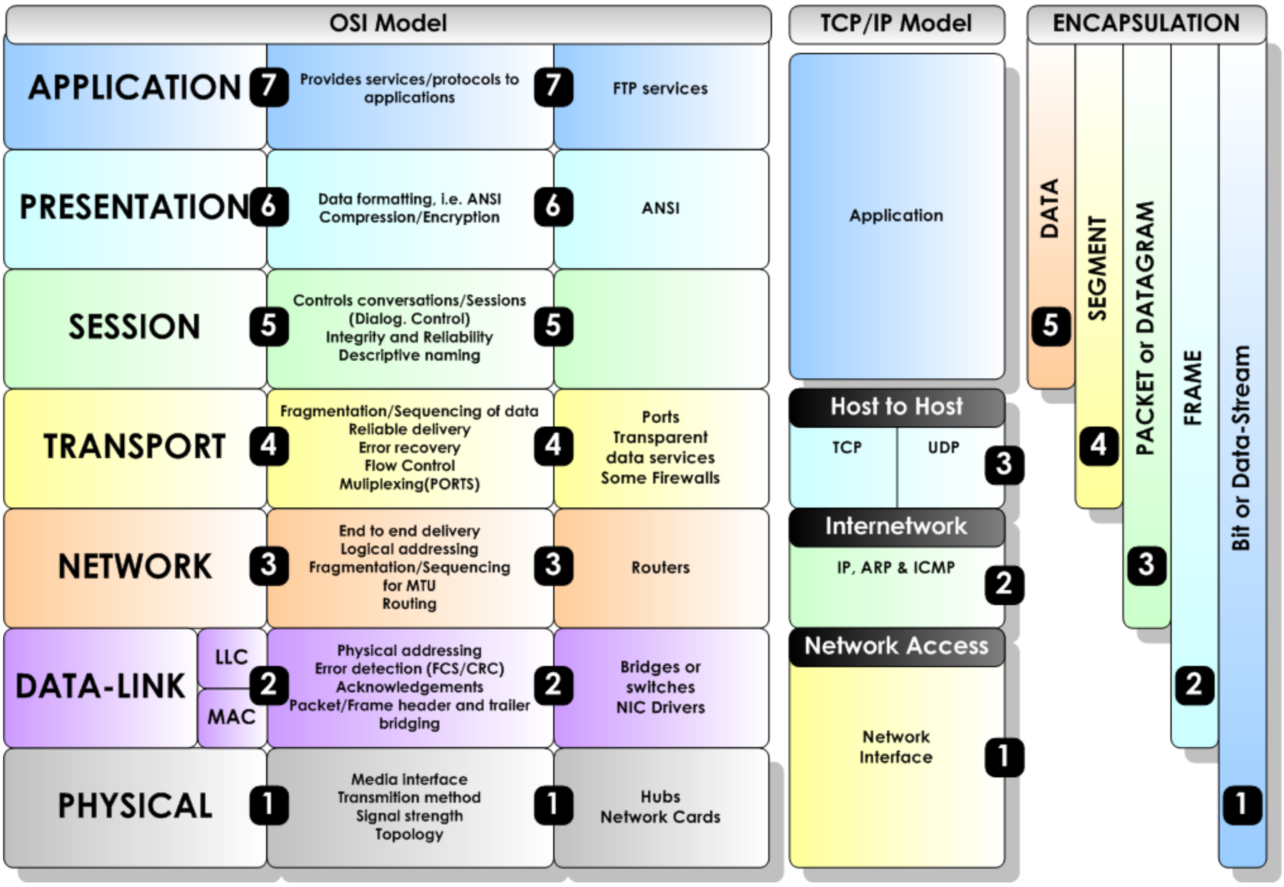

Figure 12: ISO/OSI reference model, Source: programmershelp404.blogspot.co.at

4.1 Layer architecture

The layer architecture has significant advantages if the used protocols are standard to the OSI model, as the following parts are well-defined.

- Services define what the respective layers do.
- Interfaces enable access to the layers above and below.

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[27] ISO = International standard organisation

[28] OSI = Open system interconnection

4.1.1 Physical layer

The physical layer is responsible for the bit transmission and all conditions linked to it. The PHY[29] layer describes the framework for a compatible data transmission. Its definition starts with the used medium such as light, air or copper wire, and ends with the admissible topologies the network may have. Everything in-between e.g. voltages, frequencies, bitrates or pinout also has to comply with the PHY layer.

Common devices of this layer are repeaters and hubs or media-converters, as such equipment only amplifies the original signal and leaves other parameters untouched.

4.1.2 Data link layer

The data link layer ensures that a data frame is transmitted from one end of a link to the other. This layer provides defined frames for data transmission to supply the physical layer with bit sequences and offer grouped data to the next higher layer. As the tasks of this layer cover an area which allows a further division it is subdivided into:[30]

- MAC[31]

  The MAC sub-layer is the lower one in layer two, thereby directly connected to physical layer. It receives special attention as it specifies the physical and in theory unique MAC address. Although access control procedures are a part of the MAC layer, this topic will be discussed in the next chapter, as it would go beyond the scope of the OSI reference model.

- LLC[32]

  The second part of the data link layer, which is closer to the third layer, is responsible for higher task such as flow control and error detection.

4.1.3 Network layer

The network layer deals with transmission of datagrams, which corresponds to a unit of information within the network layer. It is responsible for the path-finding process within a collection of connected nodes, referred to as routing. Routing can either be static, which follows a predefined way for each connection or dynamic meaning that paths are calculated according to special criteria, i.e. fastest path, safest path, cheapest path or whichever criteria is conceivable.

Routing describes the usage of certain algorithms to connect networks.

Services based on connections are either connection-oriented or connectionless:

[29] PHY = physical layer

[30] cf. PH Heidelberg (2017), online source [29.11.2017]

[31] MAC = media access control

[32] LLC = logical link control

- Connection-orientated services occupy a complete channel during communication. A real-life example for a typical connection orientated service is the analog telephone, as the route will be established during calling and will not be changed until the conversation ends.
- Connectionless services are based on the assumption that data consists of discontinuous bit streams.

Flow control enables the network layer to control the network load.

Error correction as already mentioned in layer two is also part of the network layer even if in this case the aim is a different one. Error correction in this context does not regard transmission errors in layers one and two, rather it is related to errors which appear on a virtual connection such as detection and elimination of duplicates, avoidance of circling datagrams or restoring the correct datagram order.

4.1.4 Transport layer

In accordance with the protocol, the transport layer delivers services which cover connection establishment and transmission rate. Depending on the services of the network layer, fault monitoring and error correction get shifted into the transport layer's field of duty.

The main focus of this layer is on functional implementations of data sequence transmission from a source to the destination, where it is not bound to a single physical network as the lower network layer manages correct routing. The upper mentioned quality of service is established by data flow control, fault monitoring and certain protocols which belong to the transport layer such as TCP. For example the TCP enables acknowledgements for successfully transmitted data sequences. Such acknowledgements combined with a proper error correction allow an error-free transmission of sensible data sequences. In cases of lower data consistence priorities, acknowledgements and error detection or correction would make no sense, as it adds latency to the connection. A solution to bypass such latencies is UDP.

4.1.5 Session layer

The fifth layer controls the logical connection between two systems and enables communication between distant processes. Organisation, synchronisation and re-establishing of lost connections are part of the session layer. To re-establish a lost connection as fast as possible and without the need to send the entire dataset, the session layer introduces synchronisation points where a new transport connection can resume. The connection establishment is a service providing acknowledgements for parameter exchange between two nodes. After both received the partner's parameters a defined session status is established.

During data transmission it would not be useful to wait for acknowledgements for each block until sending the next block, therefore the session layer handles this situation with the help of synchronisation points.

Both nodes are allowed to end the session, which can either happen by sending the last block of a session leading to a synchronised end or a simple interrupt without a synchronised end.

4.1.6 Presentation layer

As there are a countless number of different systems connected to each other via a network, an instance that manages the correct preparation of data to be presented in the correct order is required. The presentation layer enables data presentation of completely different systems with the help of its standardised mapping mechanism. The application layer (the highest layer) sends data to the presentation layer, which prepares it for transmission. However, this could include demanding processes such as data compression or cryptography[33]. In a nutshell, this layer receives information from a distant presentation layer and prepares it for the application layer.

4.1.7 Application layer

The application layer is the main interface to a program which requests information exchange and user interaction, it therefore offers functionality required to exchange data with the lower layers. The program itself and moreover the input and output of data belongs to the application layer. In this context the focus in on applications which require network access for interaction, for instance a Server-Client application.[34]

Common protocols of the seventh layer are HTTP[35] or OBEX[36] which widely represent a standard for spontaneous data exchange of two nodes.

4.2 Channel access procedures

Channel access procedures represent algorithms or laws which control the access of each node to a communication channel. These procedures are part of the second OSI layer; the data link layer. The following procedures are common for wired and wireless applications.

4.2.1 CSMA/CD

CSMA/CD[37] is tailored for wired communication as it is only able to detect collisions instead of avoiding such. The transmitter station starts to sense the current state of the communication channel prior to sending. Only if the channel is vacant, the sender starts the transmission. Otherwise a currently ongoing transmission would get disturbed by a second sender.

Although the sender listens before starting to send, collisions are still possible as two stations could sense the channel at the exact same time and both will logically expect a free channel. This will lead to the circumstance that both stations will start a transmission, without breaking a rule or acting against the algorithm. The result is a collision that destroys the data within the intersecting areas of the two senders and no receiver within this area will get any valid data.

Consequently, the collision has to be immediately recognized to dissolve it. This might raise the question how probable it is that a collision caused by two stations occurs although the signals travel with the speed of light. The answer is as obvious as it is simple: absolutely unlikely. However, if it does occur the following

[33] cf. Zisler (2012), p. 25.

[34] cf. Zisler (2012), p. 25.

[35] HTTP = hypertext transfer protocol

[36] OBEX = object exchange protocol

[37] CSMA/CD = carrier sense multiple access with collision detection

collision will block the channel for a relatively long time while other stations will wait until it is free again. Applying logic to such a case tells us that the longer a collision lasts the more stations will wait with their set of data to start transmitting. At the same instance the channel is free again, each pending node will start to send simultaneously again which leads to the next collision.[38]

This case demonstrates that another rule needs to be added. In protocols like Ethernet this scenario got solved in an elegant and easy way: After a collision, all pending nodes are assigned a random timeframe to wait until they start sending again [39].
Another approach to solve this problem would require dominant and recessive levels, which automatically makes the sender with the most dominant packet the winner of the race. The dominant sender will not even recognize that other nodes started to send, too, due to their recessive behaviour.

CAN is an example which makes use of dominant and recessive levels combined with arbitration in order to create object identifiers of different priorities. In other words the most important message are assigned to the most dominant signals, while all messages of lower priority are forced to run the loop repeatedly until no message of higher priority is pending anymore. One possible approach to build such a dominant and recessive network requires an open collector driver. In open collector circuits the low level is always dominant.

Both mentioned techniques require a listening-while-sending interface, otherwise CSMA/CD cannot be realised.

4.2.2 CSMA/CA

The enhanced solution of collision detection, which was already described in the previous chapter, is to avoid the collision instead of simply detecting it. CSMA/CA[40] is especially designed for wireless communication as the conditions are completely different.

The channel sensing is the same as in CSMA/CD. However, wireless systems offer additional potential problems such as nodes that are temporarily unreachable due to an obstacle, or a third node entering the scenario which is only reachable though one other node. Even if the third node is already sending, all other nodes will not recognise it as they are out of range and the station in the middle receives a collision.

Wireless systems bring another disadvantage into the scenario, as it is almost impossible for a station to simultaneously listen and send to the same channel. A collision detection therefore cannot be implemented and a different solution has to be found.

Therefore CSMA/CA always uses the procedure to wait for a timeframe of random length before starting to send. In detail, the station checks the channel, waits for the random time and checks the channel again. Only if the channel is free again it starts to send. This condition helps to avoid collisions.

[38] cf. Gessler/Krause (2015), p. 70.

[39] Also known as the Aloha principle

[40] CSMA/CA = carrier sense multiple access with collision avoidance

5 ESTABLISHED WIRED LIGHTING NETWORKS

5.1 DMX

DMX was first standardised in 1990, since then it has become an important part of stage equipment without which intelligent lighting would be inconceivable. Although there already is a potential successor which uses Ethernet networks, DMX still is the system of choice for most stage lighting applications due to its stability and reliability.

Until the early 1990s, professional stage lighting applications required analog 0-10 V signals to control dimmable lights in theatres or concert halls, which had two fundamental drawbacks. First, the signal is not only an analog one, but also a voltage signal which can easily be disturbed by environmental influences such as the 230 V mains supply of other parts belonging to stage lighting. The second and even more important disadvantage is the cable. Multicore cables were used to connect as many lights as possible to the controller, as each individual light required a separate wire. Therefore a modern DMX setup with up to 512 possible addresses would require a cable with at least 513 leads; unthinkable these days. The effort for cabling was tremendous and increased with each fixture. The late 80s brought moving heads into the game, which required at least four to five addresses at once, thus leading to ambitions to development a digital, addressable system. The result was a USITT[41] standard named digital multiplex enabling stage builders to utilise 512 channels with normal three lead microphone cables.

The addressing is generally done by hand and enables the user to define the start address of each node. If a node requires more than one address, such as moving heads or RGB luminaires, the fixture simply utilises the channel following the start address, until all functions are accessible. Each channel has a resolution of 256 steps. Theoretically, this enables a standard RGB luminaire to mix more than 16 M different colours.

5.1.1 Installation

Installation is easy by design and obviously focused on portable systems, as connectors and their pinout is defined in the standard DIN 56930-2. There are two permitted connectors for DMX systems: XLR and RJ-45. Over the many years DMX already dominates the market, the XLR connector was established as the more common one. The connectors are crimped onto the cables which have to comply with certain conditions. The characteristic impedance of the cable has to be at 120 Ω and it has to be a twisted pair cable with additional shielding in order to enhance the robustness against electrical inferences.

During installation, it must be ensured that a consistent bus topology of the entire DMX system is established, meaning that each device has to be connected right after one other. For this reason all DMX devices are equipped with a separate input and output. The topology can be extended with the help of splitters which generally serve as signal amplifiers with multiple outputs. Should the application require it, also a tree topology is possible with these devices. To additionally limit applications in physical dimensions, the DMX is limited to a cable length of 1,200 m.

[41] USITT = United States Institute for Theatre Technology

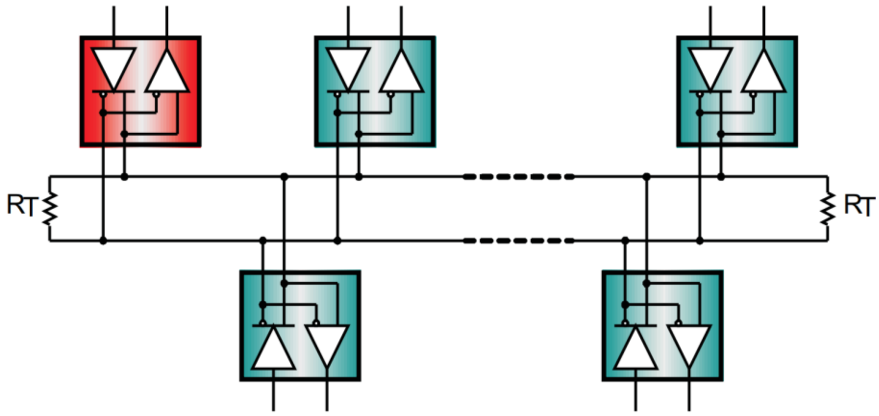

Figure 13: DMX network schematic with a master device in red and four slave nodes in green, Source: TI RS-485 Design Guide

As DMX complies with the low layer standard RS-485, an uncountable number of useful guidelines are available to ensure a perfect installation according to all conditions.

5.1.2 Electrical specification

Bitrate	250 kbit/s
Modulation	Amplitude modulated voltage
Signal level	±1.5 V up to ±5 V
Signal transmission method	Symmetric
Protections (short term)	Short-circuit
Data direction	Unidirectional
Frame structure	8N2 = 8 databits, no parity, 2 stopbits
Maximum cable length	up to 1200 m
Signal coding	none

Table 2: Basic facts about DMX, Source: own illustration

5.1.2.1 RS 485

DMX is based on the electrical specification of RS-485, which only defines the electrical characteristic but no mechanical or functional aspects. However, the specification describes the electrical requirements and limitations to build a balanced multipoint transmission line.

The RS-485 is designed to enable long-range high-speed data transmissions, which receive special attention in industrial automation technology. It is designed to enable a bidirectional connection of up to 32 nodes. However, there are already special interfaces allowing up to 128 nodes as their bus-load is only a fraction of a regular RS-485 node.

The fact that all present devices on a bus line are simultaneously receivers and transmitters requires a protocol that ensures that only one device serves as sender and the remaining devices function as high-impedance receivers, otherwise a collision occurs. The mentioned protocol is absolutely essential but is not part of the specification. The RS-485 only defines the electrical specification for differential receivers and transmitters in digital bus systems. The ISO-8482, on the other hand, also describes the network topologies and the maximum cable length.

5.1.3 Protocol

The DMX Protocol basically describes a unidirectional daisy chain system with only one master device allowed. Up to 512 slave nodes can be connected, which frequently receive their values through the daisy chain. As there are 8 bit representing the value for one node, the resolution is at 256 steps, which often fits the specifications but sometimes need an upgrade by utilising two addresses for one device function. Addressing 512 devices with an 8 bit resolution exactly takes 22.67 ms including protocol overhead such as break, startbits, stopbits and the startcode.

Compared to the other main digital lighting system DALI, the DMX protocol has one major drawback: the addressing. According to the DMX specification, addressing needs to be done by hand, which ultimately led to the invention of RDM.

5.1.3.1 RDM

The unidirectional DMX standard received an enhancement by RDM enabling status queries, monitoring and remote addressing. RDM utilises the same pins of the XLR connectors, but switches the system into a half-duplex mode without disturbing the normal operation. The first bit of each DMX frame, the startcode, tells each node how to deal with the frame. Only if the startcode is 0, the slave nodes will accept it.

RDM uses different startcodes to enable a bidirectional connection with no influence on the light output. The automatic addressing speeds up the setup by an enormous rate, as all devices can be easily mapped from the mixer. The communication before each node receives its start address requires a 6 byte UID[42] to differ between each device. The first two bytes of the UID define the manufacturer which leaves the four remaining bytes to be defined by the manufacturer.

The fact that RDM is downwards compatible to the DMX512 standard enables a mixed setup of DMX and RDM ready devices. However, care must be taken with splitters, amplifiers, and isolators, as normal DMX devices only support one data direction. The RDM backward frames need bidirectional electronics within the above mentioned devices, otherwise an RDM node would send back answers which splitters would block on their way back to the master device.

5.1.4 Common issues

The longer a system leads the market, the more additional requirements will appear and also bugs will be found by users. The same applies to DMX over the past 20 years.

A general problem with lighting systems is the multi-master concept, which allows multiple devices to send control commands. In such cases it is essential to ensure data consistency throughout all masters, as, if it

[42] UID = unique identifier

fails, wrong reactions of the nodes would be the result. DMX does not implement multi-master functionality by design, as there is generally only one control device in the context of stage lighting.

Another common issue was already mentioned in the chapter regarding RDM. Each RDM device needs an entirely RMD-ready path back to the controller, otherwise the controller is unable to identify it.

DMX as a complete lighting system, will presumably be partly replaced by Ethernet due to its higher speed and its given compatibility with standard Ethernet switches and computers. However, DMX will definitely not disappear over the next years, as it is cheaper and less much cable-demanding. Currently there are lots of different media converters to extend DMX systems with the help of Ethernet. In such systems, the Ethernet part builds the basis, including control nodes, with the last path from splitters to the lights still done by DMX. This leads to the problem that the original signals have to be converted several times which brings latencies with it. Especially fast bus systems such as DMX generally do not allow conversions into protocols without a connection-orientated structure, as time frames reserved for responses could be missed. These circumstances forced a limitation of splitters and media converters connected in series.

Another very common case is faulty bus termination. Once a DMX system is up and running, little attention is paid to correct bus termination, which is a huge mistake. If the installation is working barely on its limit, the slightest change in its parameters due to environmental factors can cause an immediate halt. For example, a changed cable routing or an additional power cable on the same track could generate enough interference to destroy the signal. Generally it can be noted that correct bus termination with a resistance value equal to the characteristic impedance of the cable is more important as the cable length increases.

6 WIRELESS NETWORKS

Since prehistoric times humans have tried to extend the range of their natural communication organ. Therefore a variety of different technologies has evolved with the purpose to support humans in communication over long distances. As electric current was not yet invented and people only had their given possibilities, only two sorts of signals were available in bygone history:[43]

- Optical signals
    - Smoke signals
    - Show of arms
    - Fire signals
    - Reflected sunlight
- Acoustical signals
    - Sounds created with the help of simple instruments
    - Singing
    - Yodelling

When communication extends up to a distance beyond the human abilities to hear or see, then it is called telecommunication, no matter whether it is established by material media like a letter or by immaterial signals such as electrical signals. As air has a rather limited range for sound waves, data has to be transformed into a physical signal which allows a transmission over the selected media.

An example of such a transformation is the modulation of a carrier signal, which is represented by a high frequent electromagnetic wave. Due to the fact that electromagnetic waves are very diverse, they can be either visible in form of visible light, invisible like it is the case with IR[44] or UV[45] radiation, or they can also be very health-damaging e.g. gamma radiation. Visible light and electrical signals can either be transmitted through wires or wireless.

As each different level of communication has to comply with the neighbouring one, the early pioneers of telecommunication decided to build a model which describes each level. The lowest level is the physical layer which ensures a proper physical connection between the participants.

The purpose of a sender and a receiver is to convert data back and forth to enable data transmission in a defined way, which requires a defined standard for each level and node to comply with. The human communication pendant is the language, as each participant of a conversation has to speak the same language.

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[43] cf. Gessler/Krause (2015), p. 9.

[44] IR = infrared

[45] UV = ultraviolet

The technical standard describing and categorising the manifold layers is the ISO/OSI reference model.

6.1 Network technologies

The enormous supply of different wireless systems on the market created an uncontrolled growth of standardised as well as proprietary solutions. When focusing on powerful lighting networks, the list can be shortened dramatically but still leaves far too many possibilities. As it is almost impossible to cover all wireless lighting network technologies on the market, filters are applied to figure out which solutions are the most promising ones.

The first filter is the standardisation or, in other words, the community behind it. This thesis will only deal with ideas which already receive support from huge companies or are at least well defined in official international standards.

The next possibility to restrict the selection is the module or product size. To find solutions which fit into a luminaire, it is fundamental to miniaturise circuit boards and housings to the smallest possible form factor. This filter already allows to define a tiny part of physical specification, as higher carrier frequencies lead to smaller antennas. Therefore another restriction is a carrier frequency higher of at least 700 MHz to ensure relatively small antennas.

The following systems are a strict selection fulfilling the filter conditions mentioned above.

6.1.1 ZigBee

ZigBee is a specification for wireless networks with a relatively low amount of data and small to middle distances which the implemented profiles underline. Home automation, light link, building automation, or health care are just a few examples out of the wide range ZigBee covers. The 2002 established ZigBee-Alliance published the first version of the ZigBee specification in 2004 and pushed its development forward. The current version 3.0 is a further development which handles certain security improvements and brought a detailed specification for the application layer. The ZigBee Alliance latest release, besides ZigBee 3.0, is dotdot, which was presented at CES Las Vegas in 2017. Dotdot focuses on media conversion as ZigBee faces increasing pressure on the market from the big players in consumer electronics e.g. Apple's Homekit. Whereas Homekit is bound to Apple end devices and their communication limited to WLAN and Bluetooth, dotdot focuses on combining different wireless networks, including ZigBee.

There are numerous application examples, for instance health monitoring systems, retail supporting systems or building automation. However, this chapter will mainly focus on the aspects of lighting control systems.

Figure 14: Official ZigBee compliance symbol, Source: zigbee.org

6.1.1.1 Framework

The ZigBee framework specifies a wireless network according to IEEE-802.15.4 and adds certain functionalities such as routing and safe key exchange. Due to the fact that IEEE-802.15.4 is limited to the first two layers of the OSI model, ZigBee specifies the missing upper layers up until the application layer, in fact IEEE-802.15.4 only defines the NWK46 and APL47 layer and skips the in-between. This approach allows to embed an application into the frameworks APL layer.

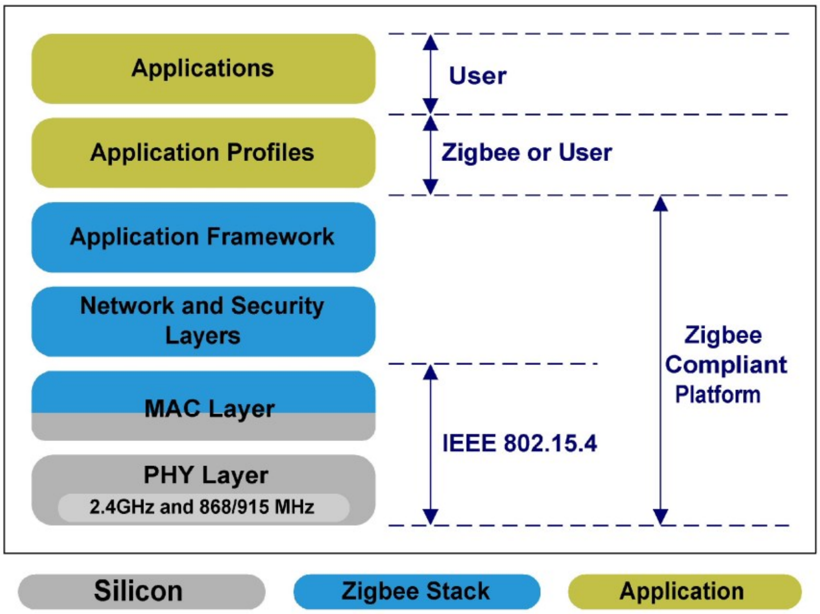

Figure 15: ZigBee OSI layer distribution, Source: m.eet.com

6.1.1.2 IEEE-802.15.4

This standard specifies a transmission protocol for the PHY and MAC layer of WPAN[48], whereas upper layers which enable routing and applications are defined by other specifications e.g. ZigBee.

The main development focus is on minimized power consumption to allow a battery powered device to last for years, low cost hardware, secure data transmission and utilisation of the license-free ISM[49] band. The utilisation for the 2.4 GHz ISM band automatically forces the standard to work on the same band as Bluetooth and WLAN, which requires special attention during development.[50]

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[46] NWK = network layer

[47] APL = application layer

[48] Wireless personal area network

[49] ISM = industrial scientific and medical band

[50] cf. Schnabel (2017), online source [1.8.2017]

These properties qualify IEEE-802.15.4 for energy efficient WSN[51], and wearable sensors and actors as part of WBAN[52]. Bluetooth and WLAN generally do not legitimate another standard in this field, but these protocols are highly complex and expensive as far as hardware is concerned. Therefore the developers of IEEE-802.15.4 put the focus on exactly these criteria, to simplify existing complex protocols. The transfer rate is not important, as the data for sensors and actuators are significantly smaller that in computer networks where transportation of big files is inevitable. The simplicity and energy efficiency is the most important benefit and justifies this standard operating between Bluetooth and WLAN.

A very typical aspect of IEEE-802.15.4 devices is a sleep mode which is generally always active, except for short time frames necessary to receive and transmit data. The time to wake up is only about 15 ms. Afterwards the controller calculates and communicates data and goes back to sleep mode immediately.

To reduce hardware cost even further, there are two different types of devices named RFD and FFD. A RFD is only equipped with a part of a FFD, as it does not require full functionality. It is therefore forced to communicate with an FFD, as these devices can communicate with each other and create the WPAN. Typical RFDs are sensors and actuators as these devices are rarely called, do not execute administrative tasks and almost consistently in sleep mode. FFDs, on the other hand, are responsible for all administrative tasks of the network, as they can communicate with all devices. The following chapters will explain the function of different devices in a detailed way related to the ZigBee standards, which is based on the two specified layers of IEEE-802.15.4.

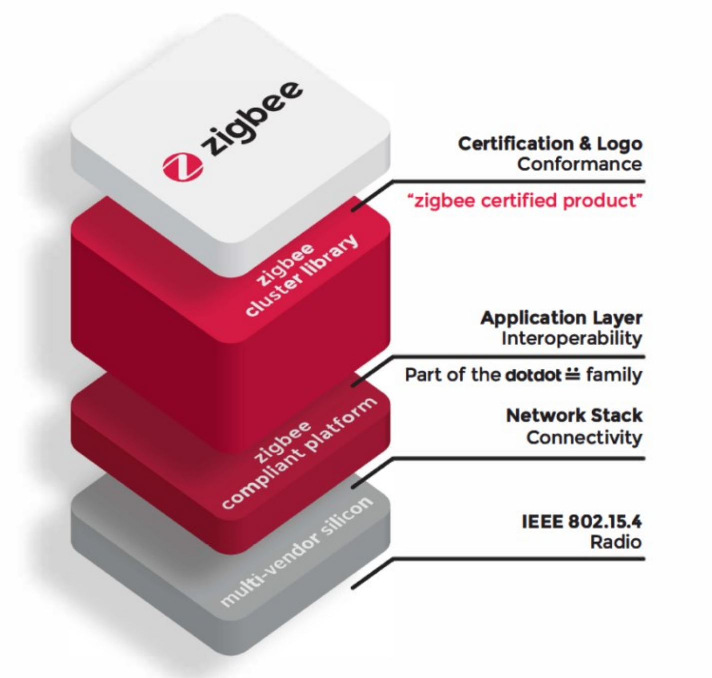

Figure 16: ZigBee stack structure, Source: zigbee.org

[51] WSN = wireless sensor network

[52] WBAN = wireless body area network

6.1.1.3 Devices

To establish a WPAN, certain functions are required to enable each device to contribute, hence why the ZigBee specification provides three different types of devices.

- **ZigBee end device (ZED)**

  Simple end nodes do not require the ability to take part in routing, therefore the implantation of ZEDs is reduced to a minimum. Examples would be switches or sensors, which do not require a permanent power supply and benefit from the low power design of ZigBee, thus enabling them to sleep while there are no tasks to execute.

  To participate the network, end devices are connected to a router which forwards their signals. If an end device is in sleep mode while the router tries to send commands, these will be stored by the router until the device wakes up again and requests the missed commands.

- **Router (ZR)**

  Routers contribute to the network by building a node end devices and routers can connect with, therefore such devices bring more functionality. In turn, this requires an increasingly powerful hardware or at least more memory. To enter an existing network, a router needs to find another router which is already part of the network to register. Depending on the selected stack, the network topology varies between a tree[53] and a mesh[54] structure, which use dynamic routing. The registration process assigns a short address to each device trying to enter the network. The fact that this short address is randomly chosen implies that an addressing conflict management is also part of the ZigBee specification.

- **Coordinator (ZC)**

The coordinator is, as far as hardware and stack is concerned, a normal router, as its only purpose is to start up the network in a defined way. When the network is up and running, the only coordinator turns into a router again.[55]

6.1.1.4 Clusters and profiles

Each typical application of ZigBee may be subdivided into several clusters which need certain system requirements. To support various products of different manufacturers, clusters describe a specific ability. Clusters are based on a client-server architecture, where each server of a cluster holds various attributes, which can be modified by the client's commands. A typical example cluster is 0x0006[56] which enables to simulate a switchable light. The wall switch represented by the cluster client tells the light, represented by the cluster server, to either switch the light on or off. This architecture allows a combination of all compatible client-server cluster constellations. The ZigBee cluster library contains all existing clusters.

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[53] ZigBee (standard)

[54] ZigBee PRO

[55] cf. ZigBee Alliance (2017), online source [1.8.2017]

[56] Cluster 0x0006 = OnOff

6.1.2 Bluetooth low energy

Bluetooth allows a short range wireless transmission of data and speech within the licence-free ISM band, where it is typically embedded into small portable devices. Throughout all currently existing versions of Bluetooth, special attention was placed on low susceptibility to interference with other wireless protocols, low power consumption and integrated security measures. As Bluetooth was very likely to be used to connect headsets and earphones or car radios to establish a continuous stream of data, things changed with the newer version BLE[57]. The version 4.0 and upwards was specifically trimmed for battery-powered gadgets and devices and is therefore optimized for a minimum of power required to exchange data.

Bluetooth is traceable back into 1994 when Ericsson and Nokia invented a simple technology to exchange data with little effort. The name Bluetooth goes back to Viking king Harald Blaatand who brought peace between Norway and Denmark. However, the translation of his name led to the brand Bluetooth. In 1998, the SIG for Bluetooth was founded and started to define the IEEE-802.15 based standard for Bluetooth which hosts thousands of companies today.

Utilizing 79 channels with 1 MHz each of the ISM band between 2.402 and 2.480 GHz, Bluetooth invented a FHSS[58] algorithm to avid interference with other 2.4 GHz standards e.g. WLAN or DECT. Bluetooth connections are relatively stable, as the frequency hopping happens up to 1600 times per second, and data packets are small. A network contains up to eight active and 248 passive devices, which are connected but do not actively contribute. Each individual device has a unique 48 bit MAC address which is needed for a definitive identification of each device.[59]

Where the most wireless standards are only capable of one transmission method, Bluetooth is able to communicate synchronously as well as asynchronously. Synchronous connections send data back and forth simultaneously whereas asynchronous connections alternate between back and forth. Bluetooth specifies the methods as follows:

- Synchronous connection-oriented

  For voice transmission, the synchronous method uses timeslots of a fixed length comparable with ISDN. As the method is connection-orientated and time integrity is important, the quality of the connection takes centre stage.

- Asynchronous connectionless link

  If Bluetooth is used to transmit any other kind of data, including audio, the asynchronous connectionless link is used. While this mode is not time-critical, the data has to reach its destination with absolute certainty.

[57] BLE = Bluetooth low energy

[58] FHSS = frequency hopping spread spectrum

[59] cf. Bluetooth SIG (2017), online source [1.8.2017]

6.1.2.1 Profiles

The profiles were invented to ensure a compatibility of different Bluetooth devices, therefore the profiles are of high importance. They specify the structure and content of a communication set depending on the application. The Profiles operate on higher OSI layers and were invented to manage the cooperation of devices on the application layer.

Each Profile contains specific rules and protocols to hide its complexity from the user and to enable an easy commissioning of new devices without the need to coordinate them manually. Due to the fact that the profiles are specifically tailored to different applications, each device can hold more than one profile if necessary. Although some applications may require more than one profile, the great advantage is that each device stays simple and application specific without the need to waste memory and processing power for needless specifications for other applications, thus enabling a cost as well as energy saving operation.

Figure 17: Official Bluetooth Low Energy logo, Source: bluetooth.com

6.1.2.2 Bluetooth mesh

Mesh is currently the latest invented Bluetooth operation mode and is available for each BLE device with a firmware upgrade functionality. Mesh, as described a few chapters earlier, is a topology which enables nodes to connect to distant nodes through other nodes, thus establishing redundant paths. Even nodes that would not be reachable can be integrated in a network by making use of the repeater function. Bluetooth Mesh extends BLE where the focus, per definition, is on energy saving. Bluetooth Mesh as a software solution which requires more memory and of course more power does not generally fit into the basic idea behind BLE. Earlier upgrades always needed a new hardware, where Bluetooth mesh is a pure software solution designed for industrial and home automation purposes. The only prerequisites are a Bluetooth 4.0 compatible hardware and sufficient storage to support the new memory-demanding mesh functionalities. As the current smart lighting market is absolutely dominated by ZigBee, Bluetooth enters the market as a game-changer. Solutions like ZigBee, Enocean and Z-Wave always require gateways to their protocols, even though the carrier frequencies all may be the same at 2.4 GHz. Bluetooth is supported on almost every mobile phone, tablet or notebook, which makes it an omnipresent technology with cheap hardware due to the massive supply.

Some Applications require long ranges to bridge between sensors, actuators and base stations. Such cases could benefit from a central repeater node reinforcing the network stability and enabling new paths if a node fails. A mesh network is established with as many participants as possible. Bluetooth mesh introduces the possibility to spontaneously include smartphones or tablets which are currently within signal range.

6.1.2.3 Flooding network

The fundamental difference between ZigBee and Bluetooth mesh is the way messages are repeated. While ZigBee uses routing that utilises self-learning routing tables, Bluetooth Mesh draws its functionality from flooding the network. Flooding means that each received message get repeated no matter whether it belongs to a neighbour of the respective node or not. Routing, on the other hand, only forwards the message if the node is part of the calculated path.[60]

A great advantage is the missing routing algorithms and tables, which makes the implementation much easier and guarantees a fast forwarding without needing time to calculate paths. To every advantage, there is always a drawback; in this case increasing latency and much higher power consumption than BLE specifies. Although Bluetooth Mesh is an add-on to BLE, it counteracts against the principles of low energy.

To prevent sending messages twice, each node contains a memory for recently sent messages. An additional algorithm called TTL ensures that a message can only travel within the network for a specified amount of hops. As the TTL get decremented with every hop, the message will be deleted by the node setting TTL to 0.

Similar to ZigBee’s end devices there, are BLE devices participating in a mesh network, which do not always contribute to the network. Therefore a friendship implementation enables a mesh node to store data for a so-called friend and transmits the data only if the low energy node wakes up and requests it. Special nodes which are able to connect non-mesh devices to the network are referred to as proxy nodes. In total, a Bluetooth Mesh network can host up to 32,000 nodes, making it absolutely competitive to ZigBee light link.

6.2 Z-Wave

Another wireless home automation standard is Z-Wave. Although the last years have caused a massive increase of smart home or smart lighting solutions, Z-Wave is the number one with regards to the number of sold items. The communication is based on two pillars: low power demand and connection stability. As a low demand of power is by far not sufficient enough anymore to create a sustainable and commercially successful product, there must be a few other factors which made Z-Wave that successful. A detailed research concluded that such factors could be the frequency range in which it operates and the stability of a connection. Unlike other protocols, Z-Wave requests acknowledgements for each transmitted message, with the exception of a broadcast telegram, which can be received by each node of the network. The receiver has up to three tries to confirm the reception of a message before the transmitter will define it as not reachable.[61]

Z-Wave was developed by two Danish engineers who wanted to create their own home automation system. In short, their product was first sold by an OEM company which was bought by Sigma Designs now holding the licences. There are currently about 1400 Z-Wave products on the market, which all contain special

[60] cf. Bluetooth SIG (2017), online source [1.8.2017]

[61] cf. Z-Wave Alliance (2017), online source [1.8.2017]

SOCs[62] sold by Sigma Designs. The fact that only Sigma Designs and a licence holder named Mitsumi are allowed to produce the specific chips for Z-Wave products entails a certain amount of risks, as these companies could become bankrupt at any time, which would lead to a halt of production. On the other hand, all systems are licensed and therefore compatibility issues are very unlikely to happen, except for instances, in which products intended for the American and European market respectively are mixed.

The Z-Wave alliance gathers about 330 manufacturers and service providers selling, developing and supporting Z-Wave licensed products. The Alliance manages exhibition appearances, marketing strategies and the further standardisation.

Figure 18: Official Z-Wave logo, Source: z-wave.com

6.2.1 Physical specification

Z-Wave operates in the frequency bands between 850 and 950 MHz depending on the country of operation. Such frequencies advantageously offer a better penetration of masonry and are not reflected very well in comparison to the worldwide licence-free 2.4 GHz ISM band. At the same time, this is the greatest disadvantage of Z-Wave, as there is no unified frequency around the globe preventing interoperability of all products. The closest competitor, as far as technology is concerned, is EnOcean as it makes use of the same frequencies and is also based on ultra-low power consumption products.

Europe and some Asian countries use the license-free 868.4 or 869 MHz band, which is not available in the US, which tends to use 908 or 921 MHz bands. The modulation method is FSK[63] with a distance between the frequencies of 20 kHz.[64]

Data rates are relatively moderate as the highest is 100 kB per second and will be switched to even lower ones as the wireless environment allows it. The transmission power of Z-Wave is reduced to just a few mW, although the maximum power in accordance to the SRD band would be 25 mW. The result of the low transmission power is a very low power consumption in a maximum range of about 150 m outdoors and 40 m indoors.

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[62] SoC = System on a Chip

[63] FSK = frequency-shift keying

[64] cf. Z-Wave Alliance (2017), online source [1.8.2017]

6.2.2 Meshing

In contrast to Bluetooth Mesh and much like ZigBee, the networking technology is based on routing, which enables a high network stability and multiple routes of a packet to reach its destination. The addressing is based on two addresses identifying the device in a network. The home ID specifies the place where the respective Z-Wave device is located or, in other words, the physical network. The other address, the node ID, specifies the local address of each device, as this address must be different from each device in a network. The maximum number of nodes can be calculated due to the length of 1 byte. Moreover, the maximum number of addresses is limited to 232 nodes as a few addresses are taken by default. For example the number 255 represents broadcast commands. To enable a proper meshing, Z-Wave uses routing tables within each master to calculate the most efficient path for a telegram to use. The older versions are based on static routing, therefore causing a node failure or change of the location of a node which could lead to inconsistences within the routing tables, furthermore resulting in communication issues, as the table will not be updated once it is created during inclusion to the network. With the help of explorer frames, the new versions are equipped with a self-healing algorithm that uses dynamic routing.

6.3 EnOcean

The basic idea behind EnOcean is the recognition that wherever there are values to be measured, there are changes of exactly these values. This implies that a sensor can be powered by the measured value or any other value which changes on site. The use of omnipresent free-of-charge energy enabling devices to act is called energy harvesting. Alongside other wireless technologies, such as ZigBee and Bluetooth, this technology is just another wireless sensor network but of course with its specific USP[65], the usage of battery-free devices.

Figure 19: Official EnOcean logo, Source: enocean.com

6.3.1 Energy harvesting

The battery-free EnOcean devices collect energy wherever it can be found. The used physical quantity to be converted differs depending on the application. Typical examples are kinetic energy, visible light or temperature differences. The energy is collected over time or with the help of a specific event and is transformed into wireless telegrams to inform a gateway about events. Especially the combination of miniaturised energy converters and energy-efficient wireless technology allows maintenance-free solutions for buildings, smart homes or industrial plants.

[65] USP = unique selling point

6.3.1.1 Energy from motion, light and temperature

This principle uses motion energy to generate wireless signals. The push of a button creates enough energy within the piezo-electrical energy converter to transmit a telegram. These signals can be used to control lights or close the blinds. Other functionalities to support a smart home are water sensors or window sensors that notify whether a window is opened or closed.[66]

Wherever there is light, energy can be harvested even down to levels of 200 lux and lower. Tiny solar cells use this source of energy to measure temperature, CO2 or presence of persons. Especially places of higher illuminance like windows or doors suit perfectly for a solar powered application.[67]

If temperature differences are used to generate energy, the Seebeck effect is used. Thermal energy converters require a difference of about 2 °C to harvest enough energy to power a wireless module. Generally, voltages coming from Peltier elements are very low and need a conversion into a higher voltage to be usable. For this reason an energy-efficient DCDC converter is placed between element and controller. This particular source of energy is rather suitable for lighting application, as luminaires do not produce any temperature difference when it is turned off. For instance, an application as electrical radiator valves makes much more sense.

6.3.2 Specification

The patented EnOcean wireless standard allows to generate a medium range signal out of energy in the environment. A telegram needs about 50 µWs to be transmitted over 300 m distance outdoors and about 30 m indoors. The main reason for the low energy demand is the tiny timeslot of only 1 ms to send a telegram.

The messages are collected by gateways to enable logic actions due to measured values. As EnOcean is already a settled technology gateways bridge the gap to KNX[68], LON[69], DALI or TCP/IP.

6.3.2.1 ISO/IEC 14543-3-10

The standard specifies EnOcean from the PHY layer up to the NWK layer but foregoes collision detection due to the low probability caused by short transmission times. Even a number of more than 100 nodes still enables a stable connection to a gateway as the probability of a collision is still under 0.01 % if all sensors send a telegram once a minute. The main difference to other smart network implementation is the lack of message forwarding by other nodes, as a very high percentage of EnOcean products is battery-free and require the complete amount of harvested energy for their own telegrams. So perhaps the word network is a bit too ambitious for a collection of EnOcean nodes.

A great disadvantage is that there are currently three different carrier frequencies of EnOcean products on the market. As it operates in the sub 1 GHz frequency area, there are no worldwide licence-free bands

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[66] cf. EnOcean Alliance (2017), online source [1.8.2017]

[67] cf. EnOcean Alliance (2017), online source [1.8.2017]

[68] KNX is a building automation field bus

[69] LON = local operating network

which would allow a unification to one single frequency. This means that potential users should be aware that it is important to know where the product is coming from and which country allows a licence-free operation. In detail the distribution is as follows:[70]

- 868 MHz in Europe
- 928 MHz in Japan
- 902 MHZ in the USA

An advantage compared to the common 2.4 GHz systems is that there are no interferences possible to and from WLAN, Bluetooth, DECT or other implementations utilizing the 2.4 GHz band. Moreover, the range of this technology is higher anyway because of lower path loss due to the sub GHz carrier frequency. The previous chapters already described the relationship between path loss and carrier frequency, which therefore needs no further explanation.

The ultra-low power specification of IEEE-802.15.4, combined with a protocol overhead as low as 7 Bytes to transmit 1 Byte of data, allows EnOcean to stay within the 1 ms timeslot for a message, while, in the meantime the supply current goes down to less than 100 nA.

Certain applications require a higher security and therefore send messages twice and with a checksum to allow the receiver to confirm the data integrity. Although there are no battery-free options to extend the range of a network, there are repeaters to stretch the range if necessary.

[70] cf. EnOcean Alliance (2017), online source [1.8.2017]

7 DMX IN PRACTICE

DMX is focused on professional applications. A certain amount of robustness and scalability is needed to enable projects with 500 fixtures and more, as well as a cable length of more than 1 km. This thesis focuses on general and architectural lighting. For this reason, DMX is widely used in outdoor applications to illuminate facades or entire buildings. In such large scales it is not rare that issues come along with the commissioning. Especially disturbances on the bus wire are very common. Less common but occurring are issues with leaking or overheating outdoor luminaires. Therefore, during development special care should be taken to enable the product to withstand environmental influences with a particular focus on rain, direct and indirect lightning strike, heat, humidity and dust.

Generally, such disturbances can be recognized via flashing of failing fixtures in smooth colour gradients or running light sequences. The first parts to check are the connectors as each one represents a parasitic resistances and, moreover, a weak point within each network.

Looking on electrical influences, poor or faulty potential equalization is a common issue for destructive or at least disturbing currents on wire shields. The electrical installation often connects different potential sources of disturbances e.g. frequency converter, capacitive bank, welding system or poor filters within SMPS.

As already mentioned above, issues with large-scale lighting systems are very easy to recognize as the human eye is very sensitive for fast changes or wrong colours within a gradient.

This chapter deals with practical work on DMX luminaires, including a case of failure, its subsequent recovery and finally the analysis of possible reasons. The investigation into the cause of the error case leads to the development of protection mechanisms and therefore a product which can be sold as a useful accessory to guarantee a long-lasting system. The last part will draw special attention to the outcome of the development of a protective PCB, including a test-setup of a significant size to get meaningful results out of it. The tests will mainly focus on different types of disturbances and where to place protective elements within a system.

7.1 Error case: SCS Multiplex

Figure 20: Fixtures mounted upwards and downwards along the facade, Source: own photograph

One of Europe's largest shopping malls, the SCS in Voesendorf near Vienna, decided to equip two entrances with an RGB LED system to highlight the design-orientated facades. With the help of the RGB system, colourful effects such as rainbows, running lights und many more are easy to implement with high-end lighting equipment. Unfortunately, a few circumstances led to a partial failure and generated a customer complaint. The following chapters will describe the system in detail and explain how reasons for the failure can be tracked down and, more importantly, how they can be prevented. As a lot of different factors are involved when it comes to a failure of an outdoor luminaire, the reasons as well as possible solutions are manifold. The main focus will be on a cost-effective way to solve the problems in a sustainable manner.

7.1.1 The XAL Stila luminaire

The Stila series is an outdoor luminaire, especially designed for effect lighting, e.g. illuminated facades. With a length of 1600 mm, it is internally separated into two parts, as on smaller facades a finer division of effects is required. The luminaire uses the colours red, green and blue with an 8-bit resolution to mix up to 16 million different colours. Each device allocates 6 DMX addresses to be controlled via a wired remote control.

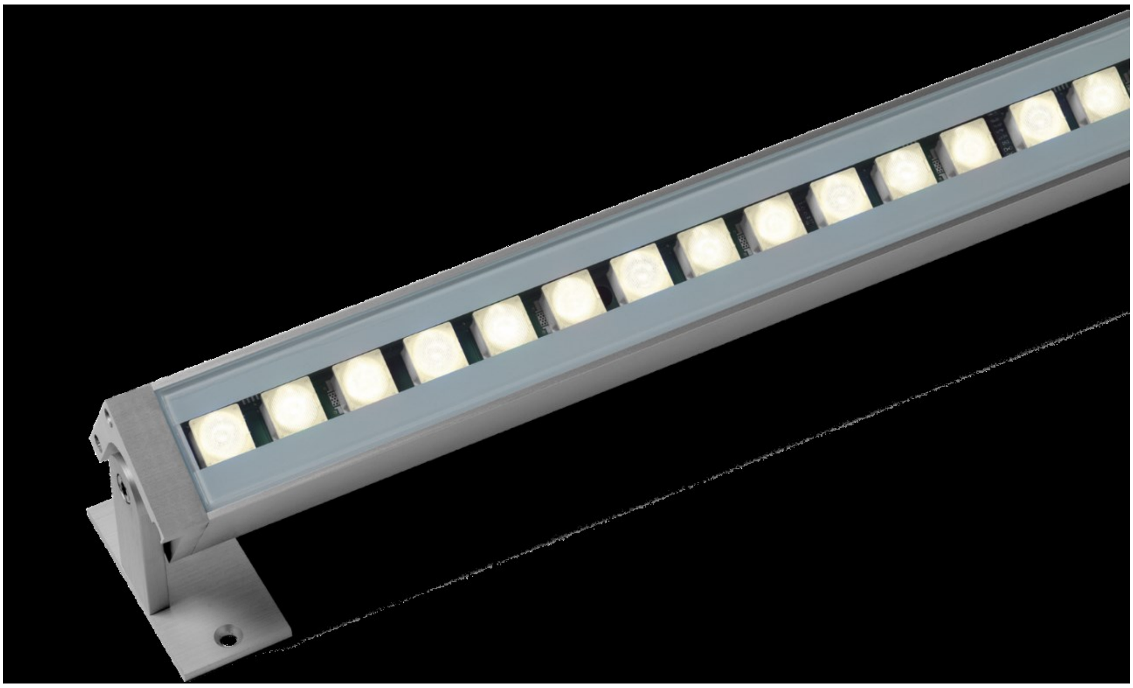

Figure 21: Stila Dynamic Spot 7° DMX, Source: xal.com

7.1.2 Mounting situation

Located on the upper and lower façade trim, the Stilas are partly protected against environmental influences. The luminaires are mounted at the entrance number 2 of the SCS[71] (property part "Multiplex"). The electrical connection is established by the sub-distribution board at the rooftop, which is powered by the main distribution board in the basement. The control systems, which are Pharos LPC DMX controllers, are located in the rooftop sub-distribution board to minimize cable length to the luminaires.

The sub-distribution board is equipped with surge protection of Type C[72]. Outdoors, the DMX and the power cables are routed in channels to an IP-Box where the first signal amplifier sits. As the façade illumination is split in an upper and a lower part, the IP-Box acts as a splitter for the wiring from which the cables are routed towards the end of each Stila chain.

7.1.2.1 Wiring schematic

- Main distribution panel; 100 m cable to
- Sub-distribution board; 50 m cable to
- IP-Box; 20 m cable to each first luminaire
- About 80 m between the first and the last luminaire of each part.

The chained luminaires are continuously cabled, regarding both the mains cables as well as the DMX wires. One fatal mistake that was detected during inspection was the DMX connecting cable itself. The cables in

[71] Shopping centre in the south of Vienna

[72] Type C = fine protection

use were shielded but the shield conductor was floating instead of being connected to the earth potential on each connector. As far as electromagnetic interferences are concerned in this particular case, the cable shield is almost useless, meaning potential differences between shield and earth could not be drained away.

7.1.3 Error pattern

The elaboration of the error pattern showed multiple faulty luminaires beginning at the IP-Box which supplies each chain of fixtures. The first 10 luminaires were completely defect and not showing any sign of function anymore. As a first step, each fixture was opened to give access to each part within. The error pattern shows typical indicators of overvoltage damage e.g. defective varistors at the SMPS[73] supply terminals and scorched housings. As the first luminaires are heavily affected and the damage becomes less severe the farther the fixtures were away from the supply, this case perfectly shows how the overvoltage wave was weakened by each luminaire. Luminaires at the edges did not contain damaged SMPS, but showed slight signs of damage on the RS485 interfaces. The error pattern obviously shows that the overvoltage at the 10th luminaire was already weakened to such an extent that it could not wreak havoc on the subsequent fixture anymore.

In conclusion, one can clearly attribute the ten defective luminaires to overvoltage.

7.1.3.1 Origins of overvoltage

- Direct lighting strike
- Switching surges

  The reason for overvoltage is highly undervalued as it is nearly omnipresent. Wherever there are heavy loads on the electricity grid, such loads require a variable speed control or at least an on-off switching function. As most heavy loads are of inductive character, switching surges are a logical consequence. In a nutshell, the inductive characteristic of a load brings the ability to store a certain amount of energy with it. Assuming the load is a rotating motor and it gets switched off immediately, the inductive stored energy cannot be removed anymore by current. As a result of this, and according to the principle of self-induction, a transient voltage rise will occur.

  Therefore, switching surges are omnipresent in industry and building services.

- Inductive or capacitive coupled disturbances

  As each conductor represents at least a part of a loop, magnetic coupling is established at the moment of installation. The coupling factor increases the closer two conductors are to each other. For example, if a supply cable for a HVAC[74] motor is guided right next to a field bus cable, both cables are magnetically coupled, causing a fault current.

[73] SMPS = switched mode power supply

[74] HVAC = Heating, ventilation and air conditioning

The same principle applies to capacitive coupling, but with the electric field being responsible for coupling instead of the magnetic field.

- Potential losses

  Indirect lightning is an illustrative example for potential losses. Applications with multiple earth conductors earthed on different places, a lightning strike can lift the earth potential close to it. At the point where different earth potentials meet, the lightning affected earth conductor can have an up to 6 kV higher potential. EMI[75] compliance tests for standard devices use test voltages of about 2 kV, which strongly suggests that such devices will very likely be harmed by the surge.

- Diverging earth potentials

  Above mentioned potential losses could also appear due to a high current on low cross section wires, which are not able to equalize two earth potentials. Especially parallel installed power lines and shielded signal cables are vulnerable to this phenomenon. A small cross-section PE conductor as part of the power line is in some cases not able to drain potential differences, which forces the current to go through the next lower impedance, the signal shield. The shield is not designed to function as a compensating lead; in fact, it could get damaged irreversibly.

- Faulty potential equalisation

  Referring to the previous point, diverging earth potentials are some kind of a faulty potential equalisation. Generally, this term can be used to describe cases which lead to compensating currents. As an example, one could assume a general purpose motor is controlled by a variable speed control which, in turn, is controlled by a distant PLC[76]. Assuming ground and earth potentials are not equalised in a proper way, compensating currents will be the logical consequence.

After elaborating the possible origins of overvoltages, it is important to look deeper into the behaviour of such transient voltages. Due to the fact that such surges persist for a short period only, resulting slew rates are of extremely high gradient, which, in turn, equals high switching frequencies. Therefore, overvoltages therefore lead to high-frequency currents, thus meaning the preferred drain path changes due to completely different characteristic impedances in comparison to the 50 Hz grid frequency. Especially capacitive stray fields are heavily affected, as their impedance significantly decreases at higher frequencies.

7.1.4 Countermeasures

There are countless ways to solve issues with overvoltages. Therefore, this subsection will focus on finding an economic solution as the entire case already raised horrendous costs. On this basis the remaining two options are:

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[75] EMI = Electromagnetic Interference

[76] PLC = Programmable logic controller

- Galvanic isolation

  Given the fact that all fixtures are installed chain-shaped and the system is stretched to about 80 m, a minimum number of four isolation points will be necessary to ensure proper separation. The already present booster boxes are theoretically designed to isolate the signals. Unfortunately, the inspection showed that the cable shields were bridged through the booster. Establishing galvanic isolation is only possible when all conductors are isolated, as each exception will void the protection mechanism completely.

  A solution that uses signal isolators will require new designed booster boxes to avoid wiring errors.

- Consistent potential equalisation

  A potential equalisation has to be done in a determined manner as all earth potentials have to be reached by a compensation lead. All connections must have a low impedance, meaning that not only a low resistance is sufficient, because inductivity of wires play an important role on high-frequency disturbances. The equalisation must ensure the lowest possible impedance in comparison to other possible HF-current[77] paths. An example of such a low-impedance lead is a shield relief conductor, which ensures proper compensating current drainage.

  Influences on electronic components or, at worst, a malfunction of such can very likely be traced back to vagrant power currents. The negative impact arises due to induced currents into signal shielding or ground wires. Such cases require a “power current” potential equalisation lead in addition to already existing ground wires to carry high currents.

- Overvoltage protection

  The present lighting system does not include measures to protect sensitive electronic components form overvoltages. The first possible drain path for lightning is represented by the overvoltage protection in the sub-distribution-board.

  However, this situation needs to be changed urgently by introducing additional fine protections and a mechanical redesign of the fixtures. Lightning protection of outdoor fixtures is a growing market segment due to the increasing number of SMPS used in outdoor applications. This, in turn, created a number of different form factors to fit in most cases. Fortunately, the price of these components have sunk as well and opened up the possibility to generally equip all outdoor luminaires with proper lightning protection. In this particular case, a type-C protection will be required, as it is the last step on a cascaded lightning protection concept. Otherwise the internal LED Converter needs to be equipped with a higher resistance against overvoltage, thus significantly raising the price and reducing the available supply of certain types or manufacturers.

[77] HF = high frequency

7.2 Development of an insulated DMX RDM signal amplifier

It was concluded that an insulation of the DMX signal on a specific point in the system is required to establish a long-lasting network, which is less vulnerable to environmental influences. The insulation creates a protective resistance between the input and output. During the layout process, it should be ensured that the highly important insulation distances between both conductors of different potentials are perfectly within the standardized boundaries. Even the required isolator IC[78] is especially designed with a larger housing to be able to bridge the insulation gap. Generally, the schematic as well as the layout of such PCBs are very easy to check due to the continuous insulation line that must not be crossed by any other wire or component than the isolator IC.

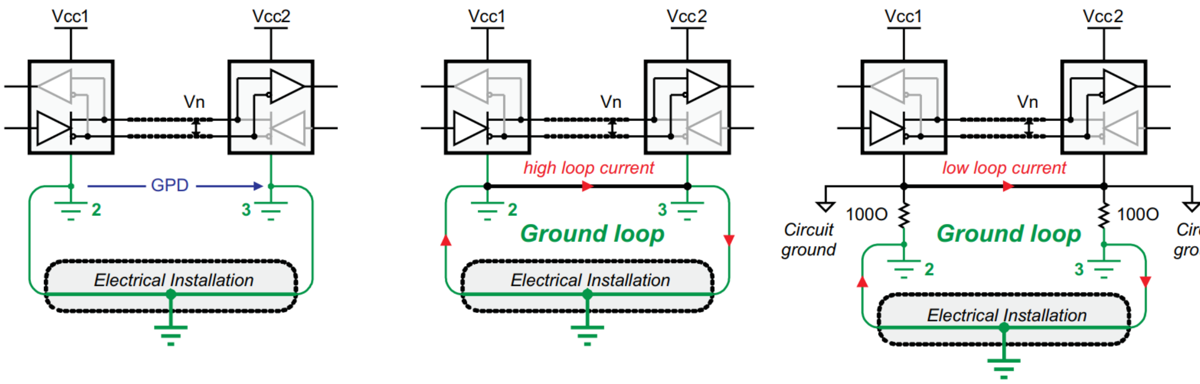

Figure 22: Three general ground/earth pitfalls in RS-485 networks, Source: TI RS-485 Design Guide

7.2.1 Isolator IC

The first and possibly most important question, even prior to starting to develop the circuit, is about the size of the end product. In this particular case, the plan requires to place the PCB within a separated IP 65 box in order to install it wherever it is needed. Out of the above mentioned issues it is not necessary to equip each luminaire with such extremely protective elements. Components that would be suitable to place within each luminaire would be, for example, a light transient protection for the DMX bus or a lightning protection for the LED converter, but no insulation. On the one hand, it would involve tremendous costs in the range of about €50 to €70 of each luminaire. This would not only lead to an enormously high production price, but to an even more expensive selling price. On the other hand, the technical aspect of such an insulation within each luminaire would cause small delays during data transmission, as each telegram reaching the isolator requires a certain time before it gets transmitted completely. The resulting propagation delay will be at least 1 µs using the internal peripheral logic of the used microcontroller Atmel ATSAM D11 Cxx. One option to speed up the entire transmission would require the use of only one non-isolated driver IC and to choose a combined RS485 interface logic isolator, resulting in saving only about 50 ns, while adding costs due to the higher price of such combined chips. Therefore it can be concluded that a three IC variant would be more suitable. Tests that involved tuning the circuit for lower propagation delays with the use of logic instead of a microcontroller, ended up in a far lower functionality. In fact the circuit lost its ability to decode

[78] IC = Integrated Circuit

the currently active protocol which frequently changes between the standard DMX daisy chain (forward frames) and the RDM backward frames.

To sum the results of the first tests regarding IC selection up, one can state that an economic product would require two RS-485 interfaces, an isolator IC and a microcontroller when it comes to signal processing. Hence the space requirement is relatively modest. From that point of specification, a PCB[79] size of 150 x 40 mm is expected to fit the entire circuit.

7.2.2 Power supply

Regarding space requirements it should be added that there will be the need of two separated, galvanically isolated power supplies to serve the ICs with constant 5 and 3.3 Volts. The Interface ICs require 5V supply, enabling these components to create a 5 V output signal. A lower supply voltage would result in lower output signal levels, which, in turn, would worsen the signal-to-noise ratio. 5 V seems to be a sensible choice as it is the maximum allowed signal amplitude and, furthermore, ensures a good SNR, which should be of high priority in stable signal transmission.

As it the case with the isolator IC, also the power supply modules are of larger size to ensure a safe distance between mains voltage and the SELV[80] DMX potential. Two varistors directly in series to the input terminals guarantee a low inrush current of the tiny power supply modules and the LED converter that is also going to be connected to the inrush current protected mains part. Varistors are the components of choice due to an excellent price in comparison to TVS[81] diodes and non-effective gas spark gaps. Overvoltage protection circuits are generally designed in a cascaded way.

- Spark gap
- Varistor
- TVS Diode
- EMI Filter

Each component is separated from each other with a coil to make cascading effective. Otherwise the overvoltage would reach all components at the same time and all energy would follow the fastest part. In this case, it would be the TVS diode, which is not designed to derive such amounts of energy. The inductivity splits the parts successfully to reduce the amount of energy with each stage.

[79] PCB = Printed circuit board

[80] SELV = Safety extra low voltage

[81] Transient Voltage Suppressor Diode

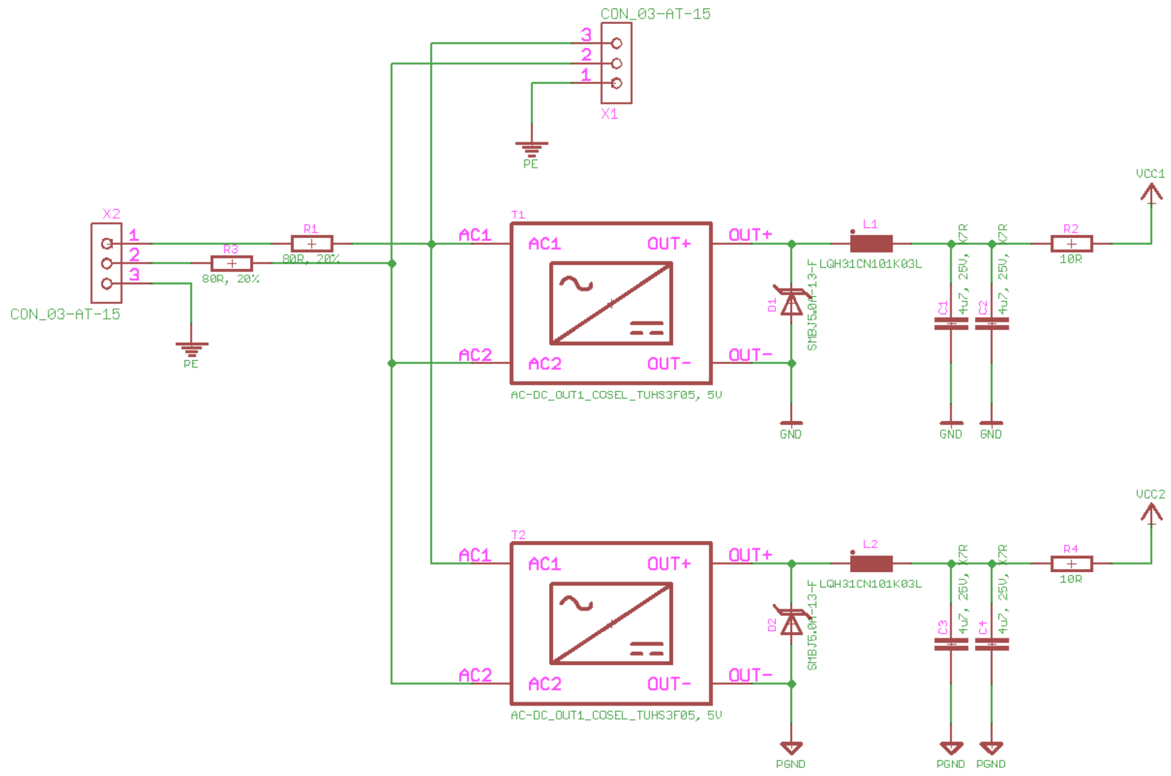

Figure 23: Double isolated power supply, Source: own illustration

The power supply modules are equipped with an EMI filter and an overvoltage protection. Generally the distribution board where the luminaires are supplied from is equipped with a strong lighting protection. These two facts lead to the conclusion that there is only need to protect the middle stage, namely the varistors. Besides the overvoltage protection, due to their electrical and thermal behaviour, these parts fortunately bring an effective inrush current limiter to the circuit.

Combining the plant's lightning protection, the varistors in use, the integrated filters, and protection elements within the power supplies results in a fully protected circuit against indirect lightning strikes.

On the SELV side, there is yet no protection for the microcontroller and the interfaces provided. Huge mains voltage disturbances can walk through the complete power supply unit, resulting in transient spikes on the secondary side. These voltages usually do not harm the components seriously, but can cause microcontrollers to stop working or disturb the interface ICs output signal, which is also not desirable.

Reasonable countermeasures can be taken by adding suppressor diodes which will derive overvoltage to ground. Furthermore, the circuit needs protection from higher frequency interferences, where a low-pass filter adds additional smoothing of the voltage.

7.2.3 RS 485 interface IC

The Interface IC is the element which is directly coupled to the field bus. Therefore it requires special attention when it comes to immunity against transient voltages and overvoltage faults. Especially on commissioning mistakes can happen and the bus unintentionally gets shortened to ground or a dc supply voltage. Creating a 230 VAC tolerant interface is, in terms of price, nearly impossible. For this reason, the external protection elements will absorb higher voltages than the receiver IC can deal with. The chosen

Interface was a TI[82] RS 485 interface which is designed to survive up to 70 V overvoltage faults. Examples of such are direct shorts to power supplies, miswiring faults, connector failures, cable crushes, and tool mis-applications. The SN65HVD1781 is protected against ESD[83] events up to 16 kV to the HMB[84]. To save cost and PCB space, a combined device containing driver and receiver was selected. The internally connected parts can be selected via two pins: The diver enabling high pin and the receiver enabling low pin.

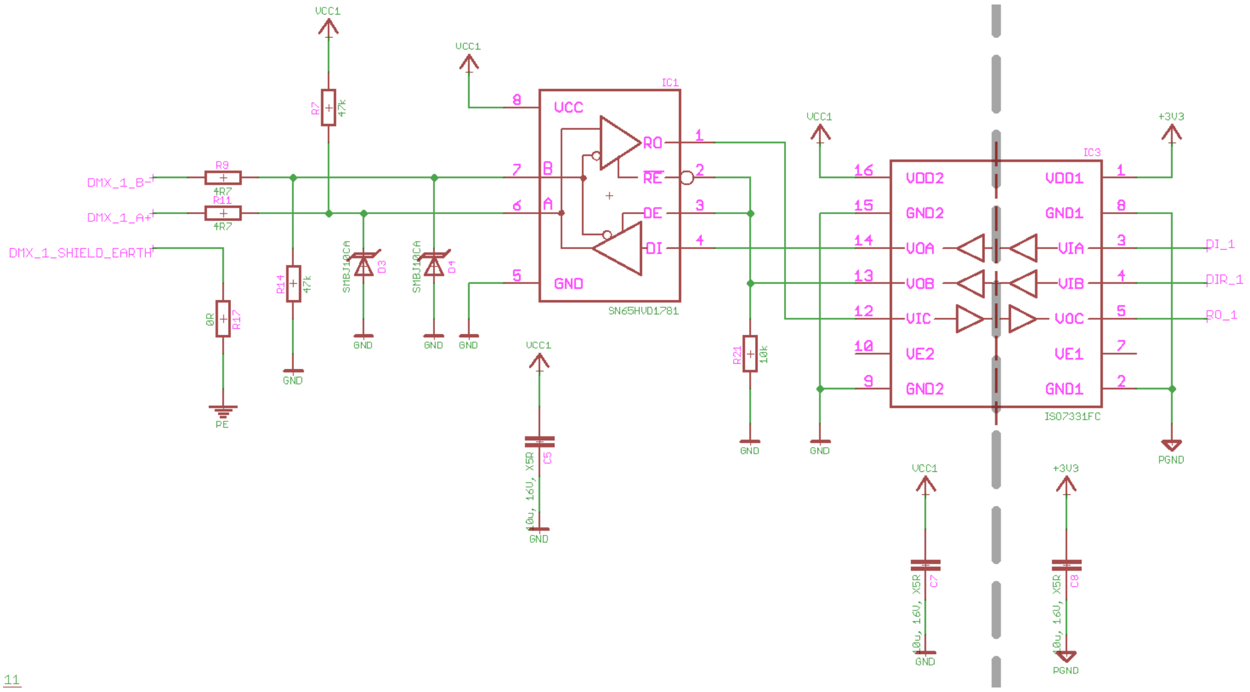

Figure 24: Protection, interface and isolator circuit, Source: own illustration

An experienced hardware developer will immediately see the reason for one pin being high active and the other pin being low active. Applications that do not support full duplex or projects that do not need two data directions are easier to design with such logic pinouts. One can connect both pins and switch the resulting input signal between low and high in order to enable the receiver part and disable the driver at the same instance. Such solutions help to save pins on the microcontroller for other purposes. While the next chapter will look deeper into the selection of microcontrollers, it should be mentioned at this point that this particular application does not require the two pins to be separated. In case of a power outage or even an interface failure, proper function of the remaining parts has to be ensured by pulling the receiver enable pin low. Otherwise the still enabled driver could pull the entire network low and data transmission on the rest of the filed bus is impossible.

There are a lot of companies that devoted lots of time to the question on how to protect a field bus interface. For example such a project is the design guide published by TI that perfectly explains how such protection

[82] Texas Instruments

[83] ESD = electrostatic discharge

[84] HMB = human-body-model

circuits should look like. In order to not put all trust into one company's knowledge, the end result is a mixture of certain recommendations.

At first, each conductor is equipped with a series resistor to limit incoming current spikes, in fact preventing high currents from destroying the interface. The next stage is equipped with TVS diodes that drain high voltages. Biasing resistors for both conductors are optional. The need for these resistors will be established by measurements on following projects.

7.2.4 Microcontroller

At first glance it is hardly believable that such an application requires high-operating frequencies of a microcontroller, but the deeper one looks into the DMX standard, the clearer it becomes. Each frame of the daisy chain starts with a long low pulse and a following short high pulse. This process is required to define the start of a frame and clear the buffers within each connected slave device. The next and by far most important reason to use a fast controller is rooted in the fact that there is only a narrow timeframe where RDM devices are able to answer if registers are queried. If a large propagation delay retards the backward frame down to a certain time, it is not possible anymore to communicate with the slaves. If a master sends out a request, it will wait a specific time for the answer to come through. Common sense predicts that the answer will not arrive in time if it is delayed by too many signal amplifiers and their propagation delays.

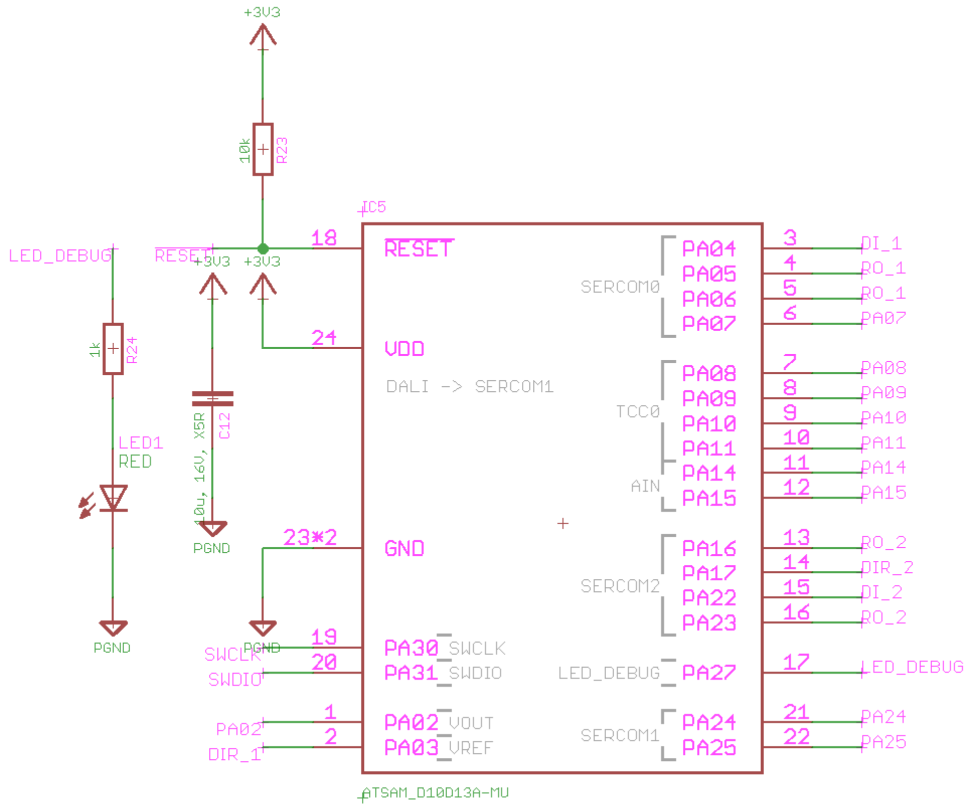

Figure 25: Microcontroller of Atmel's D10 series is used in the design, Source: own illustration

A microcontroller with a peripheral logic will be required to speed up simple logic switching of output pins. The protocol detection is quite simple, as the first indicator already is the data direction. The controller detects the first interface receiving a telegram and thereby it decides if it is RDM or DMX. If the output bus goes low after a defined amount of time in idle mode, the internal logic will switch the signal through right to the input interface, which has switched to driver mode. Such simple examples of combinational logic are easy to map into programmable logic gates. Newer Atmel ARM-based controllers powered by cortex cores support simple combinatorics with the help of a peripheral event system. This event system coordinates logic between peripherals without waking up the ALU[85] and therefore speeds up direct data transmission.

The Atmel SAM D10D13 controller supports all required functionalities and costs not more than € 0.75. The main reason why an Atmel controller was chosen is that the Atmel Studio development IDE is easy to handle and small projects can be implemented effortlessly. Another underlining advantage is that the cheap controller saves costs for other logic elements and saves precious PCB space.

7.2.5 PCB layout

An appropriate schematic is the basis for an optimal PCB layout, meaning that the look of a circuit can either help simplifying the design process or it can also destroy entire work done in circuit design. With these facts in mind one will definitely be more careful during wire routing. The following steps describe the thoughts and reasons behind certain aspects of the final PCB layout.

A logic start can be made with a proper layer count, which in this case led to a double layer PCB. The number of wires, vias[86] and components on top and bottom would not justify a four-layer PCB. Typically such multi-layer PCBs are used in high sensitive applications which is definitely not the case when dealing with up to 5 V digital signals. Dealing with small signal amplifiers or motherboards with a high number of tracks and components would be typical examples just for the sake of completeness.

The fact that there are multiple supply voltage levels with just a few components connected to it leads to the idea that a ground plain on both layers would make sense as it bridges certain bottlenecks with lower impedance compared with a single ground track. Nevertheless one very important note to mention is that the supply track is as important as the ground path. Vagrant high frequency currents can also run through supply lines if these are not routed properly.

To reduce the sensitivity for capacitive coupled disturbances the signal carrying tracks are surrounded by the ground plane which moreover is connected to the other side with each via. The vias are placed in a regular shape around the more sensitive parts of the circuit.

The previous chapter already addressed ideas and reasons of earthing and led to the result that there is no perfect solution as it always varies with the application. Therefore both, the input as well as the output can be earthed with optional resistors if required. Generally at least one resistor must be present to ensure earthing whereas the resistance value controls the connection to the earth if the application could lead to high compensation currents on the DMX shield. A resistance of around 10 Ω ensures that currents cannot reach destructive levels and still provides a proper sink for disturbances. The same idea with optional assembly variants is implemented at the bus termination. If for whatever reason the isolator PCB is not the last node, a bus termination must not be established. The optional bus termination as well as the earthing resistor leaves a certain amount of flexibility to fit for every kind of application.

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[85] ALU = Arithmetic logic unit

[86] Via = drilled hole covered with metal to connect tracks on different layers

Dealing with 230 VAC brings a few restrictions with it although the PCB will be placed in an earthed metal housing. One example for such restrictions is the protective distance between mains voltage and signal voltages which can be reduced by half when it comes to distances between mains and earth. For this reason the earth track is routed on the outside to reduce the required isolation distance.

The last but still very important rule for bus node layouts is to keep the DMX wires as short as possible as it adds parasitic impedances with each PCB connected to the bus.

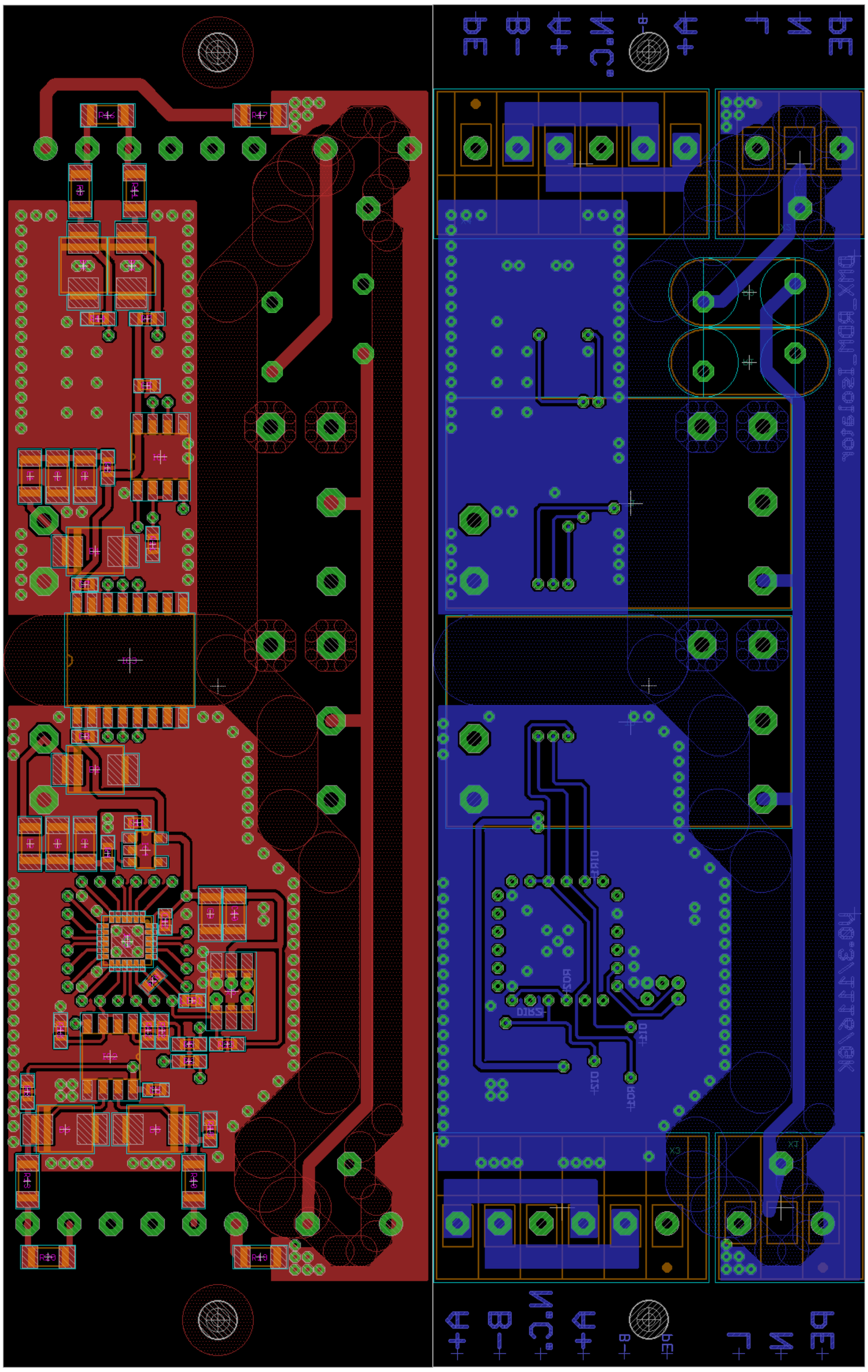

Figure 26: PCB Layout: Red: Top layer, Blue: Bottom layer, Source: own illustration

7.3 Test setup

The SCS error case led to the development of a protection unit for the luminaire against surge overvoltage. Now that the lightning protection of the DMX bus is finished the bus interface should be indestructible by standard surge impulses but still enables potential malfunction due to influences on the DMX signal. Such influences will not be able to damage the receiver irreversible but could trigger wrong colours, flashing lights or cancel entire frames.

The basic idea is to use overvoltage or at least high voltage signals with extreme slew rates to modulate the DMX signal with a parallel routed power cable. In order to ensure a good coupling of capacitive and inductive interferences the power cable will accompany the shielded DMX cable through the entire length of the test setup. To modulate the DMX signals and also the mains voltage in a proper way an according interference source will be necessary.

Figure 27: Cable routing, DMX: grey, mains: white, interference source: black, Source: own photograph

Before tests can start, a well-structured measurement plan is necessary to reduce re-cabling and modification work on the luminaires to a minimum. All necessary modification steps will be listed and categorised by time demand.

Each luminaire will be opened to get access to the connection box where the cable shields can be grounded and mains voltage gets distributed to the LED converter.

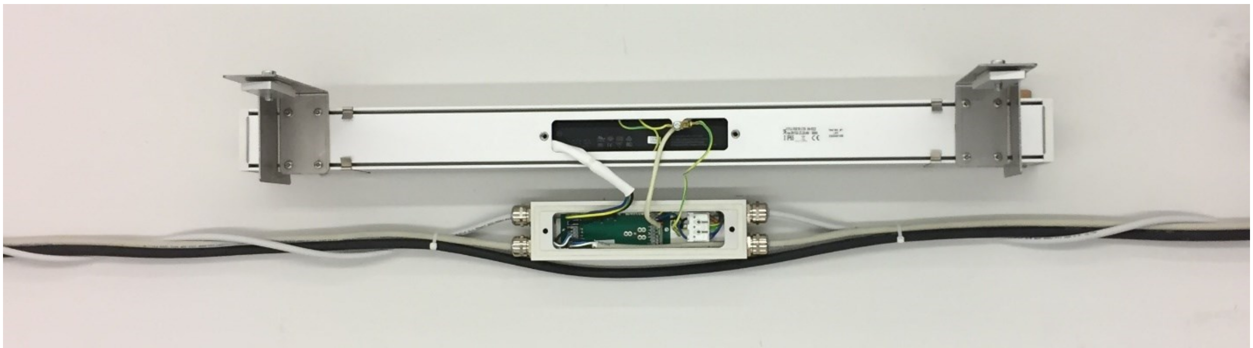

Figure 28: Stila luminaire with open connection box, Source: own photograph

The test setup is build up by 20 luminaires which got manufactured especially for the purpose to execute tests with overvoltage. While the luminaires got manufactured all required cables and measurement devices were selected in order to be ready for testing immediately when production is finished. The following list shows the basic information about the test setup and the used devices.

Description	Quantity	Unit	Manufacturer	Type
Stila Luminaire	20	pcs	XAL	Stila Dynamic DMX Spot 7° RGB
DMX Controller	1	pcs	Pharos	LPC
Frequency converter	1	pcs	ABB	ACH-01-09A4-4
Load motor	1	pcs	OEM	
Cable: FC to motor	70	m	RND cable	H05VV-F 4x1.5mm² black
Oscilloscope	1	pcs	R&S	RTH1004

Figure 29: Test setup equipment, Source: own illustration

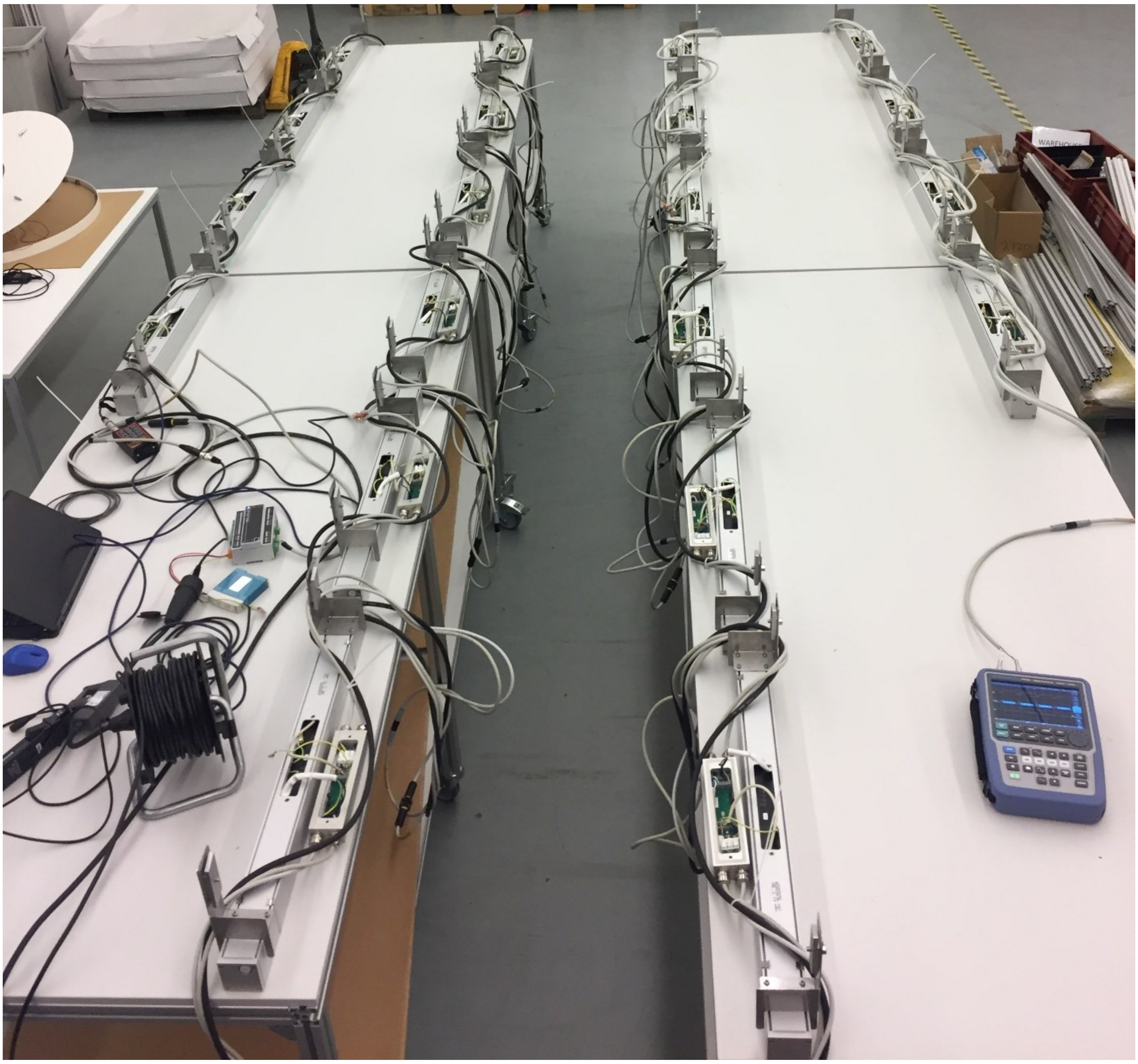

Figure 30: Picture of the test setup, Source: own photograph

7.3.1 Influence and generation of EMI

The previous chapters covered the effects of surge impulses on outdoor luminaires. As surge impulses represent overvoltage typically caused by indirect lightning strike, only complex and oversized circuits could effectively save sensitive DMX interfaces from the immense destructive force of lightning. Where indirect lightning strikes are easier to handle, direct lighting will nearly always destroy the entire fixture completely.

Burst impulses are much more likely to appear in practical applications, as lightning always requires atmospheric influences and some areas on earth are more or less completely save from lightning. It is important to mention that in this context, dealing with surge or burst impulses is always referenced on the EMI test criteria for outdoor luminaires according to Austrian national standards. Overvoltage is generally categorised by amplitude, duration and nature of cause, therefore the waveforms also vary and are being tested according to different standards.[87]

- ESD IEC 61000 4-2
- Surge IEC 61000 4-5
- EFT[88] IEC 61000 4-4
- Switching of inductive loads ISO 7637-2
- TOV[89] no standard

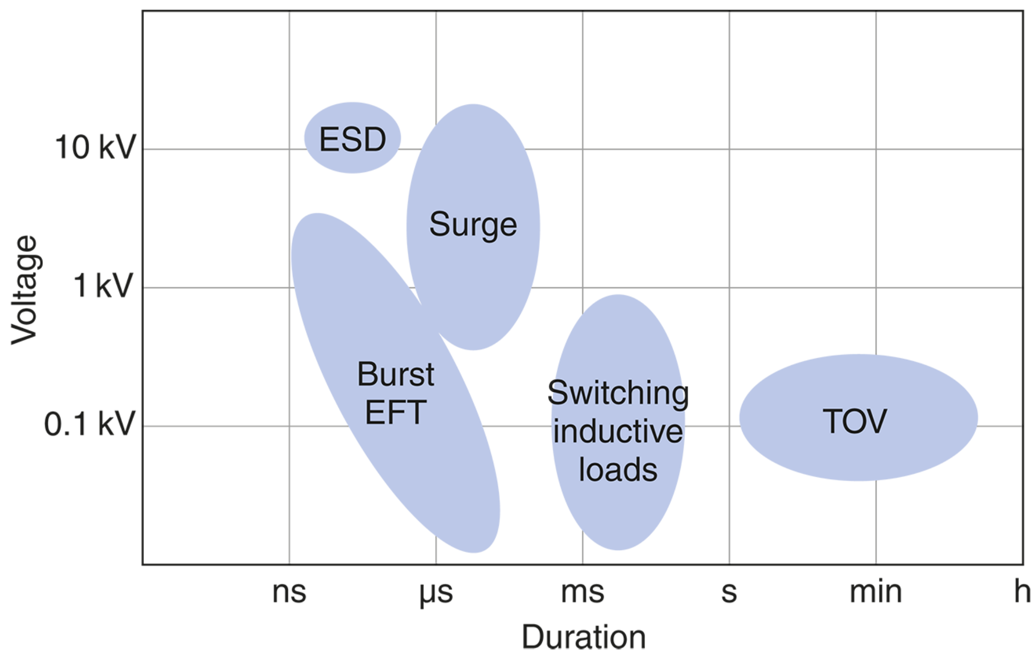

Figure 31: Different types of overvoltage sorted by amplitude and duration, Source: de.tdk.eu Website

[87] cf. TDK (2017), online source [9.March.2017], p. Applications and Cases.

[88] EFT = electrical fast transient = burst

[89] TOV = temporary overvoltage

Due to the varying standards and the probability of appearance, the burst impulses and spikes resulting out of inductive load switching are the points of interest. An outdoor luminaire often faces such influences as HVAC systems or elevator drives generally use frequency converters to drive electric motors with variable speed. The interference caused by these drives can be categorised to the EFT segment and partly to switching of inductive loads.

As the destructive force mainly depends on the energy of an impulse the duration of such is the most important variable. The voltage on the other hand also changes but not with factors of up to 1000 times. The Stila luminaire for example was tested with a surge impulse level of 2 kV and a burst of 4 kV whereas the duration of both overvoltage events changed with a factor of approximately 800.

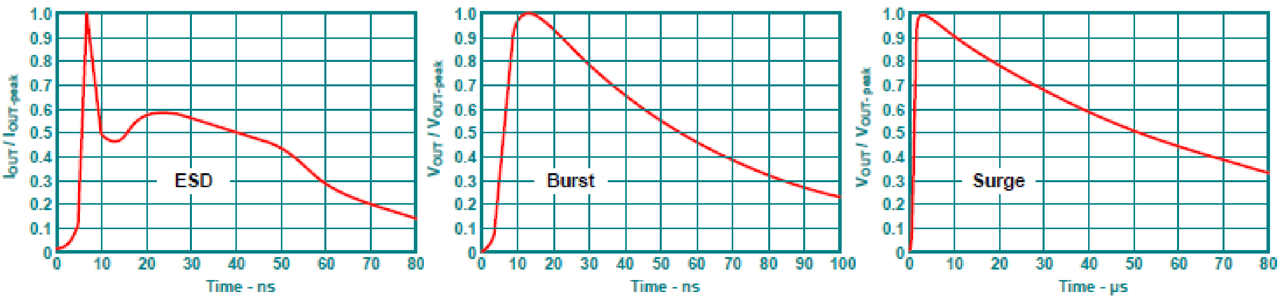

Figure 32: Waveform of ESD, EFT and Surge, Source: TI.com Website

7.3.1.1 Origin of interference

The nature of EMI influences varies as there are multiple potential sources. However, EMI can also become a problem if devices are not protected accordingly. For this reason a perfect shielding and the use of twisted pair cables is very important to reduce sensitivity for EMI to a minimum. However, even if the best cables are used disturbances will still occur for some very common reasons.

- Faulty shielding
    - Source: interference radiated from this device is not inhibited by the shield
    - Sink: interference induced into the device cannot be drained by the shield
- Poor facility planning
    - unnecessary long cable routing
    - too much load on specific tracks
    - no overvoltage protection
    - lots of extensions without general redesign of the plant
    - no distance between signal and power cables
- Cheap components with:
    - poor filtered SMPS
    - high inrush currents
    - non isolated interfaces

7.3.1.2 Simulation of galvanic and air-coupled disturbances

The test setup aims to influence the DMX cable with a parallel cable which carries transient signals or a device that modulates the supply voltage. Therefore the first step is to find typical emitter by referencing past troubles with power quality caused complaints.

The research showed that typical emitters are welding machines, faulty EMI filters of SMPS within industrial plants, power factor correction systems and of course all sorts of variable speed drives. It follows logically that an appropriate emitter for the test setup should be portable, relatively cheap and able to be triggered at any time. This thereby eliminates all listed emitters except the variable speed drive using a frequency converter.

The requirements are only a motor and the frequency converter. Both are relatively cheap in comparison to a welding system or a capacitive bank, even if the required inductive loads would be already present. A poor filtered SMPS will not cause comparable serious disturbances like a frequency converter. Also the resulting frequency of the disturbances would be higher than those of the frequency converter due to the usually higher switching frequency and resulting slew rate of the SMPS.

Additionally to the artificial-injected disturbances the power supply of each luminaire will cause its own system perturbation and therefore worsen the DMX signal on the parallel wire.

The luminaries are not placed right on the ground but will be mounted on a frame to facilitate the measurement process itself and not to shield potential fields that would impact on the signals. The test setup should be held realistic to deliver as useful results as possible.

Frequency converters are very common when it comes to any kind of controllable motor application such as escalators, HVAC systems, elevators and almost every industrial machine using motors. For this reason it is not only a cheap possibility to generate disturbances, it also is the most realistic simulation. The missing galvanic coupling simulation is established by an artificial deterioration of the grid impedance with the help of a low-cross-section supply cable. The FC to motor connection will be held as short as possible for galvanic coupling to minimise the air-coupled share of disturbances. The air-coupled part on the other hand requires a good grid impedance forcing a short connection cable with high cross section to the distribution board.

7.3.2 Measurement planning

To obtain the best results, a careful planning of the measurements is of utmost importance. A structured measurement plan improves the validity of the following analysis and saves enormous amounts of time due to necessary modifications between each measurement.

First, the relevant aspects of interest need to be found to determine respective procedures of examination. These aspects result out of the above handled error case as well as the theoretical part and led to the following elaboration of matters which are already arranged in the optimal order to minimize the amount of work due to modification.

7.3.2.1 Shielding

The basic DMX chapter already described the issues and pitfalls coming along with grounding of cable shields. For this reason the test should figure out how important it is to ground the shield with special attention on the place where the shield is grounded. To determine the number of measurements it is important to figure out which results are of interest or which constellations are possible in applications. As this part brings the largest amount of work as far as modifications are concerned.

There are three different types of how one can deal with shielding. As the used wires are always shielded, the worst case is to let the shield float without any ground connection.

The second measurement will cover a single-sided shield-grounding, which means that only the DMX output shield of each fixture is grounded. Connecting it to the next fixture will therefore indirectly ground the input wire of the next fixture in the line. This is a very promising constellation as there will be a drain path for induced currents and on the other hand the shield is still not able to carry compensation currents as it does not connect two different ground potentials.

As a logical supplement to the two described variants the last one will focus on a double-sided shield connection to ground. This variant represents a common way to deal with wire shields. As far as disturbances and effectiveness of wire shielding is concerned a double-grounded shield is the best protection against interferences but closes a ground-loop which could help to compensate potential differences of the electrical installation.

7.3.2.2 Coupling mode to interference source

As the interference source is a frequency converter with unfiltered 2.5 kW of inductive load, the idea is to change the wiring in order to either route the supply cable for the FC and all fixates along the fixtures or route the FC output parallel to the fixture’s signal cables. Changing the wiring of the setup is less time demanding than executing modifications on the shielding but still is hard work in comparison to the other tasks. For this reason the modification of the coupling mode is the second part.

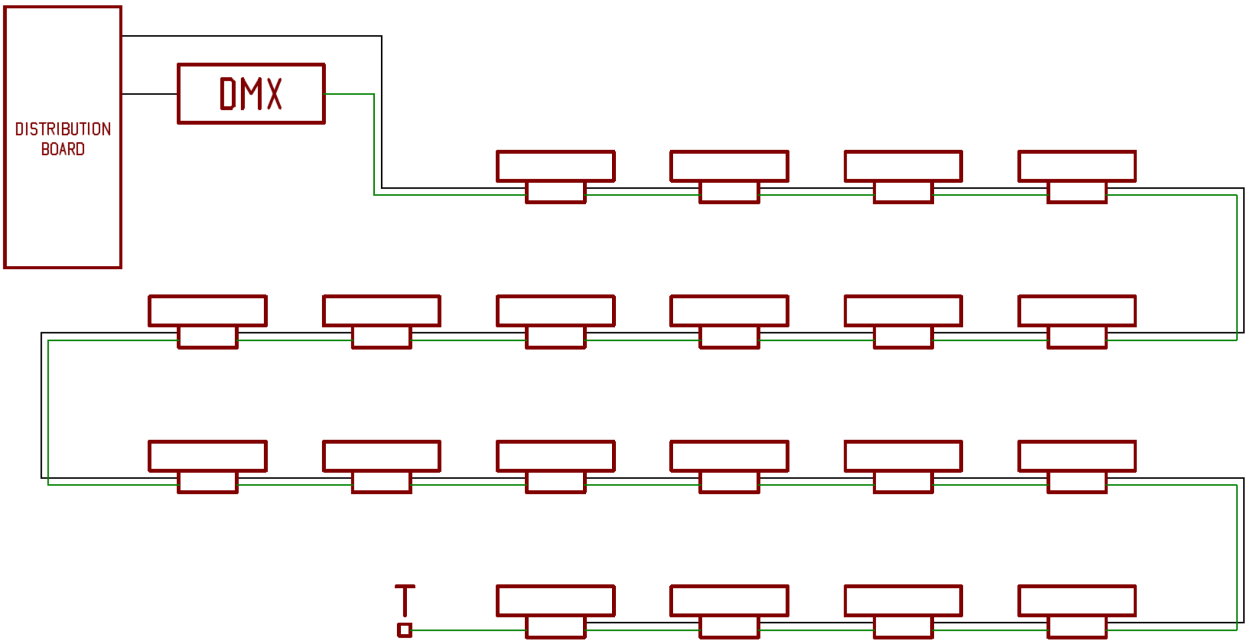

Figure 33: Reference Schematic without any interference source (xNxT), Source: own illustration

As already mentioned there are two ways planned to disturb the DMX signal with the help of the EMI source. The first concept is based on direct coupling which is typically of increasingly importance as the grid impedance decreases due to long supply cables or a bad connection to the power grid in general. The direct coupling test aims to simulate a relatively long supply cable with high resistance of a sub distribution board. This distribution board supplies both, the FC and the fixtures. A resulting modulation of the supply voltage by the FC therefore influences the fixtures and their mains. This particular test environment deliberately increases the negative influences additionally but in industrial plants this is an absolutely common aspect of EMI.

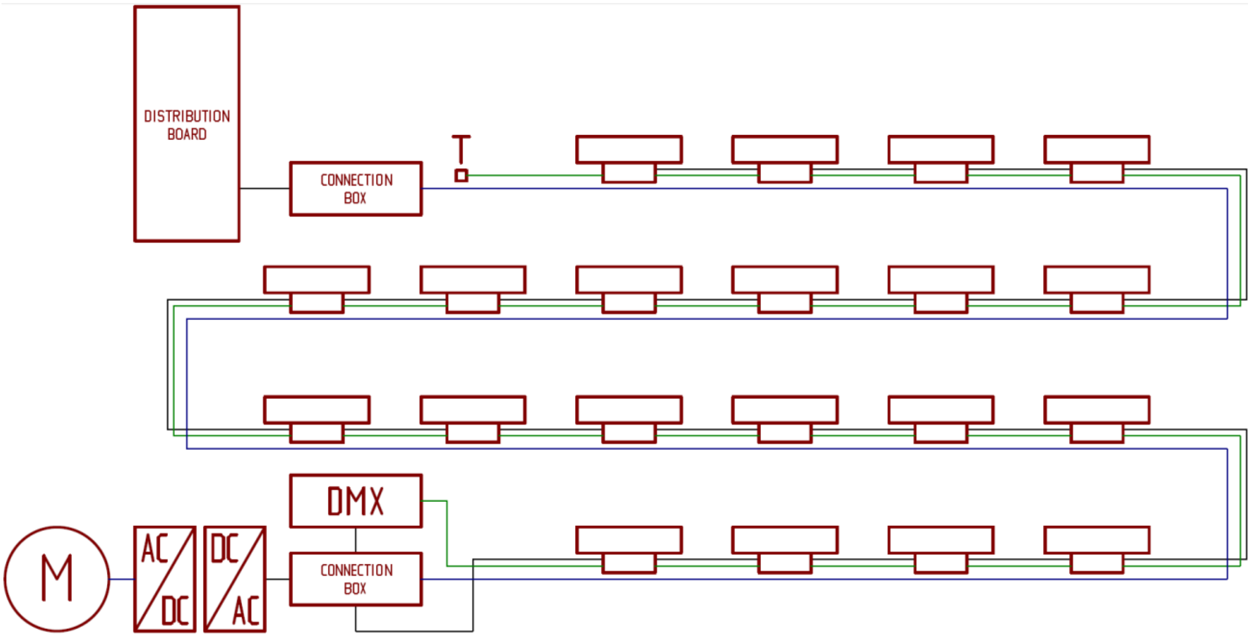

Figure 34: Schematic for the galvanic-coupled simulation (xGxT), Source: own illustration

Frequency converters are often afflicted with negative preconceptions in the context of EMI. Essentially, these thoughts have no right of existence as long as the electrical installation complies with national and international standards, but it frequently happens that installers and electrical engineers forget about these guidelines or sometimes even ignore them. This leads to massive disturbances as especially the output of a FC drives high currents and voltages combined with steep edges caused by the fast semiconductor switches. For this reason it is interesting to find out how the output of a FC disturbs the DMX signal due to capacitive and inductive coupling. Moreover this setup does not connect the fixtures and the FC in any kind as also the supply voltage for both comes from different distribution boards. In this context it is referred to as air-coupled.

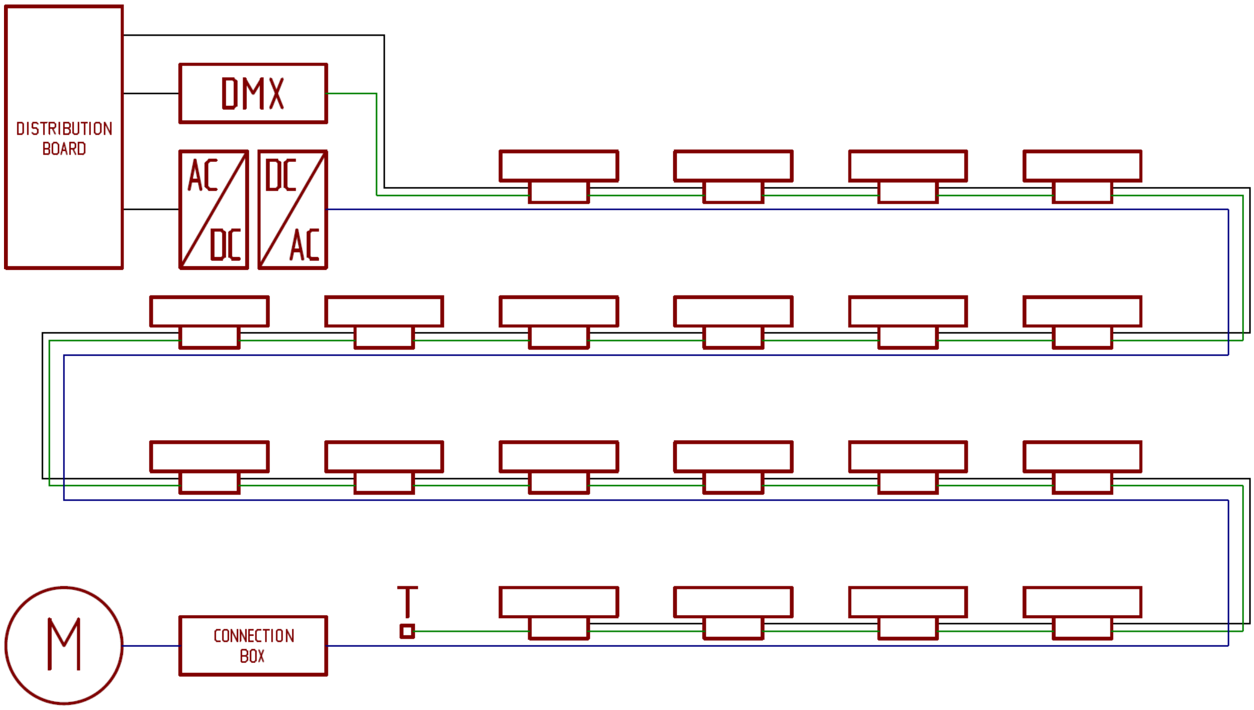

Figure 35: Schematic for the air-coupled simulation (xAxT), Source: own illustration

In this section it is important to be aware of the fact that there will not be a separation between the different coupling modes as a real application always brings all three coupling modes together. The experiment is only focused to reinforce galvanic and air coupling to get scalable results.

7.3.2.3 Measurement point

The third variable of the measurement is the local factor of influences. The DMX signal on the output of the controller will differ from all other signals along each fixture. An ideal system is built up by ideal cables with no changes of characteristic impedance and no parasitic effects but real systems add certain discrepancies. For this reason the signal level will not only decrease over distance but also receive modulation from reflexions, overshoots and interferences.

Therefore the most important points to measure the signal are at the start and the end of the cable and additionally in the middle right after the 10th fixture.

7.3.2.4 Bus termination

DMX needs a bus termination to inhibit signal reflexions from the cable's ends. Depending on the cable length the terminator is more or less important, so the test setup got a meaningful size of 20 fixtures. As the termination resistor is the easiest part to modify within the system it is the last point and toggles with every single measurement.

7.3.2.5 Measuring table and nomenclature

Measurement nomenclature: 1 2 3 4

	Shielding
1	D = double-grounded S = single-grounded F = floating shield

	Coupling
2	N = no frequency converter G = galvanic coupling A = air coupling

	Measuring Point
3	S = start M = middle E = end

	Termination
4	N = no termination T = terminated

Table 3: Measurement nomenclature, Source: own illustration

		Shielding			
		double-grounded shield	single-grounded shield	no shield grounding	
Coupling	no frequency converter	D N S N	S N S N	F N S N	start
		D N S T	S N S T	F N S T	
		D N M N	S N M N	F N M N	middle
		D N M T	S N M T	F N M T	
		D N E N	S N E N	F N E N	end
		D N E T	S N E T	F N E T	
	galvanic-coupled frequency converter	D G S N	S G S N	F G S N	start
		D G S T	S G S T	F G S T	
		D G M N	S G M N	F G M N	middle
		D G M T	S G M T	F G M T	
		D G E N	S G E N	F G E N	end
		D G E T	S G E T	F G E T	
	air-coupled frequency converter	D A S N	S A S N	F A S N	start
		D A S T	S A S T	F A S T	
		D A M N	S A M N	F A M N	middle
		D A M T	S A M T	F A M T	
		D A E N	S A E N	F A E N	end
		D A E T	S A E T	F A E T	

Measuring Point

Table 4: Measurement plan with colour coded signal quality prediction, Source: own illustration

7.3.3 Measurement results

In order to receive comparable waveforms, the DMX controller sends out the same value for each of the 512 slots within the DMX frame. This enables the oscilloscope to record a waveform with the help of a single shot, as all data frames look the same, therefore focus can be on capturing meaningful pictures of interferences.

The Oscilloscope offers a math function which enables a mathematical waveform of DMX+ subtracted by DMX-. The result is the mathematical equivalent to the internal output of a RS-485 interface. Both DMX poles are referenced to the shield potential, which will not cause any issues on the double or single-grounded measurements, while the floating shield will create a virtual ground.

In total, 54 different waveforms are captured to get an impression of each possible constellation within the measurement plan. Furthermore, there is too much information to analyse and to compare to each other. For this reason only the most differing or promising results will be compared on the following pages. In order to understand the nomenclature of the waveforms, please refer to the measurement plan and the respective table explaining the nomenclature in detail.

To keep the thesis structured and informative, the according waveforms are included in the appendix. The examples always put two waveforms in comparison with respective pictures on one page. The described waveforms are sorted according to their appearance in this thesis.

7.3.3.1 Floating shield: FAET vs. DAET

This example perfectly shows how important a proper grounding of cable shields it. The floating shield waveform is completely destroyed by the high-frequency voltages of the air-coupled output of the frequency converter. In this case the main problem is that the interferences collected by the shield cannot be drained to ground.

The distortion of the mathematical signal contains spikes which lead to a malfunction of luminaires along the DMX path, as spikes are reaching low levels which the receiver unit interprets as 0 instead of a 1. The optical effect is that some luminaires sometimes flicker as the distortion reaches their specific slot within the DMX frame.

The double-grounded shield, on the other hand, shows that the high-frequency part can be effectively drained by both grounded ends of the shield. In this case the air-coupled interferences are mainly of common-mode nature, as the subtraction eliminates it almost completely. The high-frequency disturbances, on the other hand, tend to be in differential mode, thus limiting the advantages of differential signaling.

7.3.3.2 Single-grounded shield: SAMT vs. DAMT

The huge difference between a single-grounded shield and a double-grounded shield were hardly expected, as the total cable length to the next luminaire is only 3 m. However, the luminaires showed no optical change although the signal does not appear valid anymore. As far as this thesis is concerned, this measurement perhaps is one of the most important ones. Amongst the field application engineers, there are supporters for both options of grounding. However, the waveform speaks a different language.

If it is not the case that a project already fights with massive problems regarding potential equalisation, the recommendation is to definitely ground the shield on both ends, although the signal was still valid and no influences were detected.

7.3.3.3 Termination resistance value: DNET vs. DNEN

The practically measured waveforms underline the importance of termination. To reduce other influences and focus only on the impact of termination with a 120 Ω resistor, these waveforms are measured without additional sources of interferences. The result is increasing overshoots on the edges, which could also lead to false high or low triggering. However, in this particular case no optical influences appeared.

7.3.3.4 Termination over distance: DNST vs. DNET

A bit of an unexpected result brought the comparison of the same setup measured at the start and at the end. The expectation was that signal quality will decrease over cable length and therefore the end will receive a worse signal than the start. It turned out to be the exact other way round. The reason for this phenomena is very likely the remaining signal reflexion which goes back to the start where it reaches the DMX controller. The other option is it to be a coincidence, as the difference is still absolutely minimal.

7.3.3.5 Effectiveness of differential signaling: FGMT vs. FNMT

Differential signaling is supposed to delete or subtract interferences induced into both conductors of a cable. Generally, both wires have exactly equal impedances, which the test setup proofed very well. The frequency converter, as already mentioned, tends to produce common mode interferences which can be eliminated easily with the help of differential signaling.

The galvanic-coupled test shows slight disturbances of the square wave signal. However the mathematical result eliminates the undesirable small spikes completely.

7.3.3.6 Noisefloor and environmental influences: FNMT vs. DNMT

The final comparison shows the noisefloor and the influence of shielding on it. The resulting signal is always of perfect condition although the floating shield seems to leave some capacitive common mode interferences pass through to the signal.

7.3.4 Conclusion

In conclusion, the results do surprisingly differ greatly from the expectations. The interferences generally are of two kinds: high and low frequency. It furthermore seems that this test setup also generated different modes of both. While the high frequency interferences tend to be in differential mode, the lower frequencies are drawn to the common mode. During the build-up, it was not entirely clear whether the frequency converter would be able to generate sufficient disturbances due to the fact that it is a derivate which only emits 3 % THDu[90] at maximum. However, the results definitely show that even such devices modulate the supply voltage by a significant amount.

The biggest difference between the expectation and the result is the single-grounded shield. This waveform really shows the importance of proper grounding. The general recommendation regarding shield ground therefore definitely is pro-double-grounding. It is definitely worth to take a chance of compensation current along the wire shield to protect the signal from interferences even better.

Finally, to briefly introduce the financial aspect, it can be stated that the costs for components at approximately 10,000 € and 200 working hours is definitely worth the newly acquired information about this particular product and its behaviour. Moreover, costs for potential customer complaints leading to a complete replacement of the faulty system would be many times higher.

[90] THDu = total harmonic distortion of the supply voltage

8 SUMMARY

As this thesis is well-placed between theoretical and practical aspects, it covers basic knowledge of wireless data transmission, network topologies and elaborates the most important technologies required to build the basis for a network. This knowledge helps to understand how the respective systems work and why there are certain limitations to each network system.

The practical part deals with compatibility issues between the countless wireless systems on the market, as the outcome of a specific market analysis presents a selection of the currently most important wireless lighting systems. This part will help to select the best system for an application and save time as the basic information is now appropriately documented.

The most complex and time-demanding part is definitely the DMX in practise, as it contains multiple views on one system which is still standard for professional lighting even after many years in existence. The troubleshooting part required the inspection of the electrical distribution system within an entire shopping mall, the development of an isolator PCB including the firmware, which was time-demanding, as multiple improvement loops needed to be undertaken.

The final part elaborates and simulates the environmental influences within industrial areas. It is perhaps the most interesting part, as also the client company takes the biggest advantage out of it. While it is very demanding to measure such an amount of waveforms in order to get comparable results, the outcome is definitely worth it.

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LIST OF ILLUSTRATIONS

LIST OF TABLES

APPENDIX 1: WAVEFORMS

Figure 36: FAET, Source: own illustration

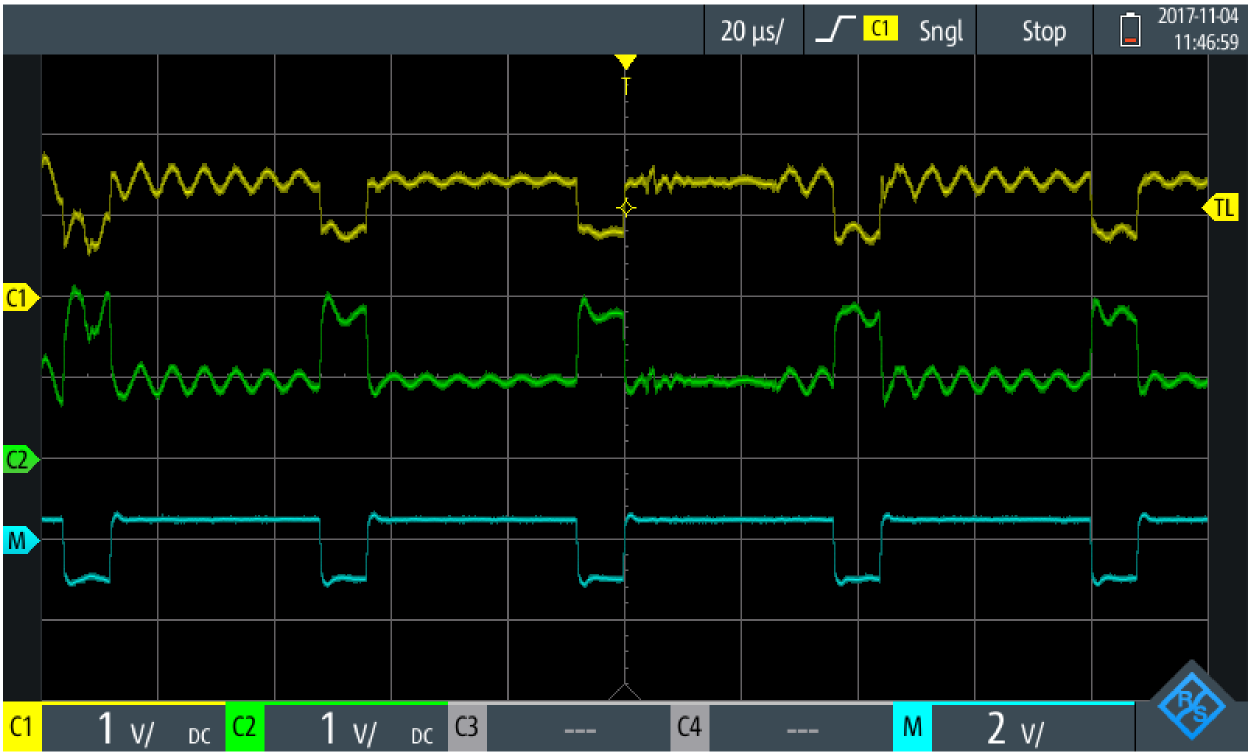

Figure 37: DAET, Source: own illustration

Figure 38: SAMT, Source: own illustration

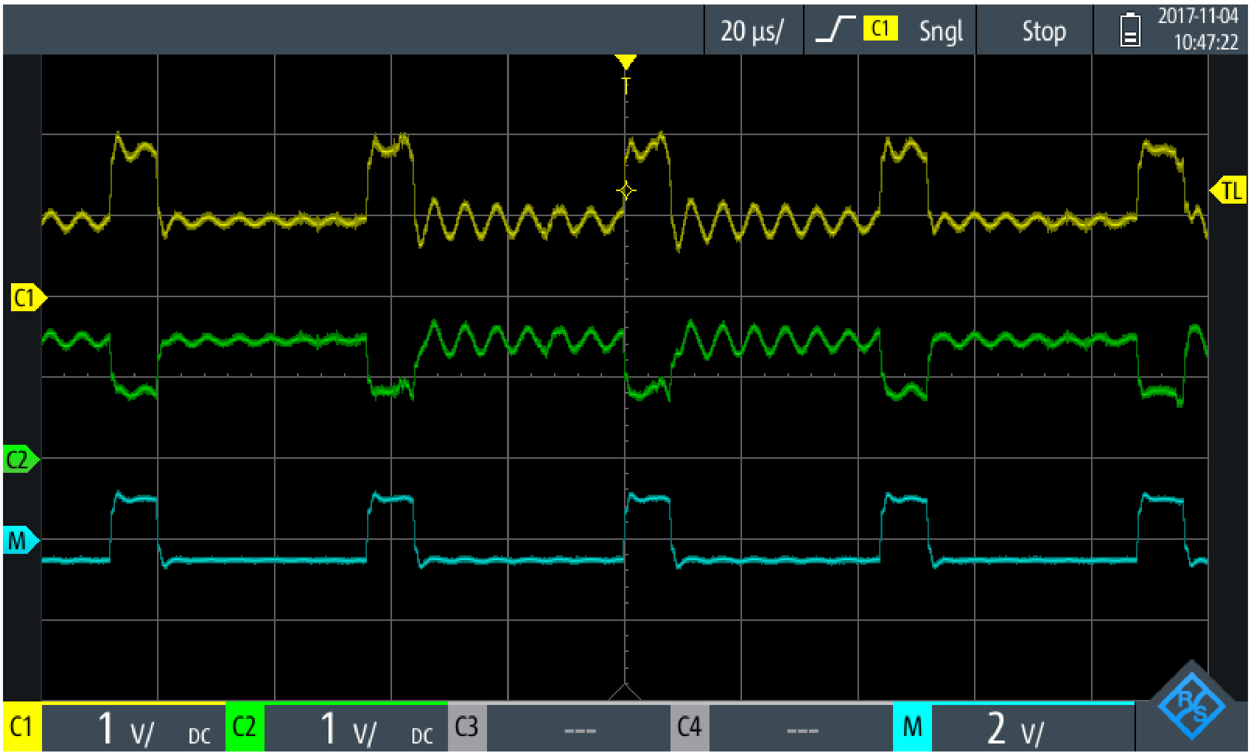

Figure 39: DAMT, Source: own illustration

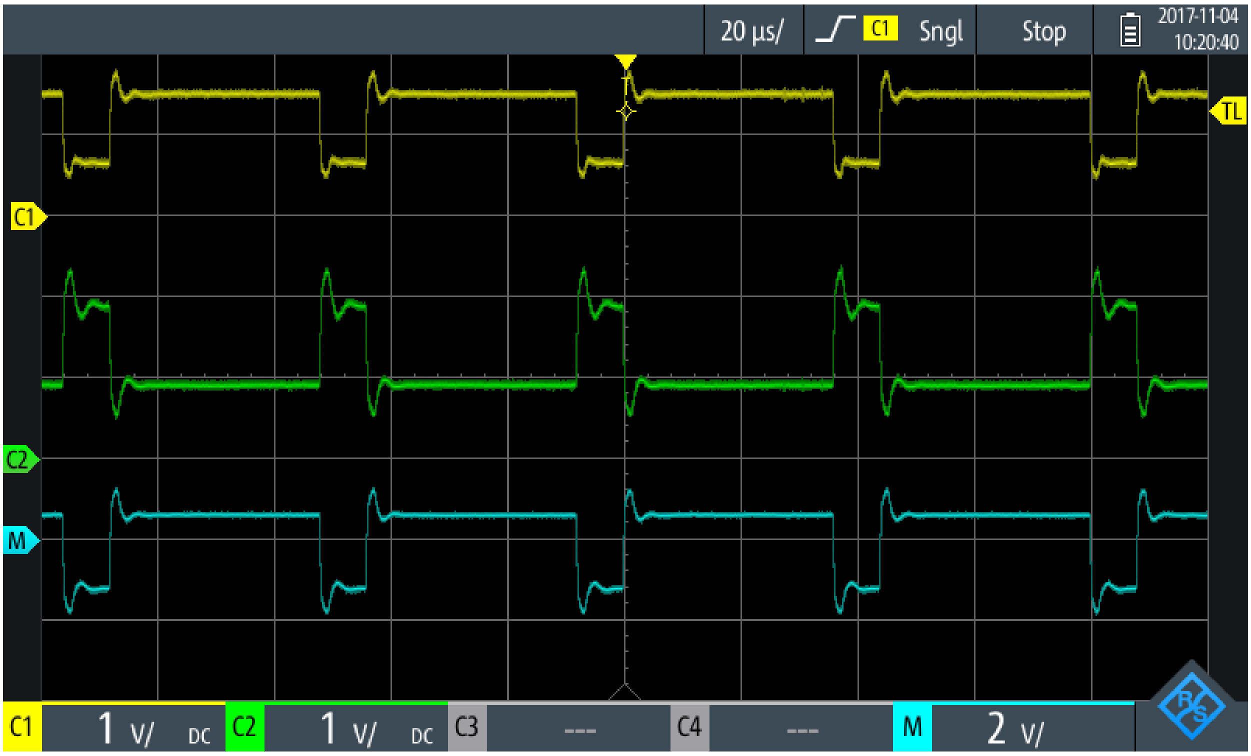

Figure 40: DNEN, Source: own illustration

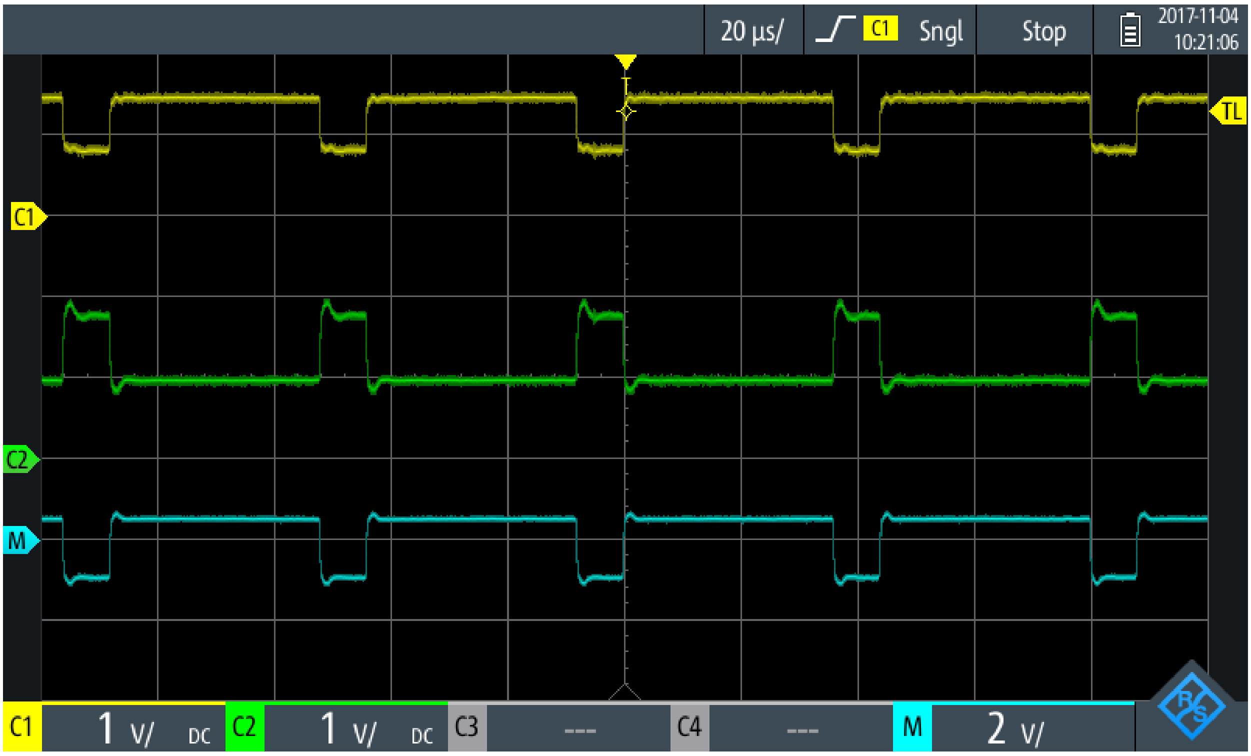

Figure 41: DNET, Source: own illustration

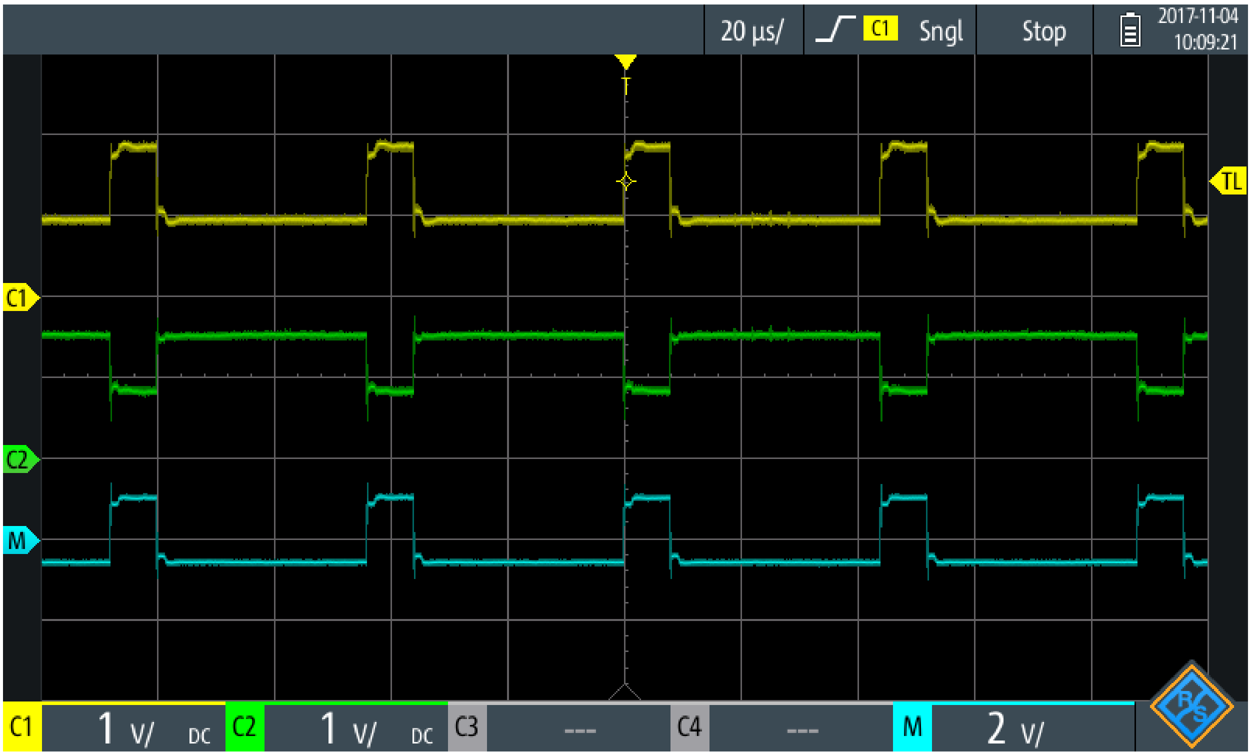

Figure 42: DNST, Source: own illustration

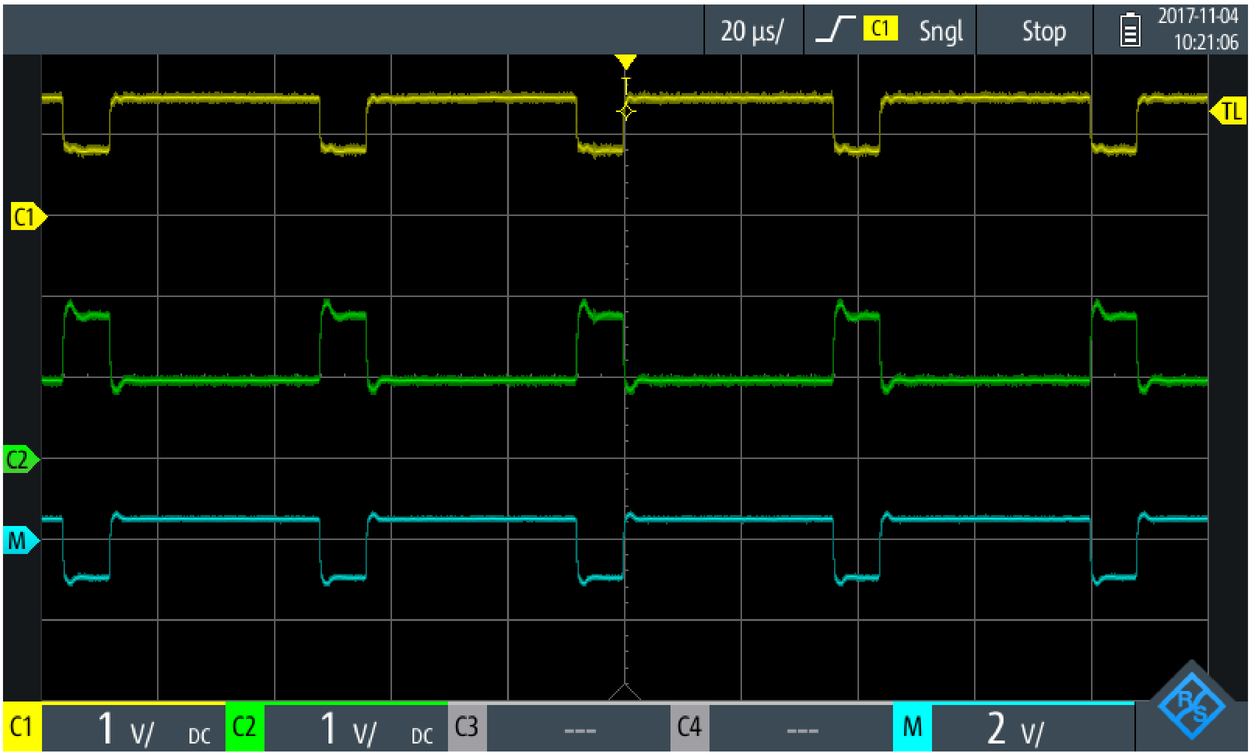

Figure 43: DNET, Source: own illustration

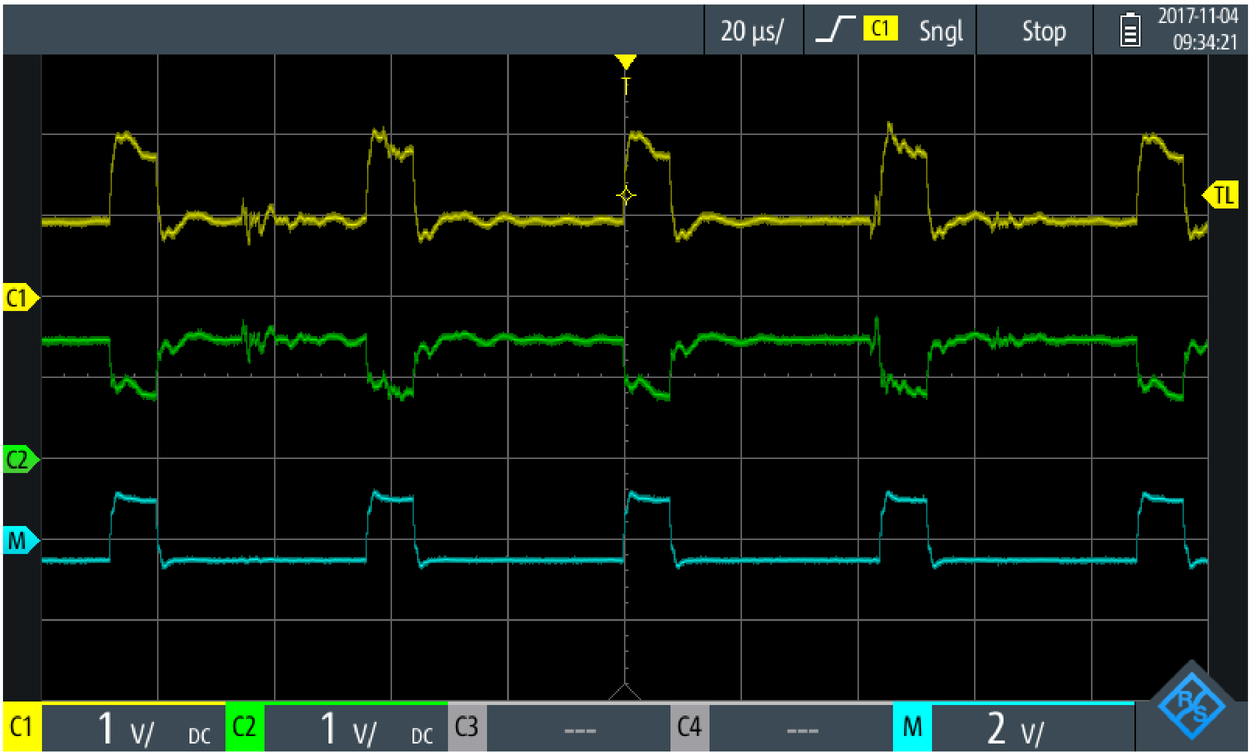

Figure 44: FGMT, Source: own illustration

Figure 45: FNMT, Source: own illustration

Figure 46: FNMT, Source: own illustration

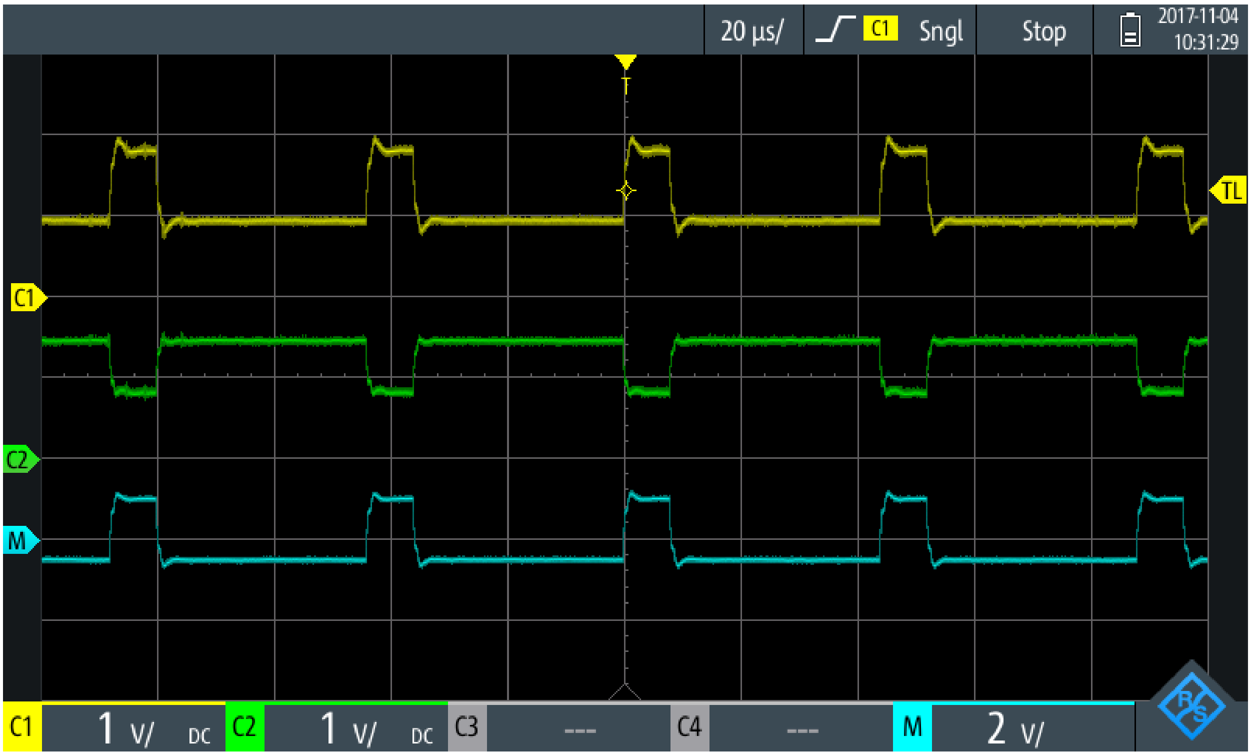

Figure 47: DNMT, Source: own illustration