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LIGHTING ADJUSTMENTS WITH DIGITAL CONTROL SIGNALS

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LIGHTING ADJUSMENTS WITH DIGITAL CONTROL SIGNALS

The purpose of this thesis was to study lighting design, lighting control and the differences between various lighting control systems. The thesis was commissioned by Meyer Turku Oy and the aim was to study the different technical characteristics of the lighting control systems and the control methods of the systems and to design a possible lighting system with DALI.

The thesis was conducted as a study to lighting design, lighting control, lighting measures and analog and digital lighting control systems and their methods of control. Information was obtained from lighting specialists and from books and standards relating to lighting and lighting systems.

The result is a fairly comprehensive study focusing on lighting design, lighting control, lighting control systems, technical characteristics of lighting control and a designed lighting system using DALI.

KEYWORDS:

DALI, DMX, lighting control, analog signals, digital signals

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VALAISTUKSEN SÄÄTÖ DIGITAALISILLA KONTROLLISIGNAALEILLA

Tämän opinnäytetyön tarkoituksena oli tutkia valaistussuunnittelua, valaistusohjausta ja erilaisten valaistuksenohjausjärjestelmien eroavaisuuksia. Opinnäytetyön toimeksiantajana oli Meyer Turku Oy ja opinnäytetyön tavoitteena oli tuoda esille eri järjestelmien teknisiä ominaisuuksia ja järjestelmien ohjausmenetelmät sekä suunnitella mahdollinen tuleva valaistusjärjestelmä DALI:lla.

Työ toteutettiin tutkimustyönä valaistussuunnitteluun, valaistusohjaukseen, valaistussuureisiin sekä analogisiin ja digitaalisiin valaistuksenohjausjärjestelmiin ja niiden säätötapoihin. Tietoa hankittiin valaistusasiantuntijoilta sekä valaistusta ja valaistusjärjestelmiä käsittelevistä kirjoista ja standardeista.

Lopputulokseksi saatiin suhteellisen kattava tutkimus valaistussuunnittelusta, valaistusohjauksesta, valaistuksenohjausjärjestelmistä, valaistuksenohjausjärjestelmien eroavaisuuksista ja teknisistä ominaisuuksista sekä suunniteltu mahdollinen tuleva valaistusjärjestelmä.

ASIASANAT:

DALI, DMX, valaistusohjaus, analogiset signaalit, digitaaliset signaalit

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LIST OF ABBREVIATIONS (OR) SYMBOLS

A	symbol of area
E	symbol of illuminance, unit lux lx
I	symbol of luminous intensity, unit candela cd
K	symbol of temperature, kelvin
kWh	kilowatt-hour, energy unit
L	symbol of luminance, unit cd/m^2
ϕ	symbol of luminous flux, unit lumen lm
p_n	Guth position index, a measure used for calculating glare
R_a	symbol used for Color Rendering Index
sr	symbol of steradian, square radian
W	symbol for energy consumption
CLO	Constant Light Output
CRI	Color Rendering Index
DALI	Digital Addressable Lighting Interface, a digital lighting control protocol
DiiA	Digital Illumination Interface Alliance
DLT	Digital Load-Side Transmission Lighting Control, a lighting control protocol
DMX512	Digital Multiplex, a protocol for digital lighting control
DSI	Digital Serial Interface, a digital lighting control protocol
EIB	European Installation Bus
ESTA	Entertainment Services and Technology Association
IGBT	Insulated Gate Bipolar Transistor
LED	Light Emitting Diode
LENI	Lighting Energy Numerical Indicator
LON	Local Operating Network, a protocol developed by Echelon Corporation to control multiple devices
PLC	Power Line Communication
PWM	Pulse Width Modulation

RDM	Remote Device Management
RGB	color model consisting of tones of red, green and blue color
TRIAC	triode for alternating current
UGR	Unified Glare Rating, a measure of glare in an environment
UPB	Universal Powerline Bus

1 INTRODUCTION

The purpose of this thesis is to study lighting design, lighting control, lighting control systems and the differences between various control systems. The main focus of the thesis is on studying various analog and digital lighting control systems and their principal characteristics. The thesis also covers lighting design requirements.

Lighting control methods have numerous studies, comparisons, reports and theses relating to the methods and their benefits, for example a report about energy performance of automatic lighting control systems by Morad R. Atif and Anca D. Galasiu for the National Research Council Canada in 2003 that compared and measured the effects of daylight on two different buildings. Lighting control systems have less studies and comparisons relating to them, but they have multiple standards, theses and also case studies focusing on a specific control system. For example a study of lighting control system for a daylit office by Chih-Jian Hu, Chung-Chih Cheng, Hsiao-Yuan Wu and Nien-Tzu Chao for the World Academy of Science, Engineering and Technology in 2012.

Good lighting requires an control system that is adjustable and suitable for the use. The lighting requirements can change multiple times a day and thus lighting control systems have a big impact on the usability of the space. Control systems also affect the comfortability, energy consumption and the ease of operation. The properties of a control system are often derived from needs and requirements of the space and its intended use.

The thesis covers some of the measures related to lighting and the theory of lighting design requirements in chapter 2. Chapter 2 also covers LENI, Light Energy Numerical Index, and energy efficiency of lighting. Chapter 3 covers the different lighting control methods, the advantages and the possible hindrances of different lighting control methods and the general advantages of lighting control. Chapter 4 and 5 cover the various analog and digital lighting control systems, the main focus of the chapters being the principal and technical characteristics of the various systems. Chapter 6 covers the planning and design process for a DALI lighting system. Chapter 7 summarizes the subjects of the thesis. The final conclusions and possible future developments are also presented in chapter 7.

2 LIGHTING DESIGN

Light is produced in relation to need and situation, which means a control system with which lighting can be adjusted flexibly in different situations is needed. This need for lighting control can be called as functional requirement, other requirements being energy efficiency and aesthetic requirements. Figure 1 illustrates the process for choosing a lighting solution. [1, 2]

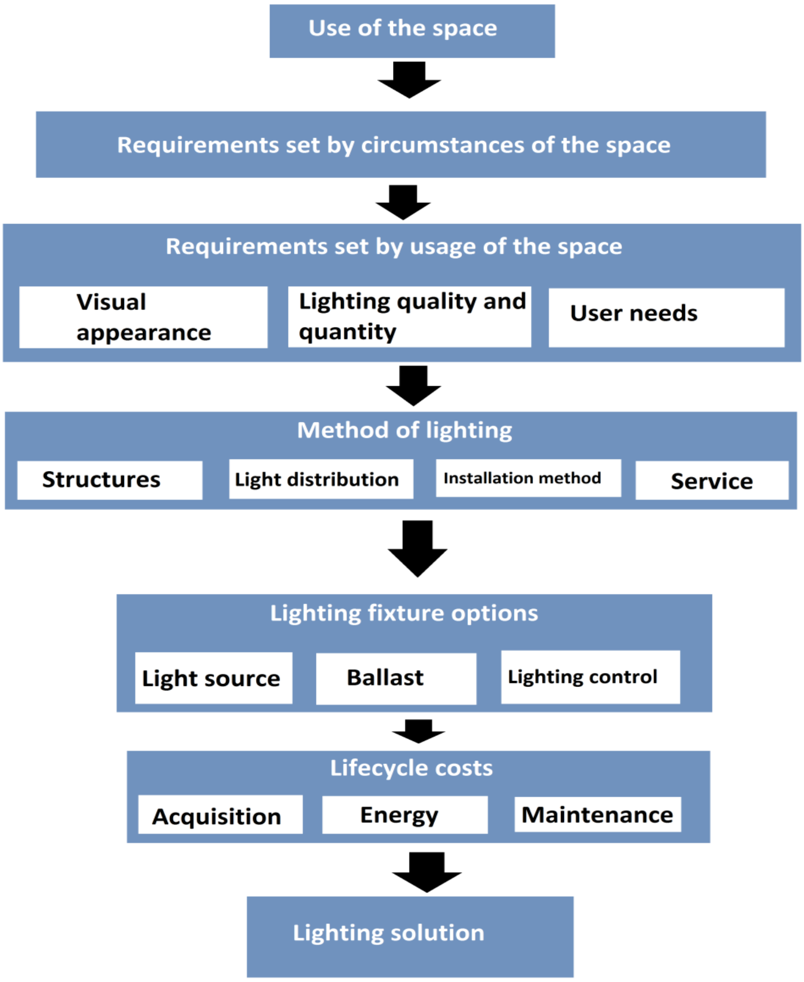

Figure 1. Example process of choosing a lighting solution.

2.1 Functional requirements

Good lighting means most of all practical, energy efficient and aesthetical lighting. Good lighting is suitable for its environment, works technically well, is overall economical and environment friendly. Lighting should also be sufficiently powerful and adjustable for the needs of the user. For example, for efficient working it's important that there is enough light. It should also be taken care of for the lighting to be adjustable to meet the requirements of daylight, season and work requirements. [1, 3]

2.2 Quality requirements

Lighting technical quality requirements are objectives and measures that help to create ergonomically working visual environment. These lighting technical quality requirements are luminous intensity, luminance, luminance distribution, glare, light output format, color rendering, color temperature and flicker. Table 1 illustrates lighting units and measures. [1, 3]

Table 1. The measurement of light. [1]

Quantity and symbol	Unit	Unit symbol	Defined as
Luminous Intensity *I*	Candela	cd	The luminous intensity of a 555,016 nm (or 540 * 10^{12} Hz) source which has a radiant intensity in a given direction of 1/683 Watts per steradian, when measured in that direction. (Formerly defined as 1/60 of the intensity of a square centimeter of a blackbody at the temperature of solidification of platinum.)
Luminance (or "Photometric brightness") *L*	Candela per square meter (also known as the "nit")	cd/m^2	The intensity of a source in a given direction, divided by its orthogonally projected area in that direction.
Luminous Flux *F*	Lumen	Lm	An isotropic (one which emits radiation equally in all directions) point source of intensity one Candela produces a total luminous flux of 4π lumens.

(continue)

Table 1. (continue).

Illuminance *E* (also Illumination)	Lux	Lx	The concentration of luminous flux falling on a surface. One Lux is one Lumen per square meter.
Radiant Intensity I_e	Watts per steradian	W/sr	Radiant power emitted by a point source in a given direction.
Radiance	Watts per steradian per square meter	$W/(sr.m^2)$	The radiant intensity of a source in a given direction, divided by its orthogonally projected area in that direction.
Radiant Flux ϕ_e	Watts	W	Radiant power of a source at all wavelengths.
Irradiance *E*	Watts per square meter	W/m^2	Radiant power incident on a surface.

2.2.1 Luminous intensity

The symbol of luminous intensity is *I*. The unit for luminous intensity is candela and the symbol for candela is *cd*. One candela is the luminous intensity, in a specified direction, of a light source that emits monochromatic radiation, meaning the radiation only has a single wavelength, in a frequency of 540 THz and that has radiant intensity in the specified direction of $\frac{1}{683}$ watt per steradian (*sr*). Figure 2 illustrates luminous intensity. [4, 5, 6]

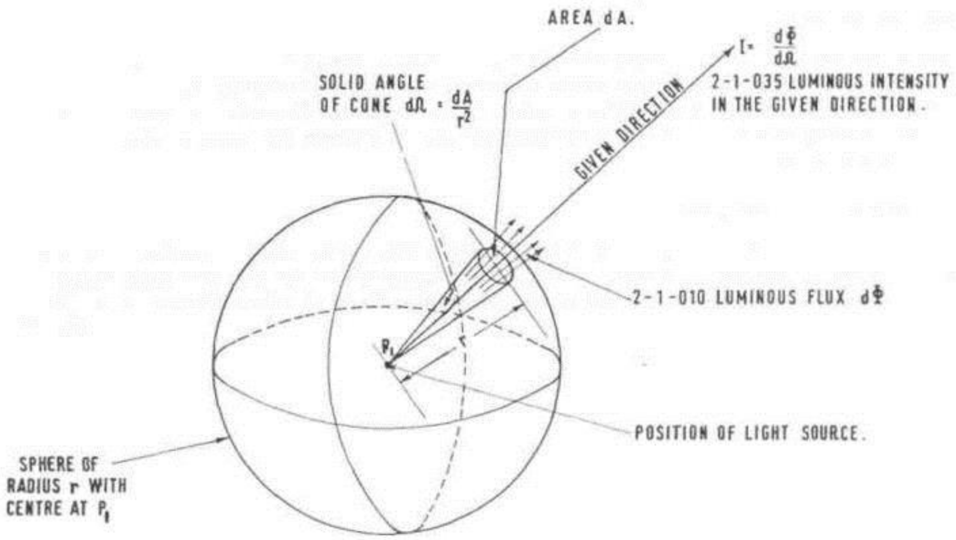

Figure 2. Luminous intensity illustration. [5]

2.2.2 Luminance

The symbol of luminance is L and the unit is candela per square meter (cd/m^2). Luminance characterizes how much luminous power an eye looking at a light emitting or reflecting surface will detect from a certain angle. Simply put luminance indicates how bright a surface will appear. Figure 3 illustrates luminance. Luminance can be calculated in the following manner:

$$L = \frac{I}{A}.$$

Where I is luminous intensity (cd) and A is area (m^2). [4, 6, 7]

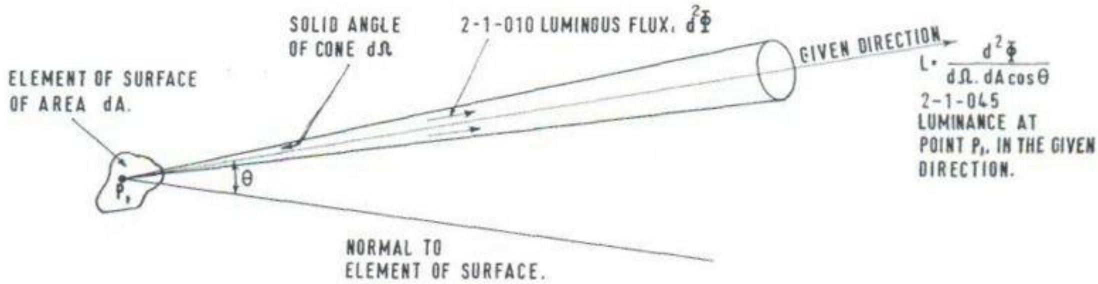

Figure 3. Luminance illustration. [7]

2.2.3 Luminance distribution

Luminance distribution in the field of vision defines the human eyes level of adjustment, which impacts the visibility of the object. A favourable luminance distribution is usually implemented by defining lighting requirements and recommended reflection factors for the most diffuse reflecting surfaces. Large variations of luminance in a field of view are prevented by setting requirements for illuminance and particularly bright object's visibility are sought to be limited for example by shielding angle requirements. [4, 6]

2.2.4 Glare

Glare is caused when the luminance of the environment is so high that the human eye can't adjust anymore. Glare in itself makes the vision conditions worse and is in general one of the most common grievances in lighting design. Glare can be divided to discomfort glare and disability glare, they are not exclusive of each other and can appear at the same time. A reflection that appears on an object that partially or wholly obscures the details by reducing contrast is called a veiling reflection. [4, 6]

A common source of glare caused by lighting in a field of vision is a luminance that is a lot higher than the other luminances in the space. This can be a light source located in the field of vision (direct glare) or a surface that intensively reflects light (glare by reflection). Daylight is a significant cause of glare that also happens indoors. Glare makes it harder to perceive details and causes discomfort to the viewer. [4, 6]

Discomfort glare of indoors is usually assessed with UGR, unified glare rating. The higher the UGR number is the more intensive the glare is. The intensity of glare depends on the lighting fixtures distribution of luminous intensity, the amount of lighting fixtures, location of lighting fixtures, mounting height of the lighting fixtures and the luminance of the environment. The UGR is essentially a logarithm of the glare of all visible luminaires divided by the background lumination. UGR can be calculated in the following manner [7]:

$$UGR = 8\, log \frac{0.25}{L_b} \sum_n (L_n^2 \frac{\omega_n}{p_n^2}).$$

Where L_b is the background lumination, L_n is the luminance of each light source, n is the number of the light source, ω_n is the solid angle of the light source and p_n is the Guth position index, which is an inverse measure of the relative sensitivity of a glare source at different locations in the field of vision. [4, 6, 7]

2.2.5 Light output format

Directioning of a light can be used to emphasize objects and to make three-dimensional objects more visible. The form and surface structure of an object can be brought up with correct shadow formation. Shadows cause luminance differences between objects and environments and thus help perceiving forms. A light that is constant and coming from every direction prevents shadows from forming, which in turn flattens the forms. Light output format is mathematically illustrated by comparing the ratio of cylindrical illuminance to horizontal illuminance. [1, 4, 6]

2.2.6 Color rendering

Color rendering conveys at which frequencies a light source emits light. Color rendering of a lamp is usually given as a CRI, Color Rendering Index, value. CRI is a measure of a light sources ability to emit colors in comparison to an ideal light source. CRI can range from 0 to 100, where 0 means a lamp emits only monochromatic light and 100 means a lamp emits light with a fully continuous spectre. The higher the CRI is the better the color rendering of the lamp is. Comparisons between light sources are done with light sources that have a color rendering index of 100. The average color rendering of fluorescent lights is about 85%. [1,4, 6]

When color rendering is poor the light source only emits at a narrow frequency range. In that case a human eye only sees colors corresponding to these frequencies from a reflection of a surface. [1, 4, 6]

2.2.7 Color temperature

The color temperature of a light source is the temperature at which a blackbody would have to be for its output to match as closely as possible that of the chosen light source.

For light sources with continuous spectrum this concept works, for example sunlight, but it breaks down with light sources with a discontinuous spectra. Color temperature of light sources are usually given as temperature ranges with kelvin (K) being the unit. Figure 4 illustrates the color temperature kelvin chart. [1, 4, 6, 9]

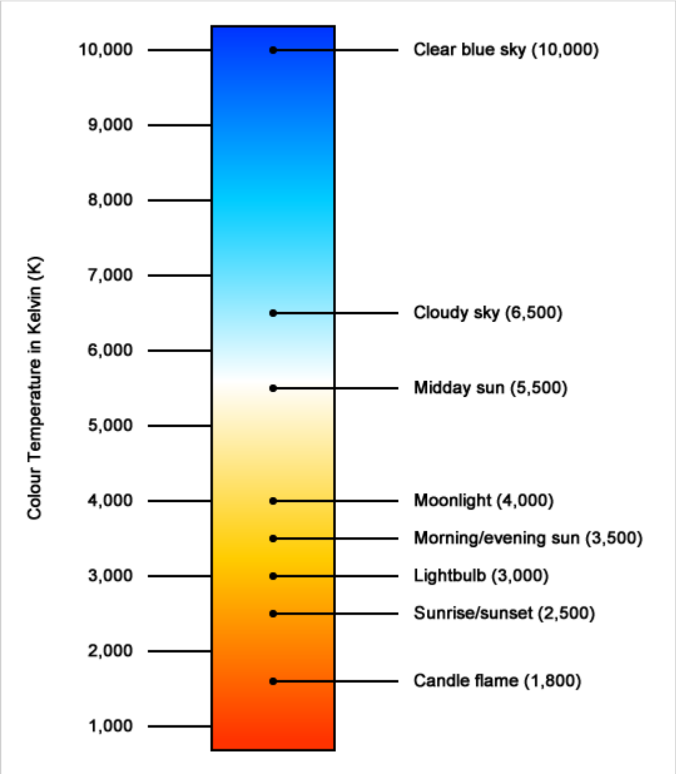

Figure 4. Color temperature chart. [9]

2.2.8 Flicker

Flicker is defined as quick and repeated changes in a light source’s light intensity. Flicker in lighting is most of the time caused by changes in the voltage supplied to the light source.

Flicker can be compared with two different metrics. The more known metric is flicker percentage, which compares the peak value and the lowest value of the voltage in two half cycles. The less known metric is flicker index which, instead of just comparing voltage amplitudes, takes into account the different cycles and shapes the signal can have. Flicker index compares the area that is above average with the total area. The higher the flicker percentage and flicker index is the more the light source flickers. Figure 5 illustrates the calculation of flicker percentage and flicker index. [1, 4, 6, 10]

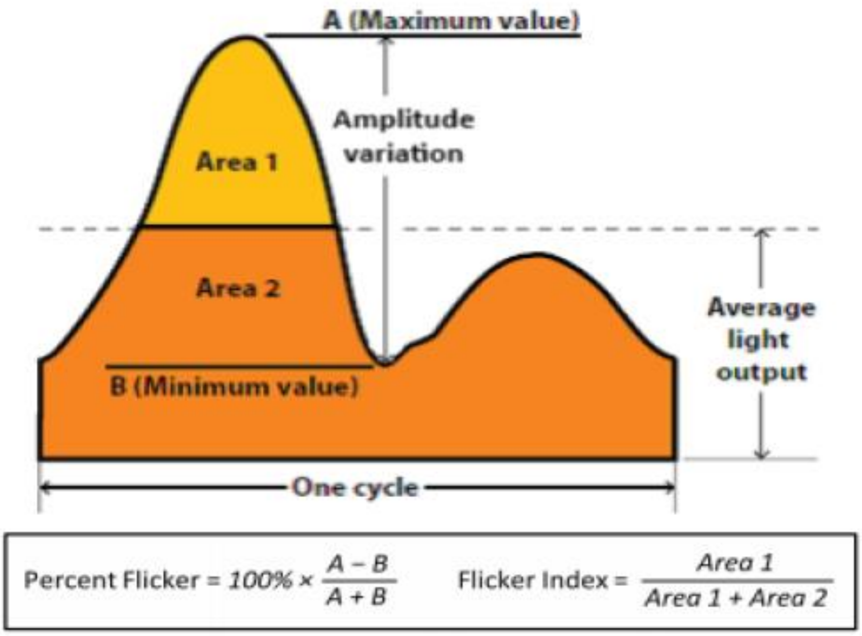

Figure 5. Flicker percent and flicker index calculation. [10]

2.3 Energy efficient lighting

Energy efficiency of the lighting is determined by the actual properties of the lighting solution, including the light sources, the luminaires, implementation of the system, purpose of the lighting and how the lighting is used. A luminaire's energy efficiency depends from the lamp, the ballast and the optics used. Lumen deprecation over time and the use of inappropriate lamps result in a low luminous flux, which has to be taken into consideration in lighting design. Furniture and surface colors also affect the lighting efficacy. The most significant part of energy efficient lighting is lighting control. [11]

Energy efficiency can be improved by instead of having all the spaces lighted only focusing the lighting to spaces requiring it. Every lighting solution is unique and even lighting solutions with same the functionalities implemented at the same locations can have drastically different energy consumptions. Lighting solutions should be designed from a quality perspective instead of focusing only on energy consumption. [4, 11]

2.4 LENI

LENI, Light Energy Numerical Index, is a metric that indicates how much actual energy a building will use in *kWh* per square meter per year. LENI can be used to estimate energy consumptions of different lighting solutions for an entire building. LENI can be calculated in the following manner:

$$LENI = \frac{W}{A}$$

Where *W* [kWh/year] is the building's energy consumption per year and *A* [m^2] is the building's lighting surface area. The higher the LENI number is, the higher the energy consumption per square meter is. [4]

3 LIGHTING CONTROL

Lighting control is based on three important aspects: Architectural and aesthetics, functionality and comfort and energy efficiency. The relations between the control requirements are illustrated on figure 6. Lighting control can be implemented in multiple different ways for multiple different purposes. [1]

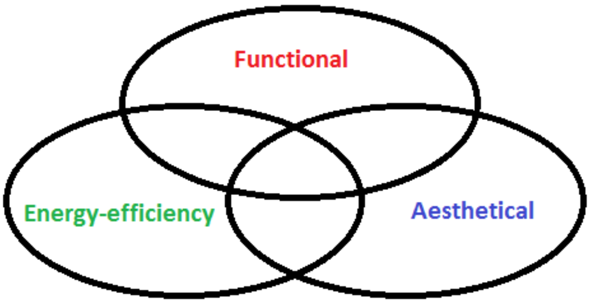

Figure 6. Lighting control requirements are connected to each other.

The customizable nature and specific requirements for lighting control makes lighting control solutions highly unique. In general most lighting control solutions are implemented with a combination of different methods, the more complex the requirements of the user are the more complex the lighting control. Figure 7 illustrates different lighting control methods.

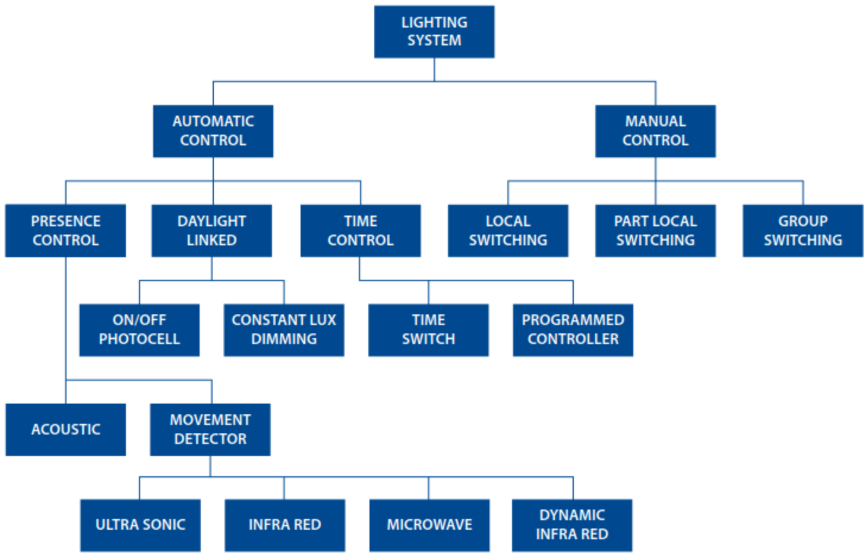

Figure 7. Lighting control methods. [12]

3.1 Advantages of lighting control

Modern lighting control systems can be used to improve the overall quality of lighting. Lighting control can be used to have the correct amount of light available at the required time and energy consumption can be lowered with the use of daylight control. Lighting needs can change multiple times a day and with the use of lighting control the need for continuous manual lighting adjustments decrease. [1, 4]

Lighting control is important to take into account already when designing the area. Correctly designed lighting control and other automated functions make it easier to use the space and can help the usage of the lighting. Correctly configured lighting control lowers energy consumption by keeping only the required lighting switched on. [4]

3.2 Methods of lighting control

3.2.1 Local control

Local control means lighting control is executed from a single point. In the simplest form it means an ordinary manual wall switch. Local control can be implemented as switches on lighting fixtures, as switches or control devices controlling a group of lighting fixtures, as a switch or a push button connected to the control circuit or by control from the ballast. [1, 4]

An extension of local control is multipoint control, where instead of a single lighting control point there are multiple control points. Multipoint control is usually implemented with switches, slide controls, push buttons or with a combination of the previous. Multipoint control can be necessary for spaces with multiple entries. [1, 4]

3.2.2 Presence and absence control

Both presence and absence control are based on a sensor detecting movement. In presence control the lighting will switch on automatically when movement is detected and also switch off when there is no movement detected for a predetermined amount of time. Absence control differs from presence control by only switching off the lighting when no movement is detected for a predetermined time and requiring the lighting to be manually switched on, for example from a push button. [1, 4]

Absence and presence control can help lowering the energy consumption of lighting by switching off the lighting when the space isn't utilized. Energy savings, depending from the space, for both presence and absence control are typically 15 – 30%, with absence control being a bit higher due to needing the lighting to be switched on manually. Energy consumption of lighting with presence and absence control is illustrated in figure 8. [1, 4]

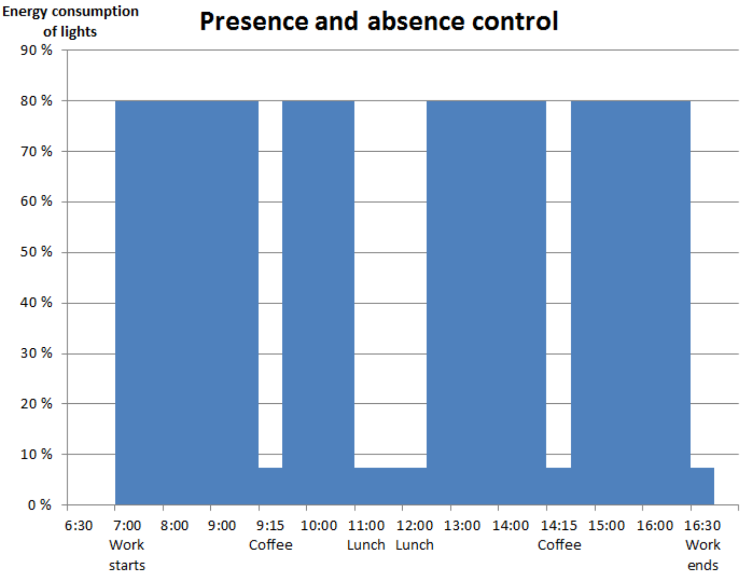

Figure 8. An occupancy sensor detects pauses and adjusts the lighting accordingly.

Low absence light is a method in which lighting is just dimmed instead of switched off when no movement has been detected for a predetermined time. Low absence light can be used with both presence and absence control. Figure 9 illustrates the low absence lighting. [1, 4]

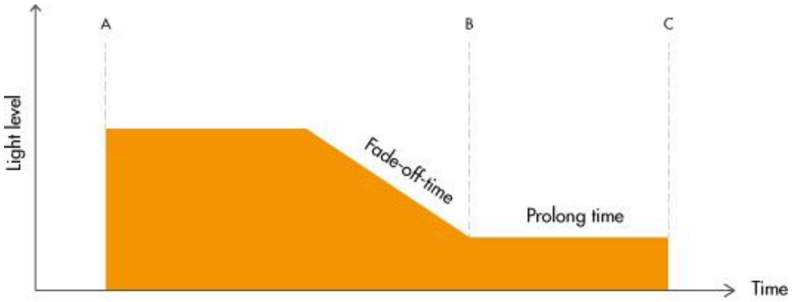

Figure 9. Low absence lighting. [12]

In order for the lighting to be practical, both presence and absence controls require occupancy sensors that are quick to respond to movement and they have to be installed to used acceseways. [1, 4, 13]

3.2.3 Constant light control

Constant light control uses sensors to measure illumination level. By utilizing daylight the artificial lighting can be lowered from maximum and thus the energy consumption from lighting decreases. Based on the data from sensors the artificial lighting is adjusted to a suitable level. With constant light control the total energy consumption of lighting decreases and the operating life of the dimmable light source and ballast increases. Figure 10 illustrates the utilization of daylight with artificial lighting. [1, 4, 14]

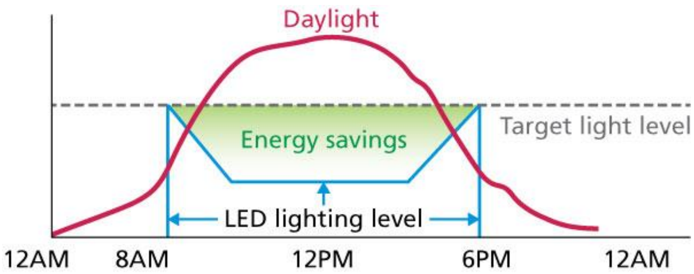

Figure 10. Utilization of daylight. [14]

Constant light control is suitable for areas that are close to windows. The higher the possible utilization for daylight in constant light control the higher the benefits are, typically the energy savings are 20 – 40 % compared to a lighting solution without constant light control. [1, 4]

Another application for constant light is for the almost linear light deprecation, which the luminaire itself compensates for, of a LED over its operating life, this is called Constant Light Output (CLO). With CLO the luminaire starts at a lower operational current at the beginning of its operating life and gradually increases the current and thus compensating for the light deprecation. CLO saves energy by not overinstalling lighting solutions to meet the lighting requirements after light deprecation. Figure 11 illustrates CLO and its energy saving. [1, 4, 15]

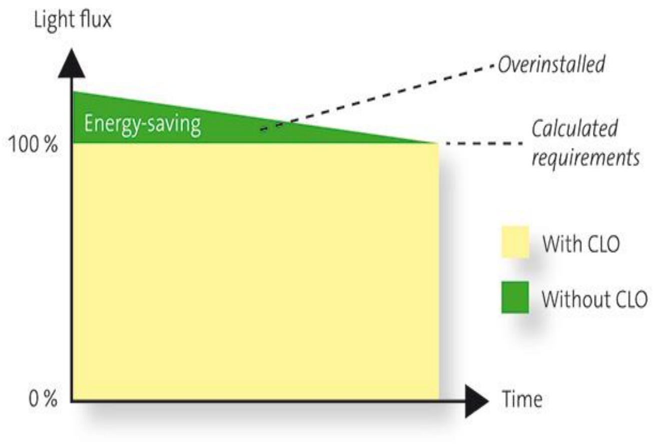

Figure 11. Constant light output. [15]

3.2.4 Situational control

Certain lighting control systems have the possibility to save different lighting situations in memory. Controls are divided into channels and thus one channel can for example control the lighting fixtures that are physically wired to a single wall switch so all the fixtures adjust at the same time. Specific lighting situations can be programmatically saved to memory when multiple channels exist. A specific lighting situation can be activated simply by push of a predetermined button when all the respective lighting group's lighting values are set to a predetermined configuration. Situational control can be used for example for cleaning purposes where the illumination level is set to higher than normal.

3.2.5 Time control

Time control is usually implemented using a time switch that is used to automatically switch lighting on or off at a predetermined time. A time switch can have different control options for different days and weeks. Time switches can also have a negative impact by switching the lighting off even if the lighting would be required. [4, 16]

3.2.6 Twilight switch control

Twilight switch controls are mainly used outdoors where a twilight switch will switch the lighting on or off depending on the illumination level. When sensor detects the illumination level to be lower than a predetermined value the twilight switch switches the lighting on. Twilight switch control is usually used in combination with another control method, for example time control, to achieve better energy savings. [4]

3.2.7 Freely configurable control

A freely configurable control can be a combination of any of the control methods mentioned before. The most commonly used combination is presence and constant light control. With the combination of these methods it is possible to achieve even 50 – 70 % energy savings compared to a non-controlled lighting solution.

Most of the time a combination of lighting control methods is required in order to achieve the best possible energy savings, to have the space function as intended and for the lighting to be adjustable and easy to use. Figure 12 illustrates potential energy savings with the use of a lighting system using presence and constant light control [4]

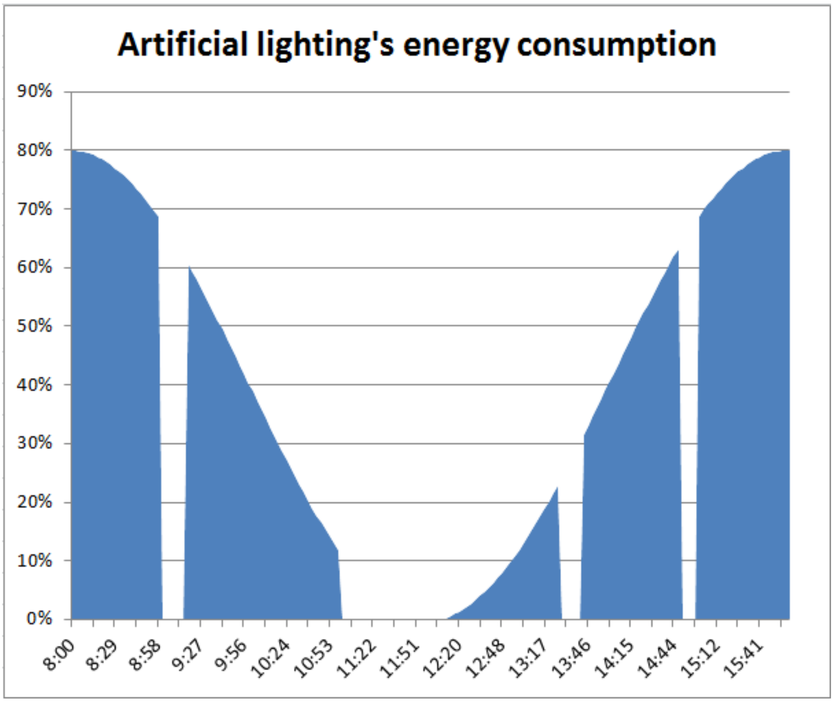

Figure 12. Constant light and presence controlled lighting solution.

4 ANALOG CONTROL SIGNAL –SYSTEMS

Control methods that are based on adjusting the sine wave are usually implemented with a dashboard dimmer or with a central controller. Analog control methods are non-addressable so control is done by a specified channel. The results of the adjustments are affected by the drivers of the lighting system. [1, 4]

Analog control is the easiest and simplest method to adjust lighting remotely for dimmers and controllers varying the voltage or another parameter. In the history of lighting many various voltage levels has been used for lighting control, some had historical reasons and others had technical reasons. [1, 4]

4.1 Amplitude control

Amplitude control is nowadays already a rare control method that has earlier been widely used. Control is done by a transformer, which makes the sine wave keep its form, while the actual changes in the intensity of the light are done by adjusting the amplitude of the sine wave. Amplitude control is suitable for resistive, inductive and capacitive loads. The principle of amplitude control is illustrated in figure 13. [4]

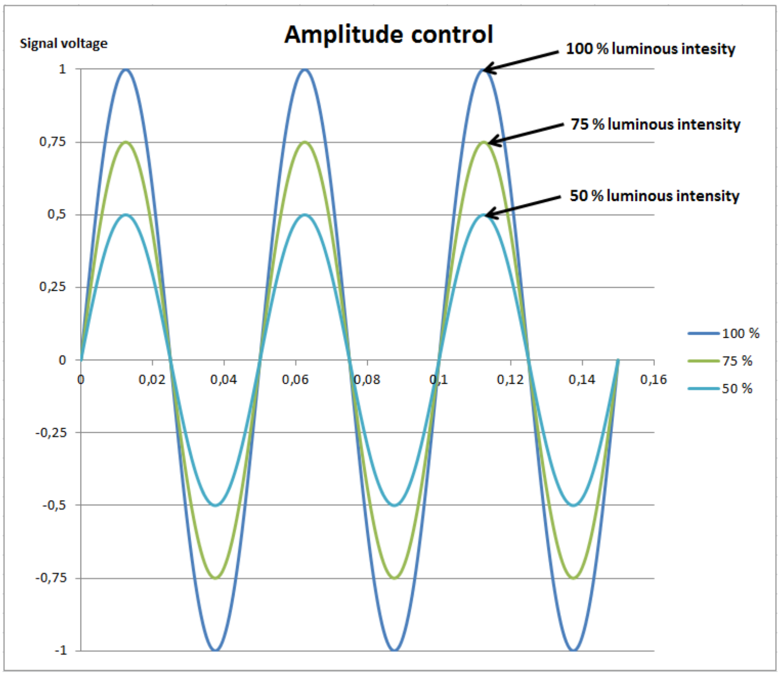

Figure 13. Amplitude control.

4.2 Thyristor and TRIAC control

TRIAC, triode for alternating current, and thyristor control are a common way to adjust lighting by controlling the phase angle of the sine wave's leading edge. Thyristor and TRIAC controls are used for example in dashboard dimmers and central controls that adjust the connected load's mains voltage. [1, 4, 17]

The principle of the control is to cut a portion of the sine wave from its leading edge. The sine wave cutting causes a high rate of current rise which in turn causes interferences, like harmonic waves and acoustic interference. And while the interferences can be filtered, the manufacturer of the controller has to take the interferences caused by the current rise into consideration. Figure 14 illustrates the thyristor and TRIAC control. [1, 4, 17]

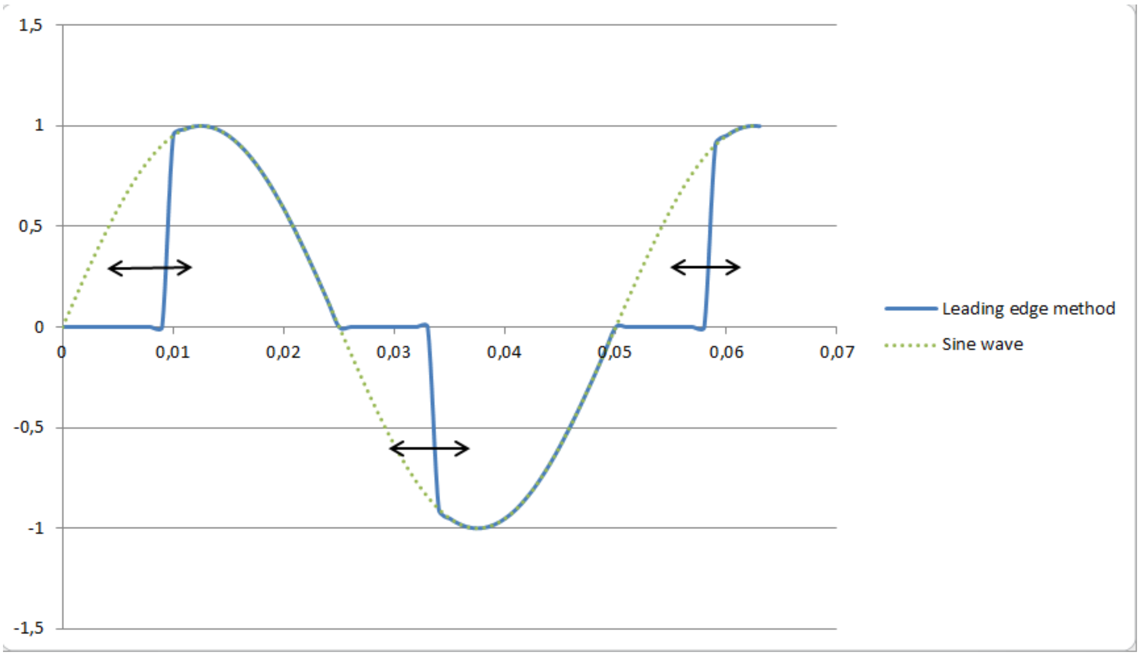

Figure 14. Thyristor and TRIAC control.

Thyristor and TRIAC controls are applicable to resistive and inductive loads. Capacitive loads can not be used due to the charge and discharge characteristics of capacitive loads. In practice this means resistive incandescent lamps, halogen lamps and inductive magnetic low voltage transformers can be used. This control is also applicable to some ballasts that have a filter circuit in the primary side. [1, 4, 17]

4.3 Transistor control

Transistor control is also based on the control of the phase angle, but instead of cutting the sine wave's leading edge, the transistor control cuts the sine wave's trailing edge. Figure 15 illustrates the transistor control. A transistor controller's most active component is MOSFET or IGBT, Insulated Gate Bipolar Transistor. [4, 17]

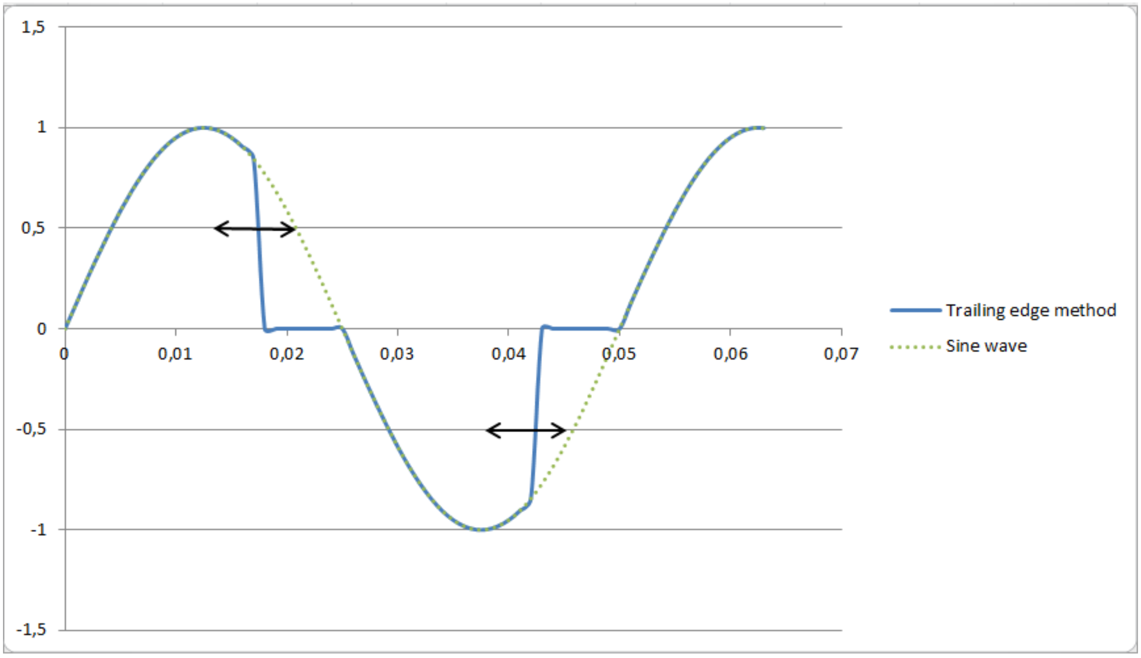

Figure 15. Transistor control.

The trailing edge method utilizes sine wave's waveform to reduce the high inrush current of the leading edge method, the reduced inrush current in turn reduces the amount of interference caused by the method. Thus the interference caused by the cutting of the sine wave's trailing edge is less than the cutting of the leading edge. Transistor control is applicable to resistive and capacitive loads, which are incandescent lamps, halogen lamps, compact fluorescent light bulbs, LED lamps and low voltage electronic transformers. Inductive loads damage the dimmer controllers used in transistor control, due to the discharge and charge characteristics, and thus can't be used. [4, 17]

4.4 0 – 10 V DC system

There is in fact no international IEC standard for 0 – 10 V system, but the Entertainment Services and Technology Association (ESTA) has a standardized 0 – 10 V DC Analog Control Protocol, which has internationally been used as a guideline for 0 – 10 V systems. [1]

The use of 10 V DC as control voltage can be justified by being high enough for avoiding signal noise problems but low enough to be safe, by being easy to express the control voltage as a percentage of output and by matching the capabilities of the components used. Table 2. illustrates the principal characteristics of the ESTA E1.3 standard used in the 0 – 10 V systems. [1]

Table 2. ESTA E1.3 standard. [1]

Controlled Device	
Control range	0-10 V DC
OFF control voltage	≤0 V
100% or ON control voltage	≥10 V
Control	Linear
Input impedance	100 kΩ ± 20 %
Controlling device	
Passive control source impedance	<10 kΩ
Active control source impedance	<100 Ω
Current source capability	>2 mA
Diode blocking capability	>15 V

The 0 – 10 V system uses a low source impedance to accommodate for the option of having a single controller providing a control signal to multiple controlled devices. The diode blocking is implemented because a single controlled device can receive signals from multiple controllers, with the highest signal taking precedence. The otherwise possible back feed is eliminated with diodes on the output of the controllers. The use of diodes has the drawback of having the bottom part of the control range unavailable until the diode forward drop is matched. In passive controls this has been solved practically by using an offset voltage and in active controls it is solved by designing the circuit to provide the required offset. [1]

4.5 1 – 10 V system

1 – 10 V systems are based on the IEC 60929 standard that defines the operation of pre-heat start electronic ballasts. The system is designed to support a single controller controlling multiple devices. The nominal voltage range is 0 – 10 V, but to prevent electrical noise from affecting the system performance the active control range is 1 – 10 V. The standard allows some deviation, 1 – 1,5 V is specified as being the lowest allowed minimum voltage and 9 V being the lowest voltage that can correlate to maximum voltage. Figure 16. illustrates the system's standard voltage curve. [1, 6]

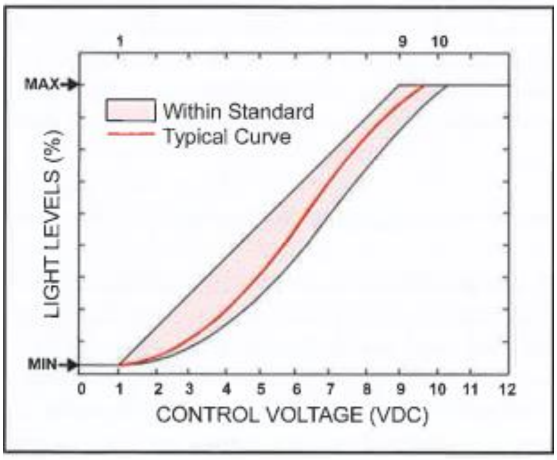

Figure 16. 1 - 10 V standard voltage curve. [1]

The standard defines each ballast as a current source, providing a minimum current of 0,2 mA and a maximum of 1 mA. The standard also sets requirements for the wiring and the properties of the wires. The light source is connected with mains, ground, shielded wire and two wires from the controller. The control wires and mains supply wires should be double insulated rated 2 kV and each controlled device has to withstand ±30 V without being damaged. The reversal of polarity of the control signals should also cause no damage to the ballast. [1, 6]

The standard was developed for controlling discharge lighting. The type of the lamp and the technical properties of the ballast determine the minimum and maximum levels. The group of fixtures connected to the same controller function together and are all adjusted as a group. And while the standard does not define maximum amount of controlled devices per controller, the amount of controlled devices is limited in practice by the capacity of switches, relays and contactors. [1, 4]

4.6 PWM

The IEC 60929 standard recognizes three methods for the remote control of electronic ballasts for fluorescent lamps. The 1 – 10 V standard, a new digital standard DALI, Digital Addressable Lighting Interface, and in between the previous the third method PWM, pulse width modulation. Even though the PWM method specified by the IEC 60929 standard is not widely used, is PWM an important lighting control technique. [1, 4]

The IEC 60929 standard defines the PWM signal to a low value of 0 – 1,5 V and a high value of 10 – 25 V. The cycle times of the PWM signal are in the 1 – 10 ms range. Full light output is given when the high signal is 5 % or less of the cycle time and minimum light output is given when the high signal is 95 % of the cycle time. When signal high is more than 95 % of the cycle time switch off is given (figure 17). The light output and pulse width have a logarithmic relationship. The maximum and minimum light output levels have been specified this way in order to help reduce the effects of interference on the light output levels. [1]

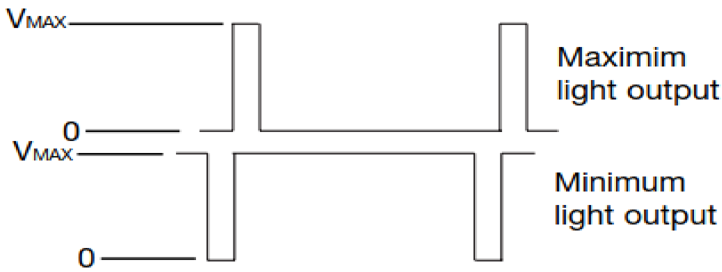

Figure 17. PWM high and low signals. [18]

5 DIGITAL CONTROL SIGNAL –SYSTEMS

Digital lighting control uses data to store the lighting levels of many channels of lighting, in most cases digital control requires at least one wire for the control. It is open to a manufacturer to use and design a proprietary method, but because such methods already exist and have been standardized it makes sense to use them. These standards can be categorized in two, the first specifies the electrical signals to be used and is only concerned about the signals technical specifications like for example impedances, voltage levels and data rates. These standards are not concerned with the actual data. The second category is application specific and may often be called a protocol. This category specifies what data and how it is transferred. Proprietary control protocols can be justified, but for practical reasons it is very rare for a manufacturer to use other protocols than the already standardized protocols. [1, 4]

Digital lighting data is usually based on using different voltage levels to represent different states of data for example +5 V can represent the state 1 and 0 V can represent the state 0. The lighting control communication can be in simplex, half duplex or duplex. Simplex is only one way communication, half duplex is two way communication but only one device can transmit at a time and duplex is two way communication where both devices can transmit at the same time. [1]

The most used lighting control communication standard is the EIA232 standard. The EIA232 standard represents the physical layer of communication, it specifies the used connectors and it is widely used, reliable and simple, but it does have some disadvantages. The disadvantages of the EIA232 standard are that it is comparatively slow, it is prone to noise problems over long distances due to the usage of single ended drive and it is limited to one receiver and one transmitter. Other widely used standards, often more advanced, are the EIA422 and the EIA485 standards. The differences between the EIA422 and EIA485 standards to the EIA232 standard are much longer cable length, lower signal voltage, higher data transfer rate and the ability to use multiple receivers and transmitters. Table 3 illustrates some of the differences between the standards. [1]

Table 3. EIA232, EIA422 and EIA485 specifications and differences. [1]

	EIA232	**EIA422**	**EIA485**
Drive	single ended	differential	differential
Number of drivers	1	1	32
number of receivers	1	10	32
Cable lenght	ca 20 m	1200 m	1200 m
Driver impedance	3-7k ohm	100 ohm	54 ohm
Receiver input	3-7k ohm	4k ohm	12 k ohm
Max data rate	20 kbit/s	10 Mbit/s	10 Mbit/s
Min drive signal	±5 V	±2 V	±1.5 V
Max drive signal	±15 V	±5 V	±5 V
Data 1 (Mark)	-V	-V	-V
Data 0 (Space)	+V	+V	+V

The EIA232 standard is specified to use a single ended drive, while the EIA422 and EIA485 standards both use a differential drive. The use of differential drives allows much longer cable lengths, EIA232 recommended 20 m compared to EIA422's and EIA485's recommended 1200 m, and also much lower drive signal voltages. The EIA232 and EIA422 have defined the number of drivers to one while the EIA485 allows up to 32 drivers. The number of drivers supported is also reflected in the driver impedance with the EIA232 specifying 3-7 kΩ while the driver impedance of the EIA422 and EIA485 has been specified to 100 Ω and 54 Ω. The maximum recommended data rate for EIA232 is only 20 kbit/s while for the EIA422 and EIA485 the recommended data rate is up to 10 Mbit/s. The EIA422 and EIA485 support 10 and 32 receivers while the EIA232 only supports one receiver.

5.1 DMX512

DMX512 is a standard for digitally controlled lighting equipment and accessories. DMX512 can be used to digitally control 512 dimming channels. DMX is an addressable simplex protocol, which means the transmitter only sends out instructions to one or more receiver. The characteristics of the standard are illustrated in table 4. [1, 19]

Table 4. DMX characteristics. [1]

Current version:	DMX512A
Electrical specification:	EIA485-A. DMX512A specifies transmitter and receiver protection to ±42 V
Connector:	5 pin XLR (no other XLR type permitted) Variations permitted under special circumstances. E.g. use of RJ45 connector in permanently installed systems based on structured cabling such as CAT5.
Connector orientation:	female on transmitting device male on receiving device
Connector pin numbering:	1 signal common 2 drive complement – 3 drive true + (optional second link on Pins 4 & 5)
Maximum number of devices controlled:	512
Number of levels per device:	256 (8 bit)
Valid levels:	0-255 decimal (00 to FF hex)
Data rate:	250 kilobits/second
Bit time:	4 µsec
Frame time:	44 µsec
Frame format:	Bit 1, Start bit Bits 2-9, Data bits (least significant first) Bits 10, 11, Stop bits
Data format in frame:	Start bit LOW, Stop bit HIGH Data bits HIGH =1, LOW = 0
Packet format:	Reset LOW (minimum 88 µsec) Mark after reset, HIGH (minimum 8 µs) Start frame, NULL (all zeros) or ASC Data frames (maximum 512) Idle, HIGH (maximum 1 second)

(continue)

Table 4. (continue).

Update for 512 dimmers:	22,67 milliseconds (minimum)
Update rate for 512 dimmers:	44,11 times per sec (fastest possible)
ASC (alternate Start Code)	1-255. Some reserved for specific purposes according to DMX512A

The DMX512A standard uses the EIA485A standard, with one exception of specifying the transmitter and receiver protection to ±42 V, for the electrical specifications for implementing the standard. The only permitted XLR connect is 5 pin, but varying connectors are permitted to be used under special circumstances. The 5 connector pins have a standardized usage, pin 1 is used for signal common, pin 2 for drive complement negative, pin 3 for drive true positive, pins 4 and 5 are reserved for optional second link. The maximum data rate is specified to 250 kbit/s with bit time 4 µs and frame time 44 µs, the bit time and frame time also specify the minimum update time for 512 dimmers to 22,67 ms and the maximum update rate for 512 dimmers to 44,11 Hz.

In DMX512 the data is sent in packets that update all the controlled devices. The transmitter does not need to send a full packet of 513 frames, but it must not send a packet with more than 513 frames and it has to comply with the timing rules. The receiver has to be able to receive full size packets at the highest possible rate and to only respond to the data intended for it. All receiving devices are expected to keep a particular dimmer level until it receives an instruction to adjust. The data selection is usually implemented with address switches. Figure 18 illustrates the data stream of DMX512. [1, 19]

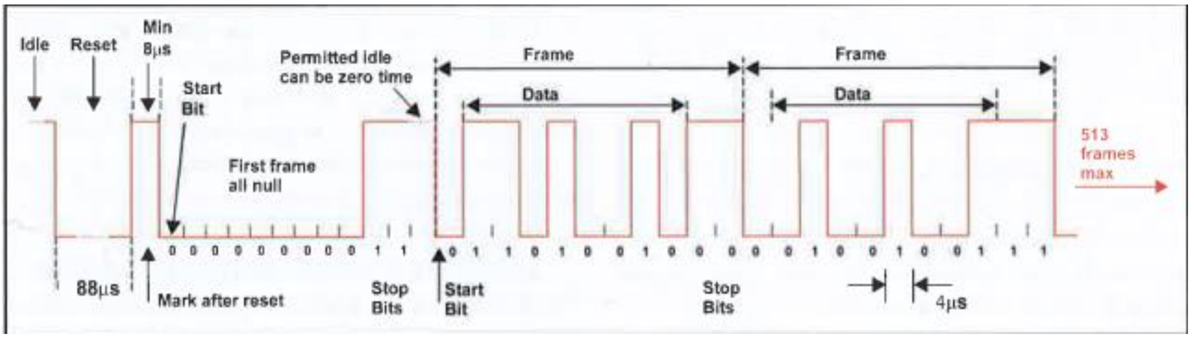

Figure 18. DMX512 data stream. [1]

The Data frames in DMX don't themselves carry any identification, the identity of the data frames is determined only by their order inside the packet. For example the first frame after the start frame is the data for first controlled device and the second frame would be for the second controlled device. This means the lighting fixtures or lighting groups have to have their address configured correctly to receive the correct packets. It would be possible for a smaller system, that is not using the full frame of 513 packets, to have a higher update rate, but in practice the full capacity 44 Hz update rate is fast enough for most purposes. Each channel has 8 bits, meaning a total of 256 levels, to use, but DMX itself does not define how the bits correspond to in lighting and the correlation between bits and lighting level is carried out in the dimmer. Figure 19 illustrates an DMX lighting control diagram. [1, 19]

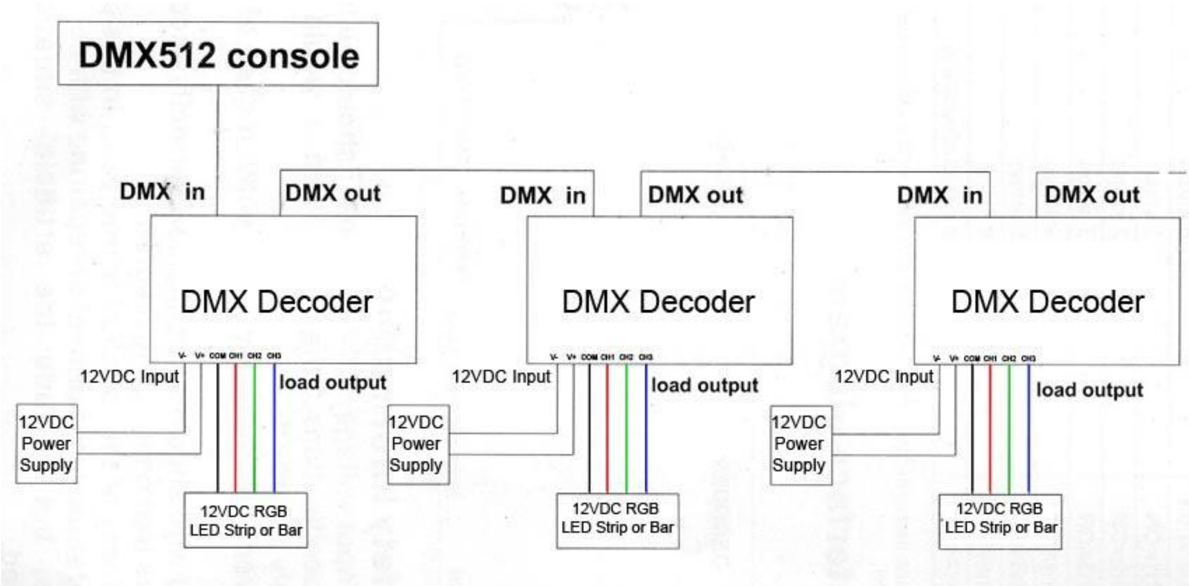

Figure 19. DMX512 example diagram. [20]

The DMX console controls the DMX decoder, or driver, the driver has a separate power supply for supplying operation voltage and each driver is connected serially to the next driver. Each driver only controls the lighting fixtures or lighting groups connected to the device. [1, 19]

DMX is a successful and widely used standard, but it also has its limitations too. In principle 256 levels of light is sufficient for entertainment and architectural applications, but in practice the difference between two levels becomes already noticeable in a long slow fade. This can be solved by interpolating additional levels, which can done by making the dimmer input always happen after a minimum timed fade, or, if the dimmer is digital, by adding extra bits at the dimmer to make the control higher than 8 bits. The advent of moving lights made the 512 control channel capacity of DMX a limitation, with each moving light requiring up to 24 channels, this has been circumvented by using multiple separate DMX outputs in. While EIA485 specifies the working cable length up to 1200 m, the practical range of DMX depends from frequency and typically works up to 250 m. Another limitation of DMX is the lack of error correction. [1, 19]

DMX is a simplex protocol and thus the transmitter only sends out instructions to one or more receiver. RDM, Remote Device Management, is an extension of DMX to allow the use of an optional second link on DMX to provide half duplex communication for the system. [1]

5.2 DSI

DSI, Digital Serial Interface, is a non-addressable proprietary lighting control protocol developed by an Austrian company Tridonic ATCO. DSI is the predecessor of DALI and the main purpose of DSI was to replace the analogue 1 – 10 V system. All controlled devices connected in the system are controlled in the same way regardless of the distance between the controller and the controlled device. DSI also enables the use of logarithmic control. [21, 22, 23, 24]

The advantages of using DSI are the simplicity of the system and not needing to program the system separately, only the lighting situations need to be saved to the memory. DSI enables the use of up to 100 controlled devices for each controller with a data rate of 1200 bits per second. DSI uses two 12 V wires to digitally send the signal. The lighting is switched on and off with a digital control command, therefore the lighting fixtures are still live even when they are switched off. [21, 22, 23, 24]

5.3 DALI

DALI is an internationally standardized addressable lighting control protocol based IEC on 60929 and IEC 62386 standards. DALI was developed in collaboration between the largest manufacturers to ensure the standardization of digital ballast control between different manufacturers and while the ballasts are interchangeable the drivers are not.

DALI has quickly become one of the most widely used lighting control protocol. The principal characteristics of DALI are summarized in table 5. [1, 25, 26]

Table 5. Principal characteristics of DALI. [1]

Maximum number of individually addressable devices in one system:	64
Data rate:	1200 bits/second
Data coding:	Manchester (Bi-phase)
Signal LOW	0V nominal; (-4,5 V to +4,5 V transmit, -6,5 V to +6,5 V receive)
Signal HIGH	16V nominal (+11,5 V to 20,5 V transmit, +9,5 V to +22,5 V receive)
Maximum volt drop on control line:	2 V
Maximum control cable length:	300 m
Signal supply current limited to:	250 mA
Nominal signal current per device:	2 mA
Number of levels per device:	255 plus OFF (8 bit)
Bit time:	833,3 µs
Frame time:	15,83 ms forward 9,17 ms backward
Frame format forward:	Bits 1, start bit Bits 2-9, Address bits Bits 10-17, Data bits Bits 18, 19, Stop bits
Frame format backward:	Bit 1, Start bit Bits 2-9, Data bits Bits 10, 11, Stop bits
Time between frames:	Minimum 9,17 ms before a forward frame Minimum 2,92 ms, max 9,17 ms before a backward frame

DALI has specified maximum number of individually addressable devices in one system to 64. The data rate is 1200 bits/second with data coding by bi-phase Manchester line coding. Bit time is 833,3 µs, forward frame time is 15,83 ms and backward frame time is 9,17 ms. The minimum time between frame for forward frames is 9,17 ms and for backward frame 2,92 the maximum time between backward frames is 9,17 ms. [1, 25, 26]

The basic idea of DALI, within a lighting system, is to be able to control every luminaire separately and to only require one control cable for the controllable devices in the system. DALI has been developed specifically for lighting control and not for comprehensive building automation. DALI is by design easy to install, has a low cost per node and even though DALI's basic form is suitable for most architectural lighting control, DALI is also intended to be easily interfacable to higher level control systems if required. [1, 25, 26]

Each lamp in the system has a load interface, an electronic ballast most commonly. A simple pair of two wires, which DALI uses for control, connect the control devices to the load interfaces. Each control device can only control specified lamps, thus when partitions are moved or there are layout changes, reprogramming the system for the required changes is easy. Figure 20 illustrates an example of a DALI system. [1, 25, 26]

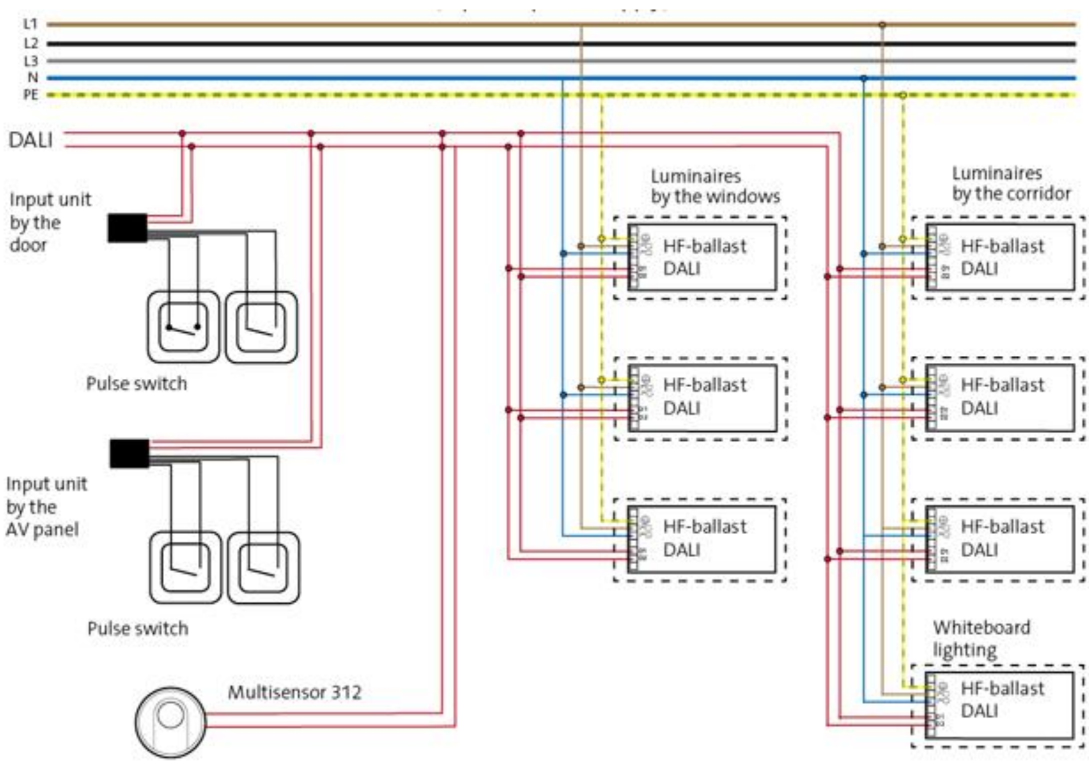

Figure 20. An example of a DALI lighting control system. [27]

Each DALI controlled lighting fixture or lighting group is connected to the two DALI control wires either by series or parallel connection. The sensors and switches are also connected to the DALI control wires. The lighting fixtures and DALI ballasts can be supplied the operating voltage how is seen fit. [1, 25, 26]

DALI has bidirectional communication, meaning it is possible for a controller to make a request to the ballast and the ballast can answer to it. Connected ballasts, control panels, sensors and the programming units all communicate with each other. The communication between the connected devices can not only be used for maintenance purposes but also for statistics, energy consumption and other administrative reasons by using third-party DALI control software. A central unit is not needed, because it's functions have been distributed to the different components of the system. It is possible to control multiple DALI systems with DALI routers connected to an Ethernet Network. DALI systems can also be controlled over Ethernet with a computer.[1, 25, 26]

The data rate of DALI is low enough to not have strict rules about how the devices are connected, but DALI only permits star connection topologies, serial connection topology or a combination of both (figure 21). Also termination of interface cables with resistors is not needed. The low-level interface voltage has been defined to nominal 0 V (-4,5 V to +4,5 V) on the receiver's end and the high-level interface voltage has been defined to nominal 16 V (9,5 V to 22,5 V) on the receiver's end. A 2 V voltage drop for the receiver and the sender has been defined as the maximum allowed. The wide tolerance at each signal level and the difference between low and high signals (figure 22) makes the system highly resistant to electrical noise. [1, 25, 26]

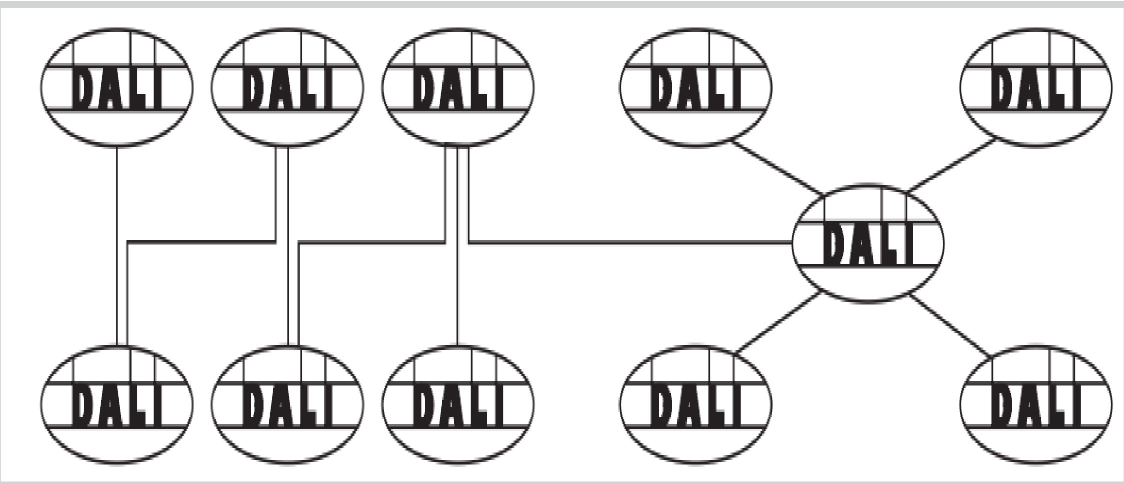

Figure 21. DALI topologies. [26]

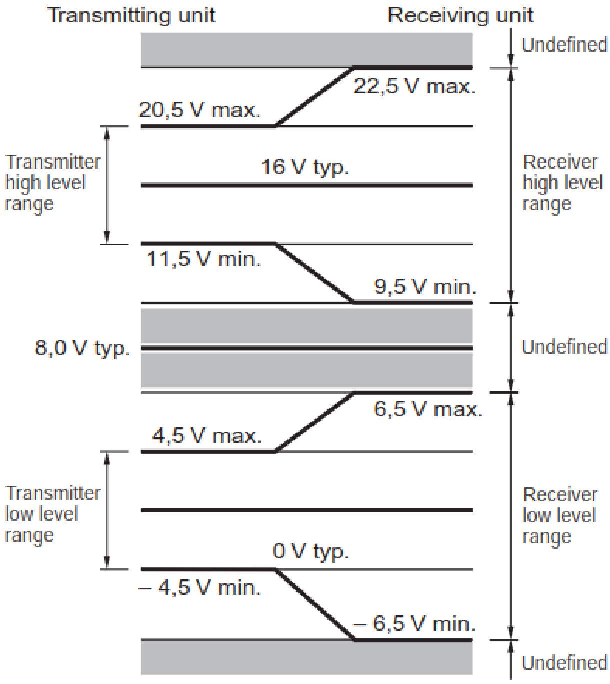

Figure 22. DALI voltage levels. [26]

The maximum distance between two connected systems is derived from the 2 V voltage drop between transmitter and receiver and thus the maximum cable length, without repeaters, for two systems or devices is 300 m with a cable with conductor area of 1,5 mm^2. With the use of DALI repeaters the distance between two devices can be extended. The voltage drop between systems or devices can be calculated as follows [27]:

$$U_V = \frac{2 * I * d}{\sigma * S}.$$

Where U_V is the calculated voltage drop, in volts, I is the current, in ampers, S is the conductor area of the cable used, in mm^2, d is the length of the cable used and σ is the electrical conductivity of the cable used, in m / (Ω mm^2). [1, 25, 26, 28]

A single DALI line can have a maximum of 64 addresses. This can be 64 devices that each require one address or it can be a number of devices requiring more than one address each, for example a RGBW-LED luminaire can require 4 addresses, one for each color. A relay unit requires as many addresses as there are relay tips in the unit. The maximum specified number of groups for group addresses is 16 and the maximum stored light scenes is 16. The number of usable addresses and groups can be extended with the use of DALI routers, which usually support two DALI subnets and thus making additional 64 addresses available. It is also possible to network DALI routers together to form even larger systems. [1, 25, 26, 28]

DALI has a standardized dimming curve with a range of 0.1% to 100%, the lower limit depends from the manufacturer, the course of the dimming curve has been adapted to the sensitivity of the human eye, which in practice means the dimming curve is logarithmic. Dali has an 8 bit light level adjustment, meaning there are 254 light levels between off and 100%. Figure 23 illustrates the DALI standardized dimming curve. [1, 25, 26, 28, 29]

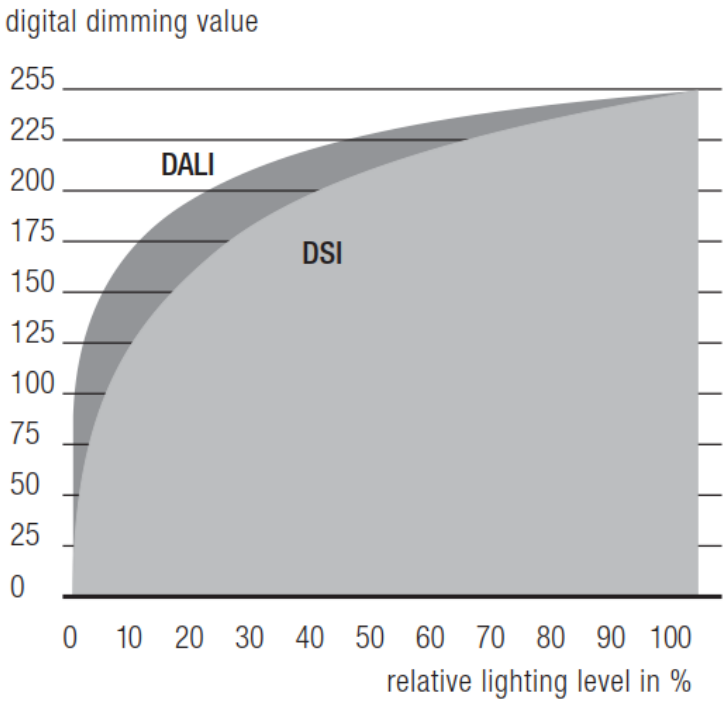

Figure 23. DALI logarithmic dimming curve. [29]

DALI 2 standard has been developed since 2015, so far the standardization is still heavily in progress, but progress has been made. The standard aims to include the standardization of control devices in addition to only ballasts, to add support for color control by covering both RGB and color temperature, to improve the information reporting of the devices and to allow the use of 64 additional addresses, specifically meant for the control interfaces. In systems with RGB or RGBW lamps, the color control support will allow more addresses to be utilized, by only requiring a single address to control the lamp instead of 3 or 4 to control the lamp with all colors. Also another DALI 2 standardization development has just started by DiiA, Digital Illumination Interface Alliance. The DiiA aims to include the standardization of DALI 2 and to add additional functions to it. [30]

5.4 LEDOTRON

Digital Load-Side Transmission Lighting Control (DLT) or the commercial name LEDOTRON is a protocol for digital lighting control developed by Insta and OSRAM. It has been developed as a replacement for the old existing one channel dimmer systems. DLT has additional options for color control, color temperature control and group control. The protocol is based on IEC 62756 standard and it complies with EN 61000-3-2 and EN 555015 standards meaning it is EMI and EMC compatible. [30, 31]

DLT contains a control unit and a lighting device. A standard conforming device can be installed to replace a 2-wire-dimmer. It requires in addition to a dimmer an DLT conforming lighting device. DLT control signal does not cause interference or uncertainty of operation to a non-LEDOTRON-lamp if it is installed to a LEDOTRON-controlled luminaire. The lamp can be switched on and off but dimming is not possible with DLT control. The maximum length allowed between the control unit and the lighting device is 100 m and the maximum load for each control unit is either 200 W or 10 luminaires. Figure 24 illustrates the block diagram of data transmission of a DLT control unit and lighting device. [31, 32]

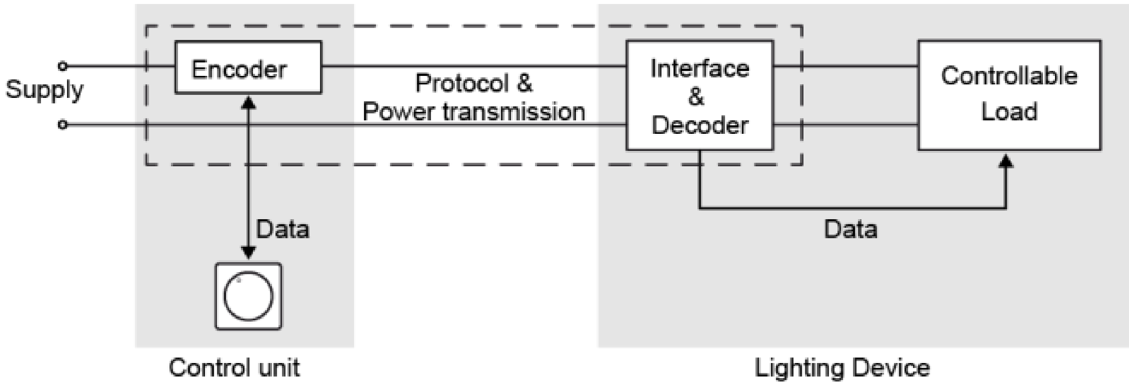

Figure 24. LEDOTRON block diagram. [31]

DLT is based on baseband data modulation utilizing the AC mains voltage zero crossing. It differs from other PLC, power line communication, protocols by having a low data transmission speed and is similar to UPB, universal powerline bus, communication protocol where also the signal is modulated trailing edge of the sine wave of the AC voltage. The DLT protocol is intended only for the control of lighting therefore it is not needed to transfer high amounts of data, thus the data transmission speed of 200 bits per second is sufficient. Low modulating frequencies can be achieved with the low data transmission speed, this noticeably improves noise resistance. Especially the harmonic waves from constant current LED drivers cause interference at the traditional PLC operating frequencies. [31, 32]

DLT works by sending a control signal from the control unit to the lighting device. The signal is modulated to the 50 Hz mains and data is transmitted on the trailing edge of the sine wave. The lighting device is supplied its operating voltage from the mains and the device demodulates the data signal sent by the control unit. The information from a decoded DLT command contains the instructions upon which the controlled device operates. DLT protocol only sends digital commands and is thus not suitable for analog dimmer solutions. Figure 25 illustrates the waveform of a DLT modulated signal. [31, 32]

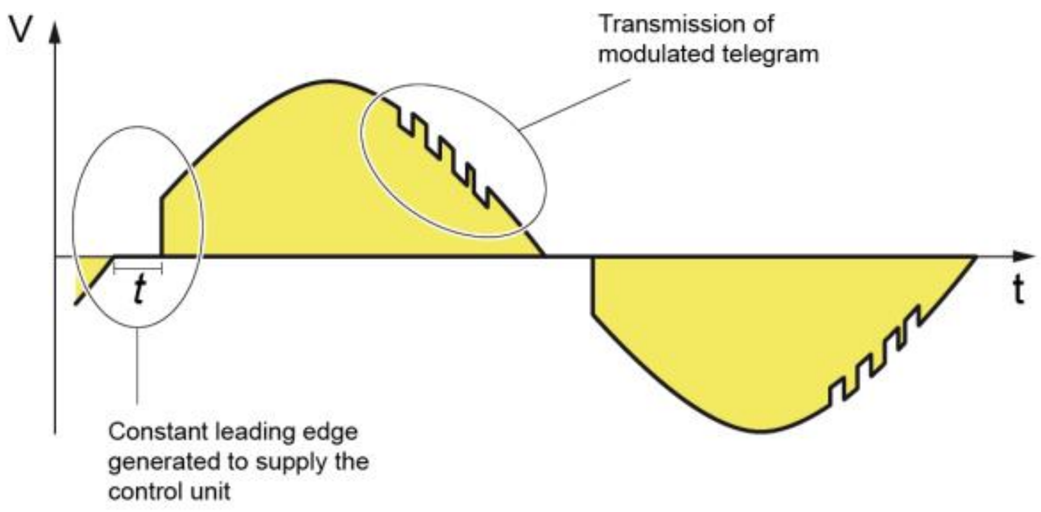

Figure 25. Waveform of a DLT signal. [30]

DLT protocol uses Manchester line coding to improve error tolerance of the communications. The DLT command consists of many frames, each half-wave incudes a data frame and 4 half bit, for a total of 6 half bits. Each frame is represented by 2 half bits located at the start and at the end of the frame. The 4 bits inside the frame are Manchester coded and thus in total there are only 2 information bits in total. DLT has a frame structure which enables the use of different operation modes for different commands. Table 6 illustrates the different operation modes. [31, 32]

Table 6. DLT operation modes. [31]

Nr.:	Mode	Suitable LEDOTRON lamp types
0	Brightness control	1-channel LED (Monochrome)
1	Color control	3-4-channel LED (e.g. TGB, RGBW)
2	Color temperature control	2-4-channel LED (e.g. RGB)
3	Reserved	To be defined
4	Reserved	
5	Commissioning, group control	Lamps with grouping function
6	Manufacturer specific telegrams	
7	Reserved for telegram extensions	

5.5 LON

LON, Local Operating Network, is a control network topology developed in 1990 by the Echelon Corporation. LON can be used to control multiple different systems and not just lighting, which is why it is often not feasible to use LON just for lighting. LON uses digital duplex communication with multipoint connections. Table 7 illustrates the trademarks of the Echelon Corporation relating to LON. [1, 33, 34]

Table 7. Trademarks of the Echelon Corporation relating to LON. [1]

Trademark	Meaning
LON	A control network using Echelon's topology
LonWorks	A general descriptor of the technology. E.g. a LonWorks node is any node device on the network. There are also LonWorks accessory devices, such as LonWorks transceivers, routers, interfaces and gateways.
Neuron	The integrated circuit (chip) that each LonWorks device is fitted with. These are made by Toshiba and Cypress.

(continue)

Table 7. (continue)

LonTalk	The communications protocol that links each LonWorks device. It is a complete 7-layer protocol according to OSI.
LonMark	Products carrying the LonMark logo are independently certified as being interoperable with any other products carrying the same mark.
LonManager	A LON network services software tool

The purpose of a LON network is to ensure interoperability of separate independent devices and devices from different manufacturers and to combine the control and use of the devices to a single non-manufacturer tied protocol. The devices, also called nodes, communicate by using the LonTalk protocol that is comparable to a full 7-layer OSI standard. A LON system includes LonWorks devices, LonBuilder and LonMaker development tools and accessories, such as bridges, routers and utilities. LON is used in addition to in home and building automation in industrial automation and the most data communication is implemented with paired cable. Each LON node in addition to the mechanical components contains a processor circuit, called Neuron. [1, 33, 34]

A lighting system implemented with LON has its control commands conveyed over a bus as a data message. The control command cabling can also be used to provide the supply voltage to the lighting devices, decreasing the amount of cabling needed. The decrease in cabling also decreases the point of connections as much as a third. Figure 26 illustrates an example of lighting control nodes in a LON system. [1, 33, 34]

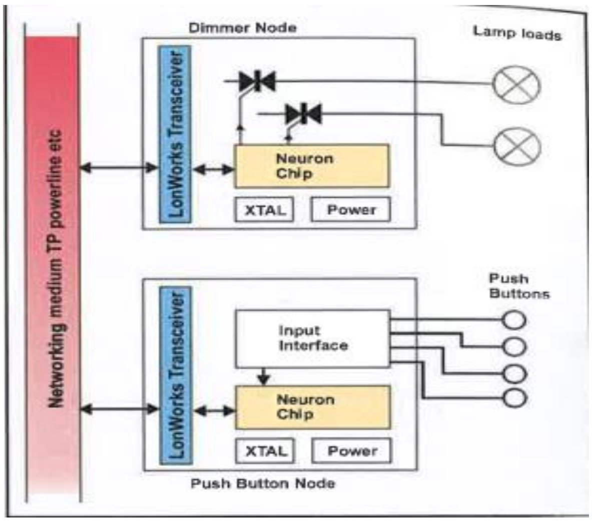

Figure 26. Example of LON lighting nodes. [1]

Each LON node has a LonWorks transceiver that both receives the incoming data and sends out the outgoing data. The LonWorks transceiver sends the incoming data to the Neuron chip which processes the data received. The neuron chip sends the processed command to be implemented by the controlled device. The Neuron chip can also receive data from input interfaces and process it and then send it to the LonWorks transceiver. [1, 33, 34]

5.6 KNX and EIB

KNX is based on EIB, European Installation Bus, which combines the technical functions of a property to a single system. KNX is an open standardized system based on IEC 1454-3 and EN 50090 standards, meaning all KNX and EIB certificated devices are interoperable and can be operated in any combination regardless of the manufacturer. Both KNX and EIB allow the use of different medias for data transfer. Both KNX and EIB are developed for comprehensive automation than just lighting control. Figure 27 illustrates an example of a KNX system. [1, 35]

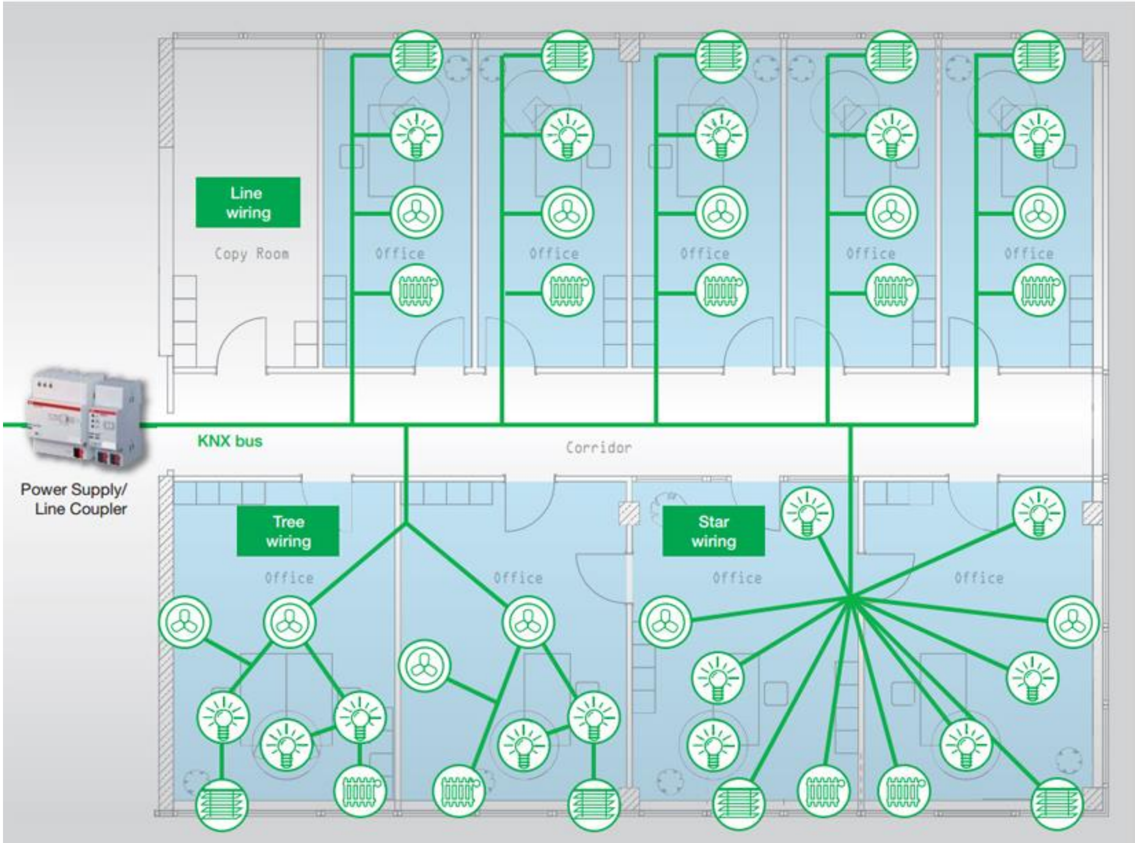

Figure 27. KNX control. [36]

KNX and EIB systems are divided to a maximum of 15 regions that are connected with a regional lines and regional switches. Each region can have 15 lines that are connected to each other with a main line. A single line can have a maximum of 256 devices and each line has to have a power supply. Thus the total amount of devices in a KNX system is 57600.

There is no need for a central control unit in KNX and EIB systems, because each coupler has a microprocessor of its own. Sensors and devices communicate with each other by predetermined group addresses, a group address can be given to any coupler regardless of its location and thus lighting fixtures in a wide area can be controlled with a single switch. [1, 35]

6 DESIGNING A LIGHTING SYSTEM USING DALI

The area planned for designing the DALI lighting system was decided to be a jazz club with a total surface area of approximately 640 m^2. The planning and design for the lighting system using DALI started by studying the jazz club's area in general. Figure 28 illustrates a section of the jazz club. The architectural design of the jazz club has a total of over 200 luminaires and LED strips.

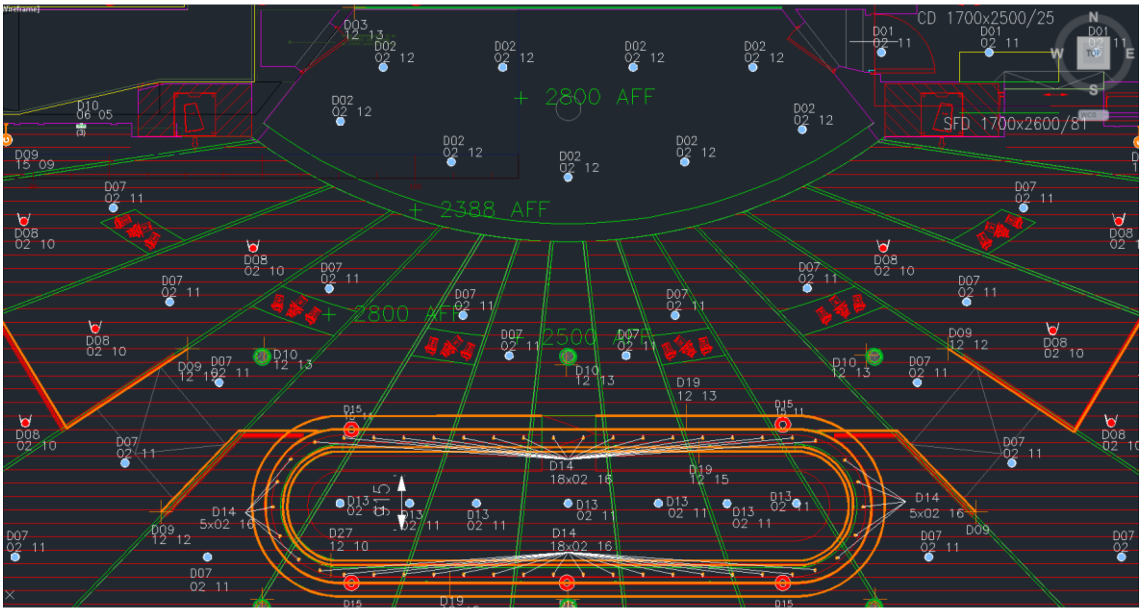

Figure 28. Section from AutoCAD of the jazz club.

The red and green lines in the figure are intended to help perceive the area, the red spotlights are entertainment spotlights controlled by DMX and thus were excluded from the DALI lighting system design, the blue spots are downlights for general lighting, the red spots are downlights for table lighting, the green circles are LED strips in pylons for accent lighting, the small orange spots are small downlights at the bar for accent lighting, the red circles are table lights at the bar and the orange lines are LED strips for accent lighting.

The next step, after studying the area of the jazz club in general, was to start sketching the lighting and dimming groups for the DALI system. Figure 29 illustrates a section of an early sketch of the lighting groups planned for the jazz club, with the lighting grouping indicated with purple clouding. The luminaires and LED strips were divided to groups first by type of the luminaire and then by the required functionality, for example if the luminaires needed to be dimmable or not. The lighting groups were formed from these groups.

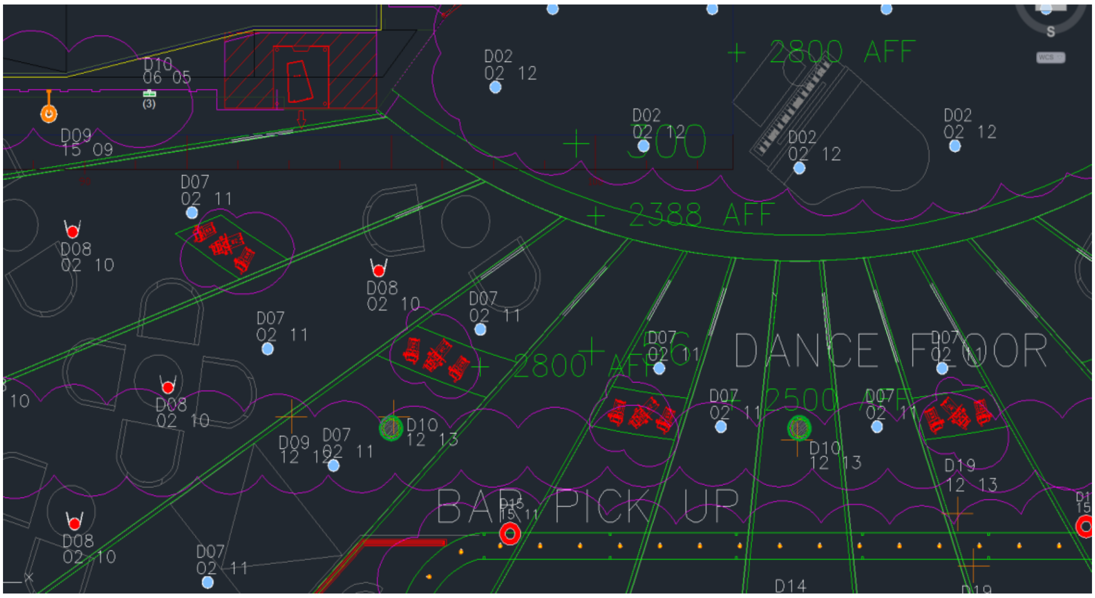

Figure 29. Sketching lighting groups in AutoCAD.

After forming the lighting groups the total power consumption of the luminaires and LED strips was calculated, with most common power consumption per luminaire being 12 W, the total power consumption was over 5 kW. Figure 30 illustrates a section of the total power consumption calculation for the luminaires and LED strips. The total length of the LED strips in the jazz club’s area is over 200 m.

Power consumption
108 W (9*12W), LED, DIM, General lighting
45 W (7*5W), LED, DIM, Accent lighting (7m)
70 W (7*10W), LED, DIM, Decorative lighting
6 W (6*1W), LED, decorative accent lighting
90 W (6*15W), LED, DIM, Decorative lighting
105 W (7*15W), LED, DIM, Decorative lighting
30,1 W (7*0.86m*5W), LED, DIM, accent lighting
30,1 W (7*0.86m*5W), LED, DIM, accent lighting
10 W (9*10W), LED, DIM, Decorative lighting
75 W (15*5W), LED, DIM, furniture integrated
75 W (15*5W), LED, DIM, furniture integrated
80 W (16*5W), LED, DIM, furniture integrated
78,75 W (5,25 m*15W), LED, DIM, Accent lighting
78,75 W (5,25 m*15W), LED, DIM, Accent lighting
78,75 W (5,25 m*15W), LED, DIM, Accent lighting
78,75 W (5,25 m*15W), LED, DIM, Accent lighting
84 W (7*12W), LED, DIM, General lighting

Figure 30. A section of the power consumption calculation.

The next step in the planning and designing of the lighting system was to approximately group the luminaires and LED strips to DALI broadcasting groups or to a group with individual DALI address. This was done by designing and planning which luminaires and LED strips could benefit from being individually controlled and which would have to be controlled either by broadcast or be individually controlled for their intended purpose. Figure 31 illustrates a sketch of the grouping of the luminaires and LED strips into the individual address group and the broadcast groups.

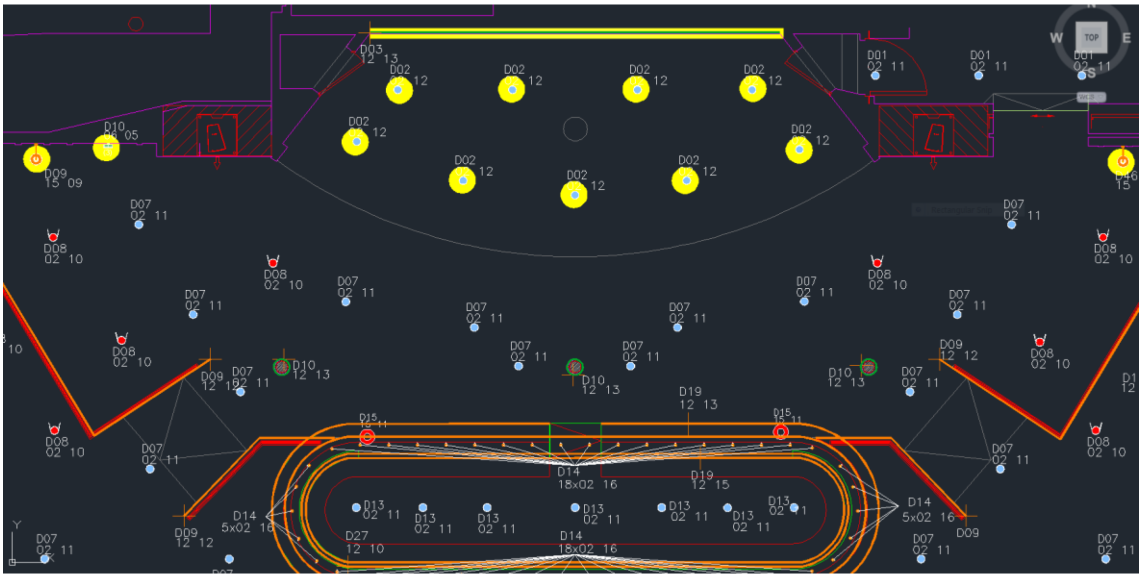

Figure 31. Sketching the DALI address and broadcast groups.

In the sketch the luminaires with individual addresses are colored in yellow while the rest of the luminaires, without the yellow coloring, are divided into broadcast groups. Majority of the luminaires and LED strips were divided to broadcast groups by their type, for example downlights into a single broadcast group and table lights to another broadcast group.

After forming the DALI groups all of the luminaires and LED strips needed to be grouped to an actual combination of DALI routers and DALI controllers. The DALI routers and controllers were decided to be Helvar's DALI 920 –router and Helvar's DALI 478 –controller, the DALI 920 –router supports a total of 128 DALI devices in two DALI subnets and is intended for controlling DALI devices with individual addresses and the DALI 478 –controller supports a total of 512 DALI devices in 8 subnets and is intended for controlling DALI devices by broadcast. For the planned design of the jazz club's DALI lighting system it was required to have one Helvar's DALI 920 –router and two Helvar's DALI 478 –controllers. While the amount of DALI controlled devices in the broadcast groups would have numerically only required one DALI 478 –controller, the amount of DALI broadcast groups required two DALI 478 –controllers. It was also decided to use Helvar's 498 8-channel relay switch to control the LED strips that didn't require dimming and for comparison to the 1 – 10 V system to use Helvar's 474 4-channel 1 – 10 V –control drivers for the 1 – 10 V system.

A consumer list containing all the previous information was done for easier maintenance, updating of the system and revision control. Figure 32 illustrates an section of the consumer list for the lighting of the jazz club.

Circuit	Breaker	Area	Description	Light source	Control group	Load/ W	Dimmer	Switch	DALI	Address	Broadcast	Cable	Note	Control
1	10A	JC	Stage Downlights	LED	JC1	110			x	x		N 5G1,5	9 pcs	R1.1.A1 - R1.1.A9
2	10A	JC	Stage LED strip	LED	JC2	45			x	x		N 5G1,5	2 pcs	R1.1.A10 - R1.1.A11
3	10A	JC	Wall scones next to stage	LED	JC3	70			x	x		N 5G1,5	7 pcs	R1.1.A12 - R1.1.A18
4	10A	JC	Decorative lights next to stage (1W)	LED	JC4	6			x	x		N 5G1,5	6 pcs	R1.1.A19 - R1.1.A24
5	10A	JC	Floor lamps at edges	LED	JC5	200			x		x	N 5G1,5		B1.G1
6	10A	JC	LED strips in pylons	LED	JC6	60		x				N 3G1,5		ON/OFF
7	10A	JC	Bar table lights	LED	JC7	90			x		x	N 5G1,5		B1.G2
8	10A	JC	Bar small downlights	LED	JC8	230			x		x	N 5G1,5		B1.G3

Figure 32. An section of the consumer list for the lighting of the jazz club.

The consumer list has columns for circuit, breaker, area, description, light source, control group, load /W, dimmer, switch, DALI, address, broadcast, cable, note and control. The description –column is a general description for the lighting group which indicates the location or function of the group, the light source –column indicates the method of the group to generate light, the control group –column indicates the dimming group and the load /W –column indicates the total power consumption for the group in watts. The dimmer –column indicates that the group has separate dimmers for the luminaires, the switch –column indicates the group is only controlled by being switched off or on and the DALI –column indicates the group is controlled with DALI. The address and broadcast –columns indicate whether the group is a DALI broadcast group or a group with DALI individual addresses, the cable –column indicates the cabling used in the commissioning of the group, the note –column indicates any important notes related to the group and the control –column indicates the module and module channel or address space reserved for the group.

Based upon the costs of earlier projects the cost for the Jazz club's DALI dimming rack, containing the lighting system controllers, would have been approximately 4600 €, including the work for the dimming rack. Other costs, for example the cost of the cabling, the computer hardware and software and the control panels, for the lighting system would have been approximately equal with other lighting control systems. For comparison the jazz club's lighting system was also designed with 1 – 10 V –system, the design for the 1 – 10 V system is mainly the same compared to the DALI system's design but with some differences. The main differences being the amount of control modules required to control the lighting, especially for the luminaires and LED strips that had individual addresses in the DALI system. Based upon the costs of earlier projects the costs for the 1 – 10 V system's dimming rack would have been approximately 6900 €. The cost was higher than the dimming rack for the DALI system because the Helvar's 474 drivers only have 4 channels to control the luminaires and LED strips, which in turn increased the total number of modules required for the lighting groups.

The design for the DALI lighting system has 10 broadcast groups and with 2 Helvar's 478 –controllers the remaining 6 channels are left for spares that could be used in the future. The DALI design also had 78 individually addressable devices in the lighting system and with one Helvar's 920 –router the remaining 48 individual DALI addresses are left to spare for possible future use. The design for the 1 – 10 V lighting system has 22 groups of luminaires and LED strips controlled by 6 Helvar's 474 –drivers and thus with this design the 1 – 10 V lighting system would only have 2 spare channels for possible future groups that could be used. The designs for both the DALI and the 1 – 10 V systems also have 5 spare channels in the relay switch for possible future use.

All in all, the costs for both DALI and 1 – 10 V system's dimming racks are approximately in the same price range and the cabling, the control panel, the computer hardware and software and other service and assembly costs are approximately the same for both systems.

7 CONCLUSION

The purpose of this thesis was to study lighting design, lighting control, the differences between various lighting control systems and to design a possible lighting system using DALI for a predefined area. The aim of the thesis was to study the different technical characteristics of the lighting control systems, the control methods of the systems and to successfully design a lighting system using DALI.

The thesis was conducted as a study and information was obtained from lighting specialists and from standards and books relating to lighting and lighting systems. The result is a fairly comprehensive study focusing on lighting control, digital and analog lighting control systems, the technical characteristics of the lighting control systems and a possible lighting system design for a specified area using DALI.

Further development of the thesis could cover the costs of implementing different lighting control systems to various spaces. Alternatively development could consist of studying the effect of interferences in control signals, both analog and digital, to different lighting control systems.

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