Light Rail Camera

- an EMC-assessment

Viktor Drakfelt & Isak Stjernrup

2021

Master's Thesis in
Electrical Measurements

Performed at
Axis Communication

Academic Supervisors: Johan Nilsson & Johan Gran
Industrial Supervisors: Simon Preutz & Nicklas Persson
Examiner: Christian Antfolk

LUND
UNIVERSITY

Faculty of Engineering LTH
Department of Biomedical Engineering

Department of Biomedical Engineering
Lund University
Box 118
SE-221 00 LUND
Sweden

Printed in Sweden by E-husets tryckeri.
Lund 2021

Abstract

When installing multiple security cameras the cable management can be a struggle. Historically cameras need one cable for power and one for communication, however, advancements in power over ethernet have reduced the number of cables down to one. Installations can still prove difficult and costly as they have to be done by professionals, especially when setting up a large number of cameras. Once they are in place they cannot be easily moved either. Wireless cameras could solve some of these issues but the fact remains that each and every camera needs a power cable. A wireless infrastructure capable of handling all the cameras also has to be set up which can be costly. This thesis aims to provide a possible solution to these problems by combining the cameras with light rail infrastructure using powerline communication. This was realized by building a proof of concept prototype that enables a camera to be attached to a light rail and have both its power and communication fed to it through the rail itself with no additional cables needed.

Many different solutions on how to realize this goal was investigated throughout the report. It was known that sending high-frequency communication on exposed wires in the light rail might lead to issues with EMC, electromagnetic compatibility. This was taken into careful consideration. The final prototype was tested for electromagnetic emissions and efforts to lower them were also made.

The results clearly show that it is possible to send both communication and power on a light rail to a camera. The implementation in this thesis did indicate that EMI is indeed a problem, however, it was also demonstrated that there might be ways of solving them.

Acknowledgments

We would like to express our gratitude to everyone who has contributed to this Master Thesis. Firstly, to Simon Preutz and Nicklas Persson, our industrial supervisors, for guiding us and being there any day we had questions or needed to bounce ideas. Secondly, we would like to thank Johan Gran och Johan Nilsson, our academic supervisors, for helping us with radiation testing and contributing with meaningful discussion to help our work move forward. We would like to offer our greatest appreciation to Warren Bates, a colleague at Axis, for taking the time to help us build housing for our prototype, this has been vital to bringing our idea into a fully functional prototype. A big thanks to Håkan Vikström at Axis for helping us acquire the materials needed to complete this project.

Lastly we would like to hand out our greatest appreciation to Axis Communications who has contributed with its knowledge and resources. We would also like to thank all the colleagues and student workers at Axis that have helped us with their expertise, meaningful discussions, and ideas that have helped us completing this master thesis.

Acronyms

AFCI - Arc-Fault Circuit Interrupter
BPL - Broadband over powerline
BPSK - Binary phase-shift keying
CPU - Central Processing Unit
DUT - Device Under Test
EEA - European Economic Area
ECAD - Electronic Computer-aided Design
EM - Electromagnetic
EMC - Electromagnetic Compatibility
EMI - Electromagnetic Interference
ETH - Ethernet
HF - High Frequency
IC - Integrated Circuit
ICMP - Internet Control Message Protocol
LTE - Long-Term Evolution
MIMO - Multiple Input Multiple Output
OFDM - Orthogonal frequency-division multiplexing
OSI - Open Systems Interconnection
PLC - Power Line Communication
PoE - Power Over Ethernet
PSU - Power Supply Unit
PCB - Printed Circuit Board
PHY - Physical layer, IC that implements physical layer functions in a network interface
QAM - Quadrature amplitude modulation
VAC - Voltage with alternating current
VDC - Voltage with direct current

Contents

1

Introduction

The concept of sending information on the same wires as the supply power is not new. There are accounts stretching back almost a century [1]. The appeal of Power Line Communication, PLC, as it is commonly referred to today, is easy to understand. Implementing communication on preexisting wiring saves material and installation costs compared to setting up an additional wireless system like WiFi. For most of PLCs lifetime, the data rates have been low and implementations scarce but in the latest decades innovations have been made. Today it is possible to reach data rates of hundreds of megabits per second. [2]

Turning the focus to cameras paired with PLC we see that such devices are already operational in homes today. The signals and power to the cameras are sent via the electric circuitry around the house. However, putting a camera on a light rail and running the communication on the rail together with the power seems to be unexplored territory. An example of a light rail is shown in Figure 1.1. Previous studies has only revolved around PLC through wall sockets. It was deemed not viable for industrial or commercial use and therefore nothing to look into further. Some problems include the need for the camera and receiver to be on the same phase of the power grid, it not working with AFCI breakers and various kinds of stability problems like dropped frames and connection errors. These issues do not pose any problems with PLC over a light rail. There is only one phase, no breakers and not nearly as many possibilities for interference to enter the system.

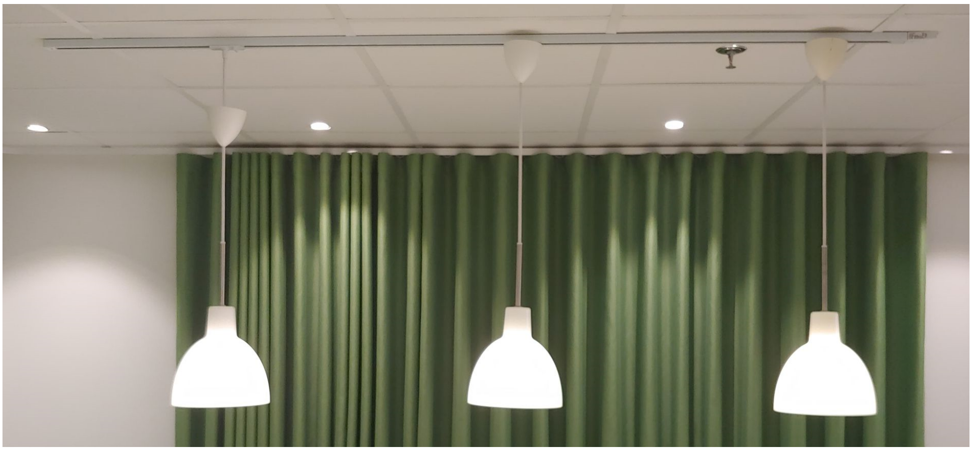


Figure 1.1 Example of a light rail, commonly used in dining halls, retail stores etc.

Problem formulation

- To investigate the possibility of transferring video communication and power on a 48 VDC light rail.
- To design prototype for light-rail camera and examine multiple camera options.
- To examine the electromagnetic radiation from the prototype.

Purpose

The main objective of this Master's Thesis was to develop a proof of concept prototype that enables communication and power over the same pair of physical wires on a light rail. The system was specifically going to be used for putting one or several cameras on the light rail and have them communicate with a computer. Traditionally, when installing a camera you need one PoE-enabled ethernet cable per camera. Installing them this way also means that the place of mounting is fixed and if the cameras need to be moved the whole process of installing them must be started again. The purpose of the prototype is to eliminate the need for additional mounting and cabling of additional cameras as the system would only need one cable per light rail, not one per camera. Additionally, the EM radiation of the prototype was to be tested.

Previous work

There has been previous work done in the area concerning light rails and cameras. The first one is called "AXIS T91A33 Lighting Track Mount", Figure 1.2, where "Lighting Track" has the same meaning as light-rail. This product is a camera mount for light-rail applications where no holes have to be drilled. Although you still need an ethernet cable to power the camera you can hide behind or alongside the rail. This is also a product that is not unique to just one camera but can be used in a variety of cameras. This mount also, to some extent, covers the need for flexibility as a movable camera. The downside of this mount is that with each movement the cable probably will have to be adjusted, either shortened or made longer without it hanging from the ceiling. This product shows that, although not yet common to the industry, it is a thought of concept and market potential. That makes this Master's Thesis most relevant as a proof of concept to be able to extend this product type into what will be call light-rail camera. [3]

Figure 1.2 AXIS T91A33 Lighting Track Mount [3].

The second part was a discussion with an engineer with previous experience working and testing with PLC to ethernet devices. As this is proprietary information the details will not be specified. From this discussion the conclusions were that to potentially use a PLC system setup in a commercial environment, the PLC system needs to be connected on the same phase and connected in the same panel. This means that the wire topography in the electricity grid must be known beforehand. Using an ethernet cable would probably be more cost effective than mapping the entire electricity grid in the building. One limitation of using a PLC system is that surge protection should not be on the same phase [4]. The surge protection can degrade the signal. These are common in a commercial environment. Finally, a commercial environment is noisy with high-demand loads like heaters, microwave ovens, power adapters, and this will degrade the signal and result in a lower bit rate.

Outline

The structure of the thesis is as follows:

Chapter 2 consists of the literature studies and background information. These serve as a base for the rest of the thesis. The most important concepts like EMC, PLC and PoE are discussed.

Chapter 3 outlines the methodology of the thesis. It begins with a discussion on how the problems of the thesis were approached, then the strategy of realizing these ideas. The rest is about how the prototype was designed, built and tested.

Chapter 4 presents all the results. Both from the prototype design itself but also from the various tests that were performed on it.

Chapter 5 discusses the results from chapter 4 and it also ties it together with the theory from chapter 2. Future work is also discussed here.

Chapter 6 is the final chapter where the conclusions of the thesis are summarized.

2

Literature Study

This chapter contains the literature studies and background information that lays the foundation for the rest of the thesis. Firstly, different parts of EMC are discussed. After that comes a few sections on Power Line Communication. Power over ethernet as well as PHY's have their own sections. Lastly ping is briefly examined.

2.1 Electromagnetic Compatibility

Electromagnetic Compatibility, EMC, describes the ability of electrical devices and components to coexist in the same electromagnetic environment. The electrical devices or component must be designed so that it does not generate, radiate and transfer interference above a certain level so that it can disturb other devices. The device must also be designed so that it will not be affected by disturbance from other devices and have a certain level of immunity to that disturbance. Complying to EMC standards ensures that the electronic devices and components works as intended without compromising safety and reliability loss. The standards can sometimes seem harsh, but with an increasing amount of electronics in everyday life EMC becomes more and more important, even simple devices could potentially affect critical things such as ABS vehicle system and pacemakers. When designing electronic products the effects of EMC restrictions must be taking into consideration from the beginning of the process, such as component choices, circuit design layout, packaging and more. To not include EMC restrictions in the process and discover that the product does not pass the requirements for CE marking can be very costly and time consuming. [5],[6],[7]

EMC should however, not be confused with EMI, electromagnetic interference. EMI can be seen as the opposite of EMC and is unwanted electromagnetic waves that can affect devices and prevent them from working. EMI can occur naturally from lightning and in some specific cases cosmic noise, it can also be man-made from electronic devices. [8]

Faraday's cage

Faraday's cage is a well known concept that is used when talking about EMC. A Faraday's cage protects the enclosed object from EMI, but it also works both ways, the object will radiate less emissions outside the cage. It is a container made out of a conducting material. Most often, solid sheets of conducting metal is used to enclose an object, but a conducting mesh could also be used depending on the emitted frequency's and the size of the mesh holes. The reason you would want to use a mesh is that cooling becomes easier and it saves material. The containment should then have a connection to the reference ground. [9],[10]

CE-marking

EMC restrictions is regulated from EU-directive using the CE marking. CE stands for "Conformité Européenne" and stands as a guarantee from the manufacture or importer that the product fulfills the environmental, health and safety requirements within EU. The CE marking can be self-declared without a third-party testing. If the self-declaration were to be challenged, appropriate evidence must be supplied to prove the claims. If a product is CE marked it can be sold freely within the European Economic Area (EEA). EMC regulations goes under (EMC) Directive 2014/30/EU [11] and ensures that electrical devices and equipment do not generate or transmit electromagnetic disturbance, neither is it affected by it. The responsible authority for this directive in Sweden is called "Elsäkerhetsverket". The CE marking logo can be found in Figure 2.1. [12],[13],[14]

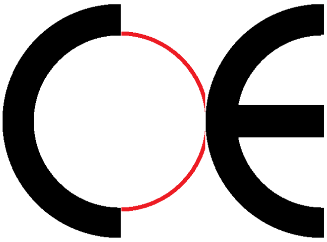


Figure 2.1 Illustrative figure of the CE marking logo, the red marking indicates the correct spacing between letters, but are not included in the actual marking.

2.2 Powerline communication

Power line communication (PLC) is a technology that enables sending data over power lines and existing cables. This means that you can control and power one or several devices using only one pair of wires. One of the advantages with PLC is the use of existing cables that is already embedded into the medium, such as a building or a car. Therefore there is no need for extra installation of, for example, extra ethernet cables, which can both be costly, cramped and aesthetically not pleasing. PLC works both for AC and DC lines since it adds a modulated signal on top of the already powered line with a much higher frequency. This will then be transported over the cables and de-modulated into power and data components by the receiver. Which modulation that is used depends on the application of the PLC and may vary. [15],[16],[17]

Low Frequency

Low frequency PLC is used for long haul applications where distance and power is more important then high data rates. It operates on frequency levels less then 500kHz and some applications can be found in table 2.1 below from CENELECT. Since higher data rates is necessary for video communication low frequency PLC will not be relevant for this project. [18]

Band	Frequencies	Use
A	3 - 95 kHz	Utilities / smart grid
B	95 - 125 kHz	Unrestricted
C	125 - 140 kHz	In-home networks
D	140 - 148.5 kHz	Alarm and security

Table 2.1 CENELECT standard of Low Frequency PLC [19].

High Frequency

High frequency PLC, also called broadband over power line (BPL), operates on frequencies above 1 MHz and can therefore achieve higher data rates enough for video and ethernet transmission. The most common use is home networking using ethernet adapters to plug straight into the wall socket to provide an ethernet local area network to other parts of the house using existing cables. Other applications of BPL is used for communication between transformer and customer outlets, e.g power companies can monitor your electrical consumption without a visit. When using higher frequencies, some already preexisting standards should be avoided, e.g FM radio frequency range 87.5 - 108 MHz, or WiFi commonly seen as 2.4 GHz or 5 GHz in households. For this project higher data rates over short distance with reliable connection is necessary and home networking standards and BPL will be most relevant. [20],[21]

PLC Protocols and standards

IEEE 1901

IEEE 1901 is a standard for high speed communication, up to 500 Mbit/s, for PLC. IEEE 1901 is often called BPL. This standard specifies usage of transmission frequencies below 100 MHz and is usable by all BPL devices. Applications for BPL within this standard is local area networks, smart energy solutions and internet access. The standard includes usage of OFDM, Orthogonal frequency-divison multiplex, to modulate the signal onto the physical layer. Other derived standards from 1901 are 1901.1 and 1901.2 which describes medium and low frequency power line communications application. These may differ but are based on similar technologies. [22],[23]

IEEE 1905.1

IEEE 1905.1 is an abstract layer for usage of multiple devices. It is a standard for a common interface for home networking technologies and joins together PLC, wireless, coaxial cable and ethernet communication. It is a necessary standard in order to use multiple devices at the same time, see Figure 2.2, to ensure quality of service and secure connections. [24],[25]

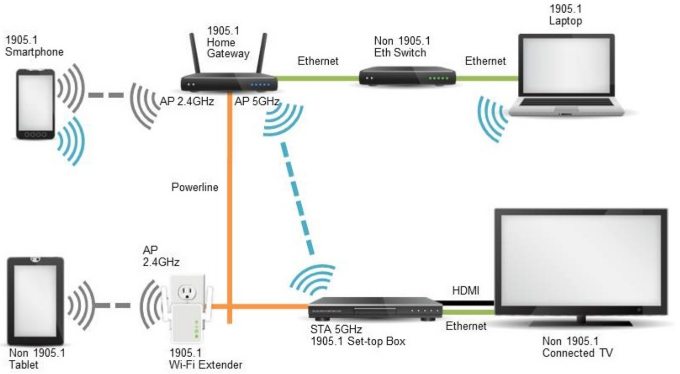


Figure 2.2 Example of where IEEE 1905.1 standard is used in a home network environment [26],[27].

HomePlug AV2

HomePlug Alliance was the organisation behind the range of protocol versions under the name HomePlug. They are all power line communication protocols but focusing on different areas. In this section only the most relevant protocol for this project, HomePlug AV2, will be discussed.

Like the protocols discussed in sections above, HomePlug AV2 is a PLC protocol. Consistent with many communication protocols of the modern era, AV2 uses OFDM to achieve its high throughput of 1 Gbps at the physical layer. It uses 128-bit AES encryption to keep the data safe. The frequency range that AV2 uses is 2 - 86 MHz. [2]

OFDM

Orthogonal frequency-divison multiplex is a transmission scheme widely used in modern communication systems. If paired with an advanced modulation scheme, like 1024-QAM, OFDM can achieve one of the highest spectral efficiencies available today. This, paired with a robustness to time dispersion, are some of the reasons it is used by LTE, WiFi, 5G, and, relevant for this thesis, also for high bandwidth PLC. The only downside is that the signal processing can become demanding and a relatively powerful CPU is needed compared to other multiplexing techniques. In OFDM the available bandwidth is divided into a number of sub-carriers. How many depends on the total bandwidth, the bandwidth of each carrier, and the frequency spacing between them. These carriers can be used independently or together to send information simultaneously. It is up to the protocol to decide how to assign each carrier or even if all carriers available need to be used. The carriers are modulated individually around their unique fundamental frequency. Most often the same type of modulation is used in all carriers, N-QAM being very popular. At first glance the sub-carriers seem very close, frequency-wise, and one might expect interference. This is not the case because each carrier's minimas are located in all the other carriers' nodes. This way they do not interfere with each other. This is illustrated in Figure 2.3. In the example in the figure the four carriers have the fundamental frequencies of 10 Hz, 20 Hz, 30 Hz and 40 Hz. These frequencies are then altered in phase to create a binary signal scheme. The arrangement of frequencies close together is made possible by the use of Fourier transform. Another benefit of OFDM is how easy it is to implement with MIMO technology. MIMO stands for multiple input multiple output and is a technique used in wireless communication. It uses multiple antennas in both sender and receiver simultaneously to increase throughput. This is paired advantageously with OFDM because each antenna can be used to send one carrier. This is of course most relevant for wireless communication and not something useful for this thesis as it focuses on communication on only one pair of wires. [28] [29]

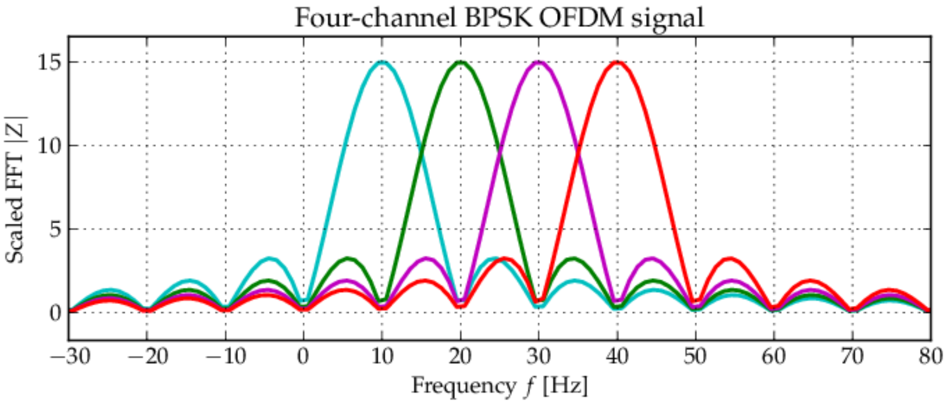


Figure 2.3 Frequency plot of OFDM signal with four sub-carriers.

2.3 Power Over Ethernet

PoE is, just like PLC, a technique used to reduce the number of cables needed to provide a device with power and communication. PoE uses an existing pair of data cables, specifically twisted pair ethernet, to send power as well without affecting the network performance. Like previously mentioned this reduces the number of cables a device needs to connect to and is therefore very useful for cameras and similar applications. The cost and installation time will decrease. Another added benefit is that the power management can be centralized. This means that many units can be controlled from one location as well as making it easier to have one back up power source for all PoE units.

Adding power can be achieved in a couple of different ways but the principle remains similar, with an added DC voltage of 44 V to 57 V at the power supply. The power transfer capabilities also differ between standards, measured at the camera it ranges from just below 15.4 W to 100 W. On lower bitrate ethernet standards not all pairs of wires inside the cable are used for communication, so allocating some for power is not an issue. On gigabit speeds the signals must be added on top of the DC voltage because all pairs are in use to send data, this makes the transceivers more complicated as they have to filter out the signals to separate them from the power.

One important aspect of PoE is that it is completely safe when it comes to backwards compatibility i.e. a non PoE device will not get damaged. The same goes for all legacy peripherals. [30],[31],[32]

2.4 PHY circuit

PHY stands for physical layer. That reveals a lot about this electronic circuit. To understand why you must first take a look at the OSI model of a network interface. A quote from IBM's knowledge center summarizes it well: *"The Open Systems Interconnection model (OSI) is a conceptual model that characterizes and standardizes the internal functions of a communication system by partitioning it into abstraction layers"*[33]. There are seven layers and as mentioned each have their own function. To understand why it is divided like this it can be oversimplified. Imagine two people wanting to send messages to each other. The first consideration is how the messages are physically transferred from person A to person B. Is it electrically in wires, smoke signals or maybe cars driving the messages between people? This represents the physical layer in the OSI model, the bottom layer. Then the messages have to get organized and labeled so that the correct people receives them. This represents the middle layers of the OSI model. Things like encryption and error correction also takes place here. Lastly it must be made sure that when the message gets delivered, it is presented in meaningful way, so that the receiver can actually read and understand it. This represents the very top layers of the OSI model. [34]

In electrical circuits, like in this thesis, the physical layer is the actual wires connecting the devices. The PHY has the responsibility to take the messages and transmit them on the wires as bits, ones and zeros. This can be achieved in number of ways. One example is by altering the voltage, maybe a high voltage represents a one while a low voltage represents a zero. Another example would be to alter the frequency of sine wave. High frequency represents a one, low frequency a zero. Either way you chose to implement this, it is the PHYs job to realize it.

2.5 Ping tool

Ping is a simple and fundamental networking tool that is built into almost all operating systems. It started as a command-line program but exists in many forms today. In its most simple form, the program sends an echo request to the desired destination IP, when the target receives the request it sends back an echo reply. The messages are sent on the ICMP layer, Internet Control Message Protocol. It is primarily used for error reporting and network diagnostics. It can be compared to how a sonar sends out an audible ping that echoes back when it hits targets in the water. This is also believed where the name ping comes from. Similarly to the sonar system, the ping measures the time it took for the message to bounce back. This can then be used to analyze the network system.

3

Methodology

This chapter describes the process of how this master thesis was conducted, it explains the methods used in order to achieve the end results which can later be read.

First there will be a discussion about different strategies and which one of them was suitable for this thesis to move forward with. It takes time management into consideration. The chosen strategy was then used to develop a prototype with a selected light rail.

Following sections describes testing of functionality of the prototype. It also explains the process of making the prototype into a stand alone product with housing and attachment for the light rail.

Finally a description of the EMC testing and possible improvements to evaluate future development of this product idea.

3.1 Strategy and development of prototype

The idea of transmitting both power and data over the same set of wires is not a new concept, therefore it was clear from the beginning that some form of power line communication, PLC, had to be used. From initial research there was no obvious solution of how to transform two-wire 48V power and communication to power over ethernet for the camera. After investigating different developer kits regarding PLC the same conclusion was reached on every occasion. Developer kits for PLC are slow, expensive, and hard to acquire. Because of this, a few meetings were set up to discuss the strategy to move forward. The first meeting was with an engineer with PLC experience, see previous work under 1.1 introduction. The conclusion of the meeting was that outside noise and stability problems must be considered when using devices connected to the electricity grid. Since the goal was to only use an isolated 48 VDC light rail not connected directly to the grid it could potentially avoid some or most of these problems. The second meeting was with Texas Instruments, a company working with designing, manufacturing, testing, and selling analog and embedded semiconductors [35]. In this meeting, several possible solutions were discussed. Some of which are presented in the sections below.

For this project, a device was needed capable of taking an ethernet RJ45 I/O and converting the data to a PLC signal to be modulated onto a physical layer, the 48V light rail. It must also work in reverse to enable two-way communication over the rail. From the research, three options were considered.

Using existing products

Finding a finished product that fitted the demands was seemingly impossible. The scarce products that worked on appropriate voltages were outdated and could only send a few Kbps of information which is not enough for the HD video stream from the camera. There were a very limited number of development kits for newer products that may have suited this projects demands but they were either impossible to buy or way out of budget. The conclusion was that there were no existing products out there that fitted the goals of this project.

Designing a PLC PCB

There was always the option to create the design, drawing the schematic and PCB layouts from scratch. The principles behind a PLC device that fitted the demands were simple enough, not too many IC parts were needed, the execution however was not. To simplify an analog front end was needed to handle the communication onto the light rail, a PHY to handle the communication onto the ethernet cable and a processing unit to tie the whole thing together with a few other components like regulators, protection, etc. This was entirely possible but would most likely take more than 20 weeks for us with limited ECAD experience and was therefore out of reach for a master thesis. It was therefore decided that this route would not be pursued.

Modifying an ethernet PLC device

The last option involved opening up, reverse engineer, and modify an ethernet PLC device. These are originally intended to send internet communication through the electricity grid in a house by adding a signal to the 230 VAC line. The problem is that these devices are also powered by the 230 VAC and the rail runs on 48 VDC. Although this means that the device could still be used if there was a way to power it from another source other than mains voltage and keep the signal intact. This was the method that was chosen to be explored further.

Choosing the right ethernet PLC device

There were many ethernet PLC devices that could potentially be used for the prototype. Axis had a few different brands from previous projects that were looked at, first testing if they even worked as intended together with an Axis camera. To achieve this, the PLC devices were connected to the same wall socket to ensure they are on the same phase. All devices could connect to each other, but only some of them could connect to a camera stream. Those that did not work were discarded. For further evaluation they were opened up with an attempt to reverse engineer them, remove the power electronic section and power it externally. With limited knowledge in power electronics, they turned out to be more complex than previously thought. A simpler and lower-end device was needed. The PLC device that was chosen to investigate further was the TP-Link TL-PA4010, an image of which can be seen in Figure 3.1. This particular model was, except for being simpler in design, chosen because it was cheap, readily available and there were examples of similar projects working with it. They come in pairs and can communicate with each other at speeds of hundreds of Mbps using the PLC protocol HomePlug AV2 and has a range up to 300 meters electrical wiring. The ethernet ports on the devices, however, are bottlenecks and are limited to 100 Mbps which sets the speed of the system as a whole. This is not a problem as a speed of 100 Mbps provides enough bandwidth for several HD camera feeds. When connected to the wall socket, the TL-PA4010 had a successful camera stream. This product was chosen as the best candidate to continue the development with.

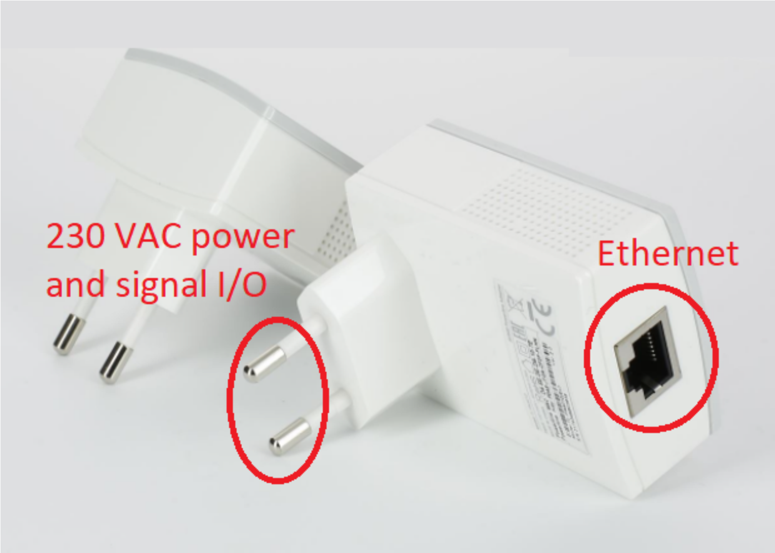


Figure 3.1 TP-Link TL-PA4010, modified image, original provided by Kjell & Company [36].

Reverse engineering of ethernet PLC device

As previously mentioned all parts were not needed of the ethernet to PLC device. It was therefore decided to reverse engineer the circuits to see if it could be modified to fit the requirements. The PCB of the TL-PA4010 could roughly be divided into two main parts. The high voltage side is dominated by power electronics where mains voltage is down-converted to more appropriate levels. The schematic of this part can be seen in Figure 3.2. This schematic is an overview and each part is highlighted in Figures 3.4 - 3.6. This part was connected to the European power plug, this is also where the PLC signals were transmitted and received from. The other part was the low voltage side where all calculations, communications, and PLC signals are sent and received. The low voltage side was the part that was needed for this project. Since the light rail is not running on 230 VAC there was no need for the high voltage side, this part was removed from the circuit. Figure 3.3 below shows the PCB of the TL-PA4010 with the high voltage side highlighted.

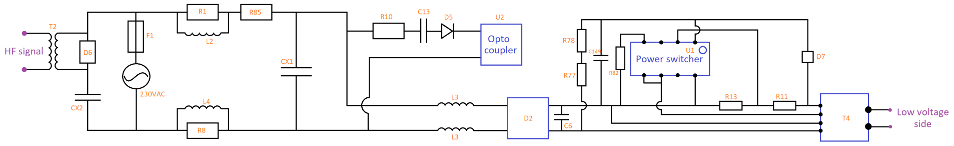


Figure 3.2 Full schematic of TL-PA4010 high voltage side.

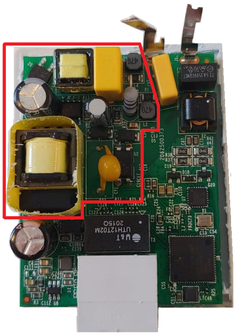


Figure 3.3 Deconstructed TL-PA4010, PCB layout, high voltage side highlighted.

The high voltage side could be clearly identified when the PCB was lit from underneath, this is shown in the results, Figure 4.1. To remove the high voltage side of the PCB, it was important to understand the overall functionality so the right components could be removed. Therefore the high voltage side of the PCB was divided into three parts for a better understanding of the PCB. The first part was the circuitry surrounding the 230 VAC plug. This can be seen in Figure 3.4. To the left in the figure, marked "PLC", shows the section that is the bridge from the low power side, to high power side. This is where the signal connects the high frequency modulated signal to the 230 VAC side. The part to the right is just a common filter step that is connected before any voltage conversion to protect it from conducted noise and unwanted emissions.

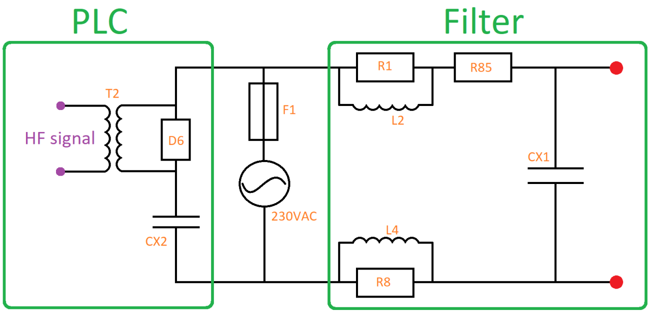


Figure 3.4 Schematics of filter and PLC part of TL-PA4010.

After the filter, there were two remaining parts of the TP-Link schematic. These parts were connected in parallel to each other. One is the optocoupler circuit, see Figure 3.5. An optocoupler is a device that can transfer signals between two circuits while still keeping them electrically isolated. A common way to implement this is by using a LED and a phototransistor. In short, a LED sits on the high voltage side and emits light when there is a signal. The light gets picked up by the phototransistor on the low voltage side. The signal has now been transferred safe and isolated. The reason it is used here is to give the low voltage side information about the high voltage side, a feedback system. The last part of the TP-Link schematic is the voltage step down, 240VAC to roughly 12 VDC.

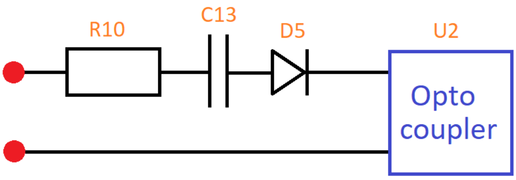


Figure 3.5 Schematics of feedback part of TL-PA4010.

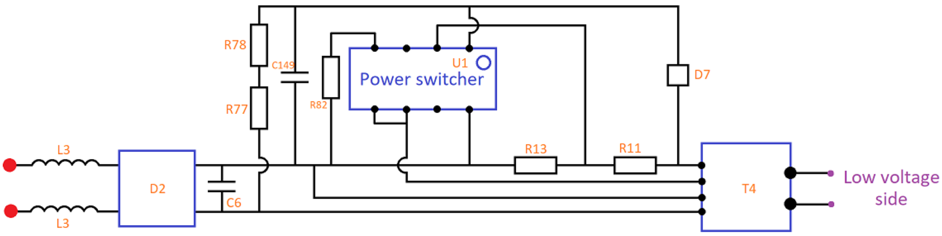


Figure 3.6 Schematics of voltage step down part of TL-PA4010.

Light rail

Light rail, track light, spot rail, all are various names for the same thing. In this report, it is referenced as a light rail. The light rail is used as a wall or ceiling socket for lamps. It consists of metal rails, one or several on each side with a fixed distance, and is used as an extension of the electrical grid. Most light rail are connected directly to the grid 230 VAC (or 110 VAC) without any extra electronic devices, such as protection or filters involved. Most common rails provides options for either 1 phase or 3 phase, see Figure 3.7. The 1 phase option gets simply connected as a pure extension of the grid. In a 3 phase option different settings can be provided for each lamp, these settings may include on/off functionality and dimmer. In light rails different light sockets can be attached with various designs and functionality. In this project, the goal was to use a 48 VDC light rail in order to give power to the camera with minimal extra electronics.

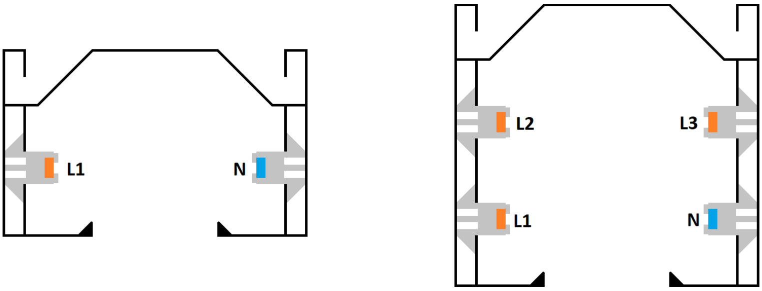


Figure 3.7 1 phase and 3 phase illustrative schematic.

Home-made light rail build

A home made light rail was build for this project to be able to start initial testing of the prototype. The materials needed were readily available. For simplicity a 1 phase light rail was constructed. The light rail was built using two metal rails, 120 cm long, screwed into a wooden plank. At the ends and in the middle of each rail a female connector was attached for easy setup,see Figure 3.8. Ongoing research on finding a commercial 48V light rail was conducted in parallel to this build.

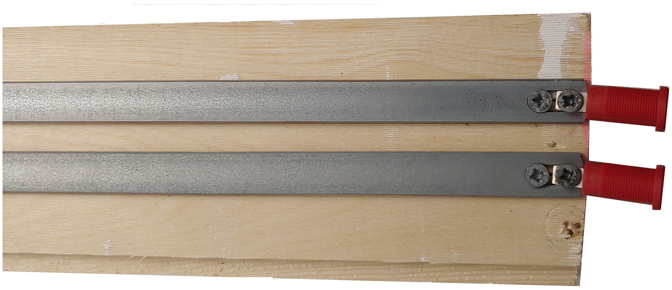


Figure 3.8 Home made light rail.

Store bought light rail

As mentioned above, a 48 VDC light rail was needed for this project, however most light rails are connected to directly or powered by 230 VAC, but there are limited supply of 48 VDC light rail options. To evaluate relevant light rails, price and shipping time had to be considered. It was also preferred to have a 1 phase rail instead of a 3 phase due to a simpler design for the prototype to be attached to the rail.

The closest company found retailing 48 VDC light rail options is located in Stockholm. Unfortunately, this was a new product at the time and their launch was postponed due to late deliveries, therefore these could not be acquired during the time of this thesis.

One retailer was located in Belgium where a 48 VDC light rail was accessible with 2 weeks of shipping. After a discussion with the supervisors, it was decided that the shipping and the rail was too expensive to be seen as a reasonable option for a prototype build.

Finally, it was decided to look for simpler 230 VAC models. Since the rail itself only consists of two parallel metal rails, the idea was to power it using a 48 VDC power supply unit. After researching several models, a model from a local Clas Ohlson branch, where two lamp socket were included, was found to be most interesting, see Figure 3.9 [37]. The lamp sockets could potentially come into use both for designing an attachment for the prototype, but also to see if the lamp itself could cause any issue on the communication line. With these arguments this light rail was ordered.

At the time of ordering the light rail, it was also concluded that it would be necessary to acquire 48 VDC lamps with the GU10 socket to use it on the rail. 48 VDC LED lamps were found and ordered simultaneously [38].

Figure 3.9 230 VAC light rail used in this project [37].

3.2 Final design of prototype

The modified TL-PA4010 cannot work fully on its own with the 230 VAC parts removed. It needs to be powered by a 12 VDC supply and since the rail runs on 48 VDC a step down is needed. There are two versions of the prototype because in cases where a camera with PoE is connected, an additional PoE injector has to be added. The simple variant can be seen below in Figure 3.10, it is going to be used for connecting the rail to the internet. The slightly more complex variant with PoE can be seen in Figure 3.11, this is used for connecting a camera to the rail. Since this variant is going to be connected to the rail, like a lamp, it is going to need an attachment and a housing to contain all the individual parts.

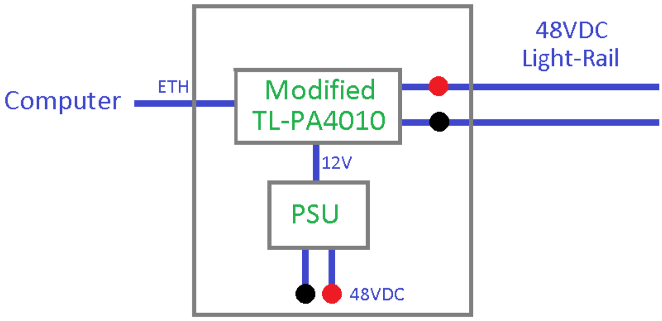


Figure 3.10 Block schematic of Prototype 1 without PoE.

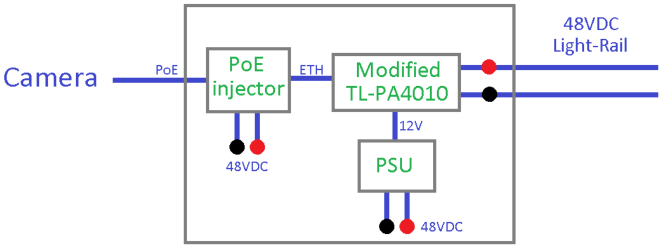


Figure 3.11 Block schematic of Prototype 1 with PoE.

PSU

Choosing a PSU was not a difficult task. There are many voltage converters on the market. A safe, cheap and reliable 48 VDC to 12 VDC converter was needed, the power requirement was not demanding as the PLC unit runs on low power. With these requirements in mind, it was not hard to find a working PSU for this project. A supplier commonly used by Axis presented several options and even the smallest and cheapest one would fulfill the needs. This happened to be the SD-15C-12 by MEAN WELL. It has an input voltage range of 36 VDC to 72 VDC and outputs 12 VDC. The maximum output current is 1.25 A which corresponds to a maximum power delivery of 15 W, well enough to power the PLC unit.

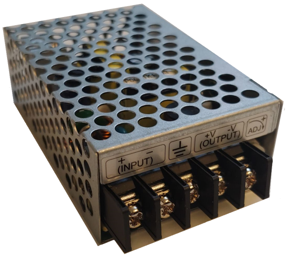


Figure 3.12 MEAN WELL SD-15C-12 DC/DC Converter.

PoE injector

The camera itself needs power and a way of communication in order to work, this can be achieved using a power cable and an ethernet cable. This could potentially be messy as many cables would be in use and a goal for this project is to minimize cable management. There is a better solution, namely PoE. Most of Axis cameras can be driven using PoE, this solution saves one cable. There was already an ethernet port coming from the PLC unit, the only thing needed was to add PoE to it. This could be easily achieved using a PoE injector made by Axis, see block diagram in Figure 3.13 below. It conveniently runs on 48 VDC, takes ethernet in one end and converts it to PoE enabled ethernet in the other.

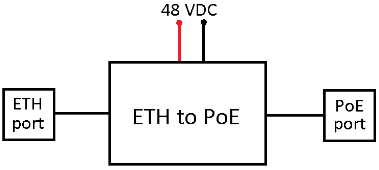


Figure 3.13 Block diagram of PoE-injector.

Housing

The prototype that was going to be attached to the rail consist as discussed above of three components. The PLC unit, a PSU, and a PoE-injector. They needed to be connected together and put in a housing with an attachment for light rail connectivity. In order to construct such a housing, it was decided to consult a mechanical engineer, Warren Bates, for help. Discussions were had about what parts needed to fit inside the box along with their dimensions. Leaving room for cables to connect the parts inside the box was also considered. After these discussions Warren provided 3D mock-ups, see Figure 3.14. In the rightmost 3D render the PL unit, PSU and PoE-injector can be seen fitted inside the shell with one ethernet port showing. The models were then sent to 3D printing. The only remaining problem now was to attach the box to the light rail. There already existed a light rail attachment (white part in Figure 3.14), it just needed to stick to the box somehow. The electronics box is attached to the light rail bracket by simple means of a modified bolt and washer. The bracket was cut, and the metal shaft was machined flat. Then a thread was machined on the inside of the shaft for the bolt to thread into. A special Axis bolt was then shortened and the thread lengthened slightly in order for it to fit. A washer was also included so to not damage the fragile plastic electronics box.

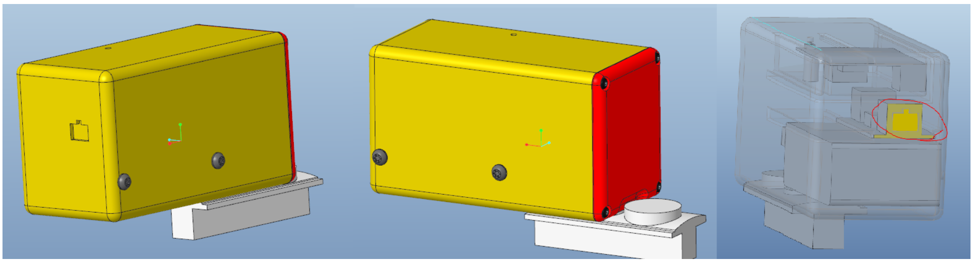


Figure 3.14 3D renders of the housing.

When putting lots of electronics inside a closed case one needs to evaluate the heat inside. There was only one part of all the electronics that was heating up notably, the PHY on the PLC unit, see Figure 3.15. This was done with feel only as the components were deemed not hot enough to warrant further investigation, with heat cameras for example.

Figure 3.15 Deconstructed TL-PA4010, PCB layout, PHY highlighted.

Camera mount

The housing of the electronics were to be 3D printed using a material that is rather fragile. It was decided together with Warren Bates that, since the camera is heavy, a different strategy was looked at when deciding on how to attach a camera to the light rail. Here Axis previous work came to play as they had already developed a finished product for this application. The developed light rail mount can be seen in Figure 3.16.

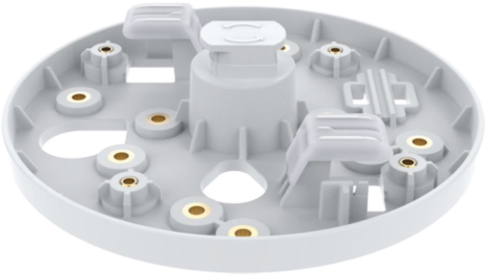


Figure 3.16 AXIS T91A33 Lighting Track Mount [3].

How it is connected

Figure 3.17 shows how a full setup of how the prototype is connected.

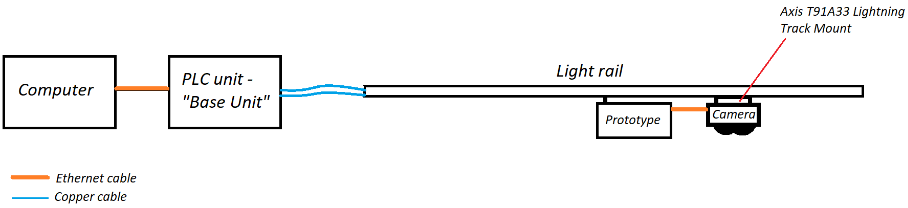


Figure 3.17 Full setup of working prototype.

3.3 Testing of prototype

A few different tests were conducted on the prototype to evaluate its reliability, data speed, and suitability. Different test setups were also run, enabling comparison of the results in a more meaningful way. An explanation of the varied setups can be found in Table 4.1. EMC tests are separated from these tests and have their dedicated section in this report.

Power consumption

Measuring the power consumption of the TP-Link unit was trivial. Powering the unit with a power box fitted with voltage and current displays made it easy to simply read these values and multiplying them to get the power.

Ping test

Ping is a crude utility software used to determine how good the connection is between a host and the tester. In this case between a computer and a camera. It simply sends out a message to the host and waits for it to echo back. This program was used to determine the robustness of the communication link. It measures how long it takes and if there are any errors or even any loss of packets. To test a system properly the program sends hundreds of thousands of ping requests and gathers all the data and summarizes it. The tests performed consisted of five test loops of 100000 pings each for different test setups. Presenting things like average time for a ping and how many packets were lost. From this test it was chosen to present the packet loss as well as the average ping time, result data are displayed in Table 4.2.

General data speed test

While a ping test can show the reliability of a communication link, a data speed test can show the throughput capabilities of that link. The first prototype has a theoretical max data speed of 100Mbps set by the ethernet ports, keep this in mind while looking at the results in Table 4.3. The speed tests were performed using the in-browser application on Bredbandskollen.se. It connects to a server and measured top download and upload speeds, in the result table marked "Download speed" and "Upload speed" respectively. The same server was chosen for all tests. It also includes a simple ping time to that same server, named "delay" in the table. The theoretical maximums are 100 Mbps for both up and down speeds as set by the ethernet protocol used.

Data speed test between units

The TL-PA4010's have a built-in feature that allows for a speed check between two units, named "TP-Link speed" in the result Table 4.3. The theoretical maximum speed between the units is specified as 600 Mbps by the manufacturer.

Multiple cameras

One important feature of a system that enables cameras to sit on light rails is to be able to have multiple cameras running simultaneously on that rail. According to TP-link's own website the units can connect up to 16 devices [39]. This means that you could theoretically have 1 master unit and up to 15 cameras simultaneously, on the same rail. For these tests, three modified TL-PA4010's were used. One connected to a computer and the others to two cameras. The results can be viewed in Section 4.3.

3.4 EMC testing

For this project EMI emission was always a concern. HF signals over open, unprotected, unshielded parallel rails are bad words to hear for any electrical engineer. Even though the products that were used are CE marked by themselves, in their own casing, there is no guarantee that they will meet the emission standards when deconstructed and put together in another way. The reason for this is that you put the electronics in an environment or setup they are not designed and tested for, therefore unwanted characteristics may occur. As discussed in section 2.1, Electromagnetic Compatibility, the devices must be designed so that it does not radiate, generate or transfer interference above a certain level so that it can disturb other devices. The device must also be designed so that it will not be affected by interference from other devices and have a certain level of immunity to it. For the prototype designed in this project, however, emissions and immunity were not considered. As stated in the problem formulation, this thesis was investigating the possibility of transferring video communication and power on 48 VDC light rail. Therefore the focus has been on proof of concept and generating a working prototype.

Despite not being planned or designed for passing EMC testing. It was nonetheless important to see how the emissions look in order to evaluate if this prototype could have a future in product development. This could be done in Axis own anechoic chamber. Before testing the prototype in the anechoic chamber with calibrated tools, in await of the booked time, it was decided to do a preliminary test. This test was performed at LTH with their spectrum analyzer.

Prestudy

The main purpose of pretesting the prototype was to see if the frequencies that the communication is operating on, 1.8 MHz - 86.13 MHz, could be detected from afar. This was done using a biconical antenna specified in the range of frequencies from 20 MHz to 200 MHz, which will cover the majority of emissions within the frequency range of HomePlug AV2. The antenna was then connected to a spectrum analyzer, Siglent - SSA3021X. A resolution bandwidth of 120 kHz was used aswell as a video bandwidth of 300 kHz. The prototype was set up 3 meters from the antenna due to limited space. When measuring EMC for CE marking the standard distance is 10 meters, it is however possible to use a 3-meter distance if the amplitude of the signals are reduced by 10dB to compensate for this. The prototype was then placed on a table to align the antenna and the DUT vertially. This test was also done on the store-bought light rail but without the housing, since it was under construction at the time. The prototype was tested on different positions and different set ups, see section 4.4 in results.

An overview of what frequencies to expect problems with was the main goal of this study. It was therefore decided to present the results with a waterfall graph, see section 4.4. This type of measurement uses the max hold setting for 3 minutes on the spectrum analyzer for peak detection. This is then converted into a colour spectrum. The color depends on how high the emissions were at a specific frequency and gives an illustrative picture easily comparable between each other. Therefore it is not possible to see exactly at what amplitude each frequency has but instead a clear visual overview. Some of the highest peaks detected were noted to estimate the possibility to pass the EMC test in the anechoic chamber.

EMC chamber testing

Axis has its own anechoic chamber for EMC testing of their products that they use daily. It is a room designed to completely absorb all electromagnetic waves so that reflections do not occur and are also completely isolated from outside emission. This means that when measuring a device you can test for what that particular device is emitting with certainty. The chamber has a stationary antenna that can rotate around its axis located at the far end. This chamber is also equipped with a rotating table to provides different angles that can affect the measurement level. The EMC test works by first sweeping through the whole spectrum with a fast and rough measurement. The user can then mark interesting peaks, these can be seen as blue and red markings on certain peaks in the graphs in the results section. These specific frequency peaks are then analyzed more precisely with quasi peak detection.

To make more accurate measurements the prototype was set up inside the chamber. At this time the housing was done and the testing was done on the fully constructed prototype with the store-bought light rail. This test was also using an Axis camera. All the components were placed on the rotating table. Long cables were then drawn from the table, outside the chamber, and to the power supply, taking into account that the table would rotate. The power supply was placed outside the chamber to avoid any unnecessary emissions from it. The same process was done for an ethernet cable connected to a computer outside the chamber to have a video steam active while the tests were running. Then the test was done automatically by a preset up computer outside the chamber.

The EMC tests were then performed by a spectrum analyzer connected another computer using an automated process. Several tests were made with different positioning and active components, see section 4.4 in results for more details. In some of the tests the camera was covered with aluminium foil to act as a Faraday's cage since the emissions from the camera itself was not interesting, only the emissions from the rail.

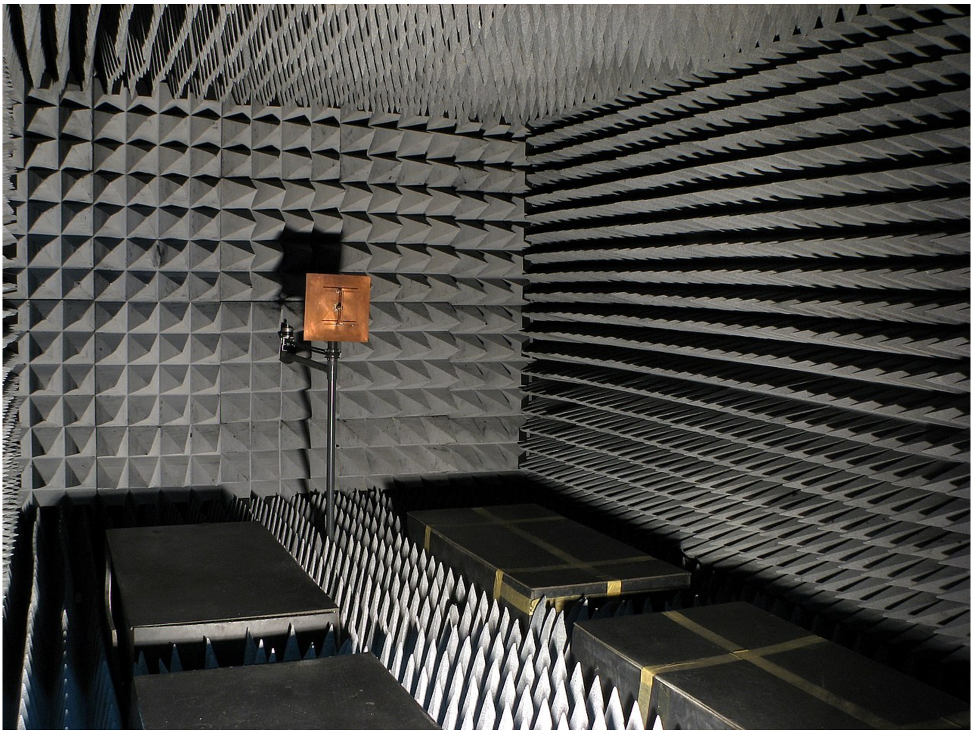


Figure 3.18 Anechoic chamber for EMC testing located in Democritus University of Thrace, Greece [40]. Similar to the one at Axis.

3.5 Fixing EMC problems

There was a discussion with supervisors here at Axis on how to reduce the emissons in the EMC tests. One of the biggest problems was the open light rail. Since the rail itself must be open in order to be able to move the camera around or switching out lights, this could not be altered or covered. Therefore the PLC device was the main focus in the discussion of how to reduce the emissions. The PCB of the PLC device that produces the HF signals were store bought and could therefore not be altered. This lead the discussion onto shielding the device with a Faraday's cage and putting ferrites sleeves on the signal cables. There were also a discussion of adding a filter after the camera to reduce the signal.

Faraday's cage

There were two Faraday's cages built. One for the device attached to the light rail, and one for the base unit. The cages were build from two paint cans. For the base unit a 1 liter paint can were used, two holes were drilled, one in the bottom for the power and signal cable, one in the lid for the ethernet cable. The inside was covered with cardboard to avoid contact between the PCB and the can. For the other device a bigger paint can, 3 liter, had to be used because of the size of the housing. Two holes were also drilled, one for the ethernet cable, and one to connect the light rail attachment, see Figure 3.19. All holes drilled in both cans were then covered with copper tape to ensure as tight seal as possible. The cans would then be connected to a secure ground when tested in the EMC chamber. The results can be seen in section 4.5.

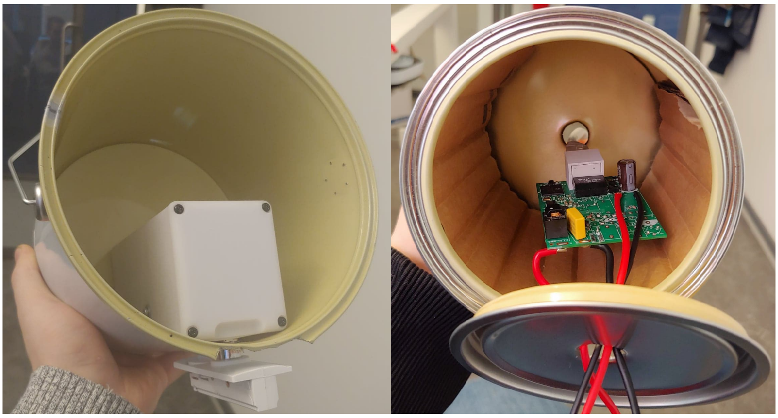


Figure 3.19 Two Faraday's cages built using paint cans. The left figure shows the prototype with attachment. The right shows the base base unit.

EMC reduction filter

In total 3 filters were tested. The filters were based on first order high pass filters and the idea were to reduce some of the additional signal. A capacitor in series with the rail would block of the DC signal and let the HF signal through, this would then be reduced by the resistor and possibly send out less emissions. The following filters in the Figures below were produced and added to the light rail when tested in the EMC chamber. The results can be seen in section 4.5.

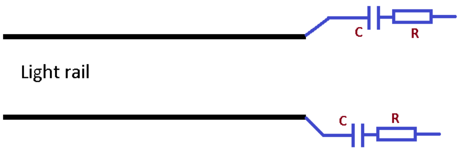


Figure 3.20 Circuit diagram of filter 1.

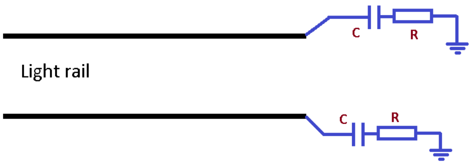


Figure 3.21 Circuit diagram of filter 2.

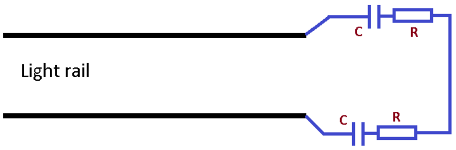


Figure 3.22 Circuit diagram of filter 3.

Filter	R - Value	C - Value
1	27 Ω	220 pF
2	820 Ω	10 nF
3	820 Ω	10 nF

Table 3.1 Filter values.

4

Results

This chapter introduces the results of this master thesis. A few comments are made to guide the reader through the results but as per formalities all of the results are discussed in chapter 5.

The first section gives a brief summary of strategy and development of the prototype to ease into the results.

Next is a section dedicated to the results from all the different tests that were performed with the prototypes. Each test has it's own subsection.

The following section describes the final design of the prototype. The parts and how it all fits together.

Lastly are two section for the results of the two different EMC tests. The first being the preliminary test done at LTH and the second the proper one performed at Axis EMC chamber.

4.1 Strategy and development of prototype

Initially, several strategies were considered to achieve the goals of this thesis. With previous research and help from resources at Axis, several options were considered before further development was made. Firstly, it was considered using an existing product. From research, this gave indications of slow performance, expensive and hard to acquire. Secondly, it was considered designing a PCB for the task. With limited time and experience in this field, this route was not pursued. Lastly, modifying an ethernet PLC device gave indications to be the best option for this master thesis.

Choosing the right PLC was decided by first testing some models that were used in previous projects here at Axis. Some could not connect a camera stream. Those who could connect were considered too complex to be reversed engineered. Therefore a simpler model was chosen, the TP-Link TL-PA4010. Inside the casing, it consisted of one PCB with a clear boundary dividing the low voltage and high voltage sides apart. Since the high voltage side was going to be removed a schematic was made of the overview to be sure the right components were removed. Therefore, these circuits diagrams, see Figure 3.4 - 3.6, were considered more as a tool rather than a result. The PCB with removed high voltage side can be seen in Figure 4.1. By highlighting the PCB with a lamp underneath a clear view of the high voltage side can be seen in the same Figure.

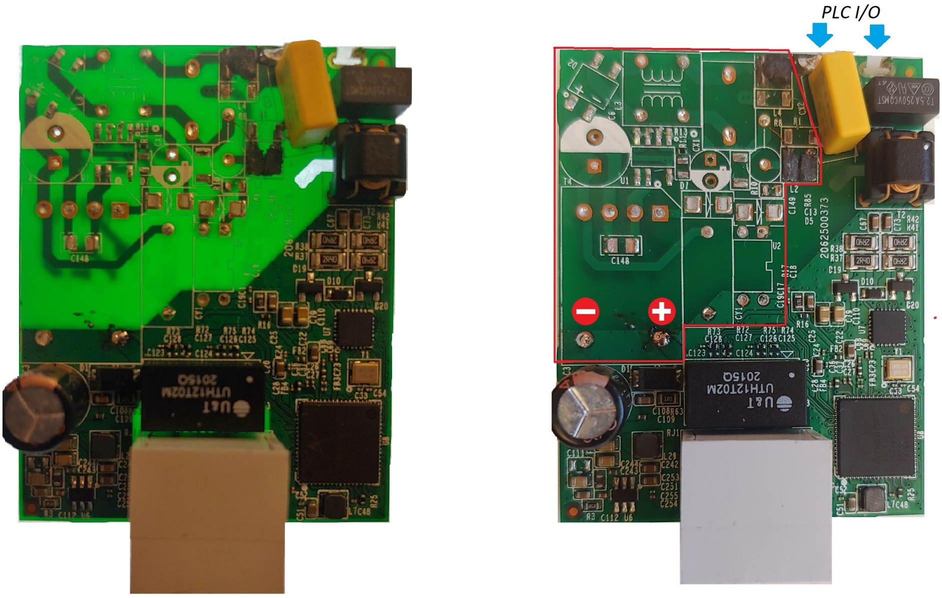


Figure 4.1 Deconstructed TL-PA4010, PCB layout, high voltage side removed. In the left Figure is the PCB, lit from underneath. In the right Figure the input voltage and PLC communication lines are marked.

4.2 Final design of prototype

The final design of the prototype consist of the electronic components explained above, see section 3.2. These consist of tree main parts, the PLC unit, the POE injector and the PSU. These were then put into the 3D printed housing, see Figure 4.2. The housing consist of 3 compartments, one for each component. The PSU has two threaded holes and was screwed in place from the outside. For the PoE injector and the PLC device a custom lid with long rods were printed to hold the devices in place. The housing has the outer dimensions 13.5x6.5x7.5 cm when put together.

The housing was attached to the modified lamp socket, see Figure 4.3. To hold it in place a threaded but hollow screw was used. This to be able to connect cables from the attachment to the inside of the housing.

In Figure 4.4 the full setup for the prototype is presented. To the left, an unmodified lamp socket with a 48 VDC LED lamp. In the middle, the prototype is presented in its housing attached to the modified lamp socket. To the right, the Axis track mount with an attached camera is shown hanging from the light rail.

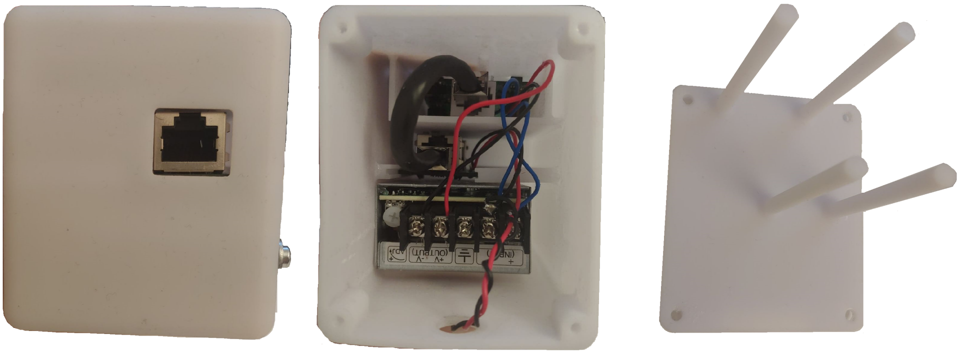


Figure 4.2 3D printed housing for prototype.

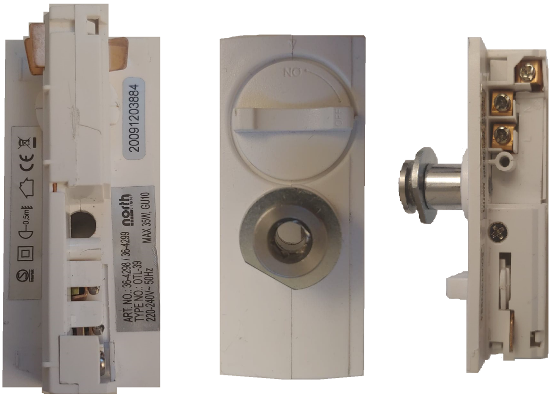


Figure 4.3 Light rail attachment modified for prototype.

Figure 4.4 Fully setup prototype on light rail with lamp and camera.

4.3 Testing of prototype

This section is for the results of the various tests performed on the prototype. Each test corresponds to a subsection.

Power consumption

- The power used by the TP-link PLC unit was measured to an average of 2 W.
- The power used by the 48 VDC LED lamps was measured to an average of 5.5W.
- The power used by the camera was measured to an average of 8W.

Multiple cameras

Multiple camera support was tested on both the homemade light rail as well as on the store-bought. Both tests were successful in running two cameras at the same time with communication to a computer.

Ping tests

The results from the ping tests that were performed using the Axis-made program PyTools can be viewed in Table 4.2 while Table 4.1 explains the different test setups that were used in both the ping and the speed tests.

Setup	Descriptione
A	Unmodified TL-PA4010's used as intended by manufacturer
B	Two modified TL-PA4010's connected tightly together
C	Two modified TL-PA4010's tested over the home-made light rail
D	Final design tested over the store-bought light rail

Table 4.1 Explanation of setups in Speed and Ping tests.

Setup	Avg. Packet Loss	Min/Max Packet Loss	Avg. Ping Time	Min/Max Ping Time
A	0.01‰	0.0‰ / 0.02‰	23.18 ms	2.6 ms / 47 ms
B	0.035‰	0.02‰ / 0.11‰	23.12 ms	2.7 ms / 99 ms
C	0.038‰	0.01‰ / 0.07‰	24.73 ms	2.9 ms / 75 ms
D	0.062‰	0.0‰ / 0.18‰	24.02 ms	2.9 ms / 98 ms

Table 4.2 Results from Ping tests.

Data speed tests

Results from the speed tests are shown below in Table 4.3. Keep in mind that the maximum theoretical speeds are 100 Mbps for both download and upload.

Setup	Download speed	Upload speed	Delay	TP-link speed
A	95 Mbps	62 Mbps	16 ms	450 Mbps
B	94 Mbps	65 Mbps	17 ms	426 Mbps
C	94 Mbps	70 Mbps	20 ms	402 Mbps
D	93 Mbps	84 Mbps	14 ms	380 Mbps

Table 4.3 Results from Speed tests.

4.4 EMC testing

Prestudy

The following test results were performed at LTH with the Siglent - SSA3021X Spectrum analyzer. All amplitude values must be subtracted by 10dB to compensate for the tests being performed at three meters instead of the standard 10m. The antenna factor is also not included but this does not really matter since these tests were performed to give an indication of what frequencies that were giving off high emissions, not to give accurate readings of the levels.

The spectrum range measured was 1.8 MHz - 86.13 MHz, because these are the frequencies that the PLC protocol uses. Note that according to the standards of EMC testing the lowest frequency that needs to be tested from emitted fields is 30 MHz but lower frequencies were included in this measurement for research purposes.

There is one regular spectrum vs amplitude plot and one waterfall-diagram. The latter is an accumulation of the maximum amplitudes at each frequency. Horizontally we still see the frequency but vertically is time. The colours change according to the maximum amplitude that was been recorded at that specific frequency. The tests were run for 3 minutes to accumulate maximum values. Only the three most interesting and relevant results are shown in this section, all the results from this test can be viewed in Appendix A.

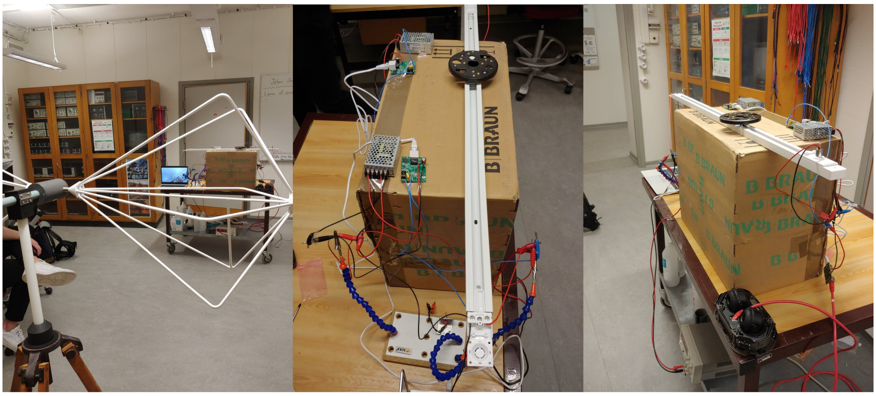


Figure 4.5 EMC preliminary test at LTH.

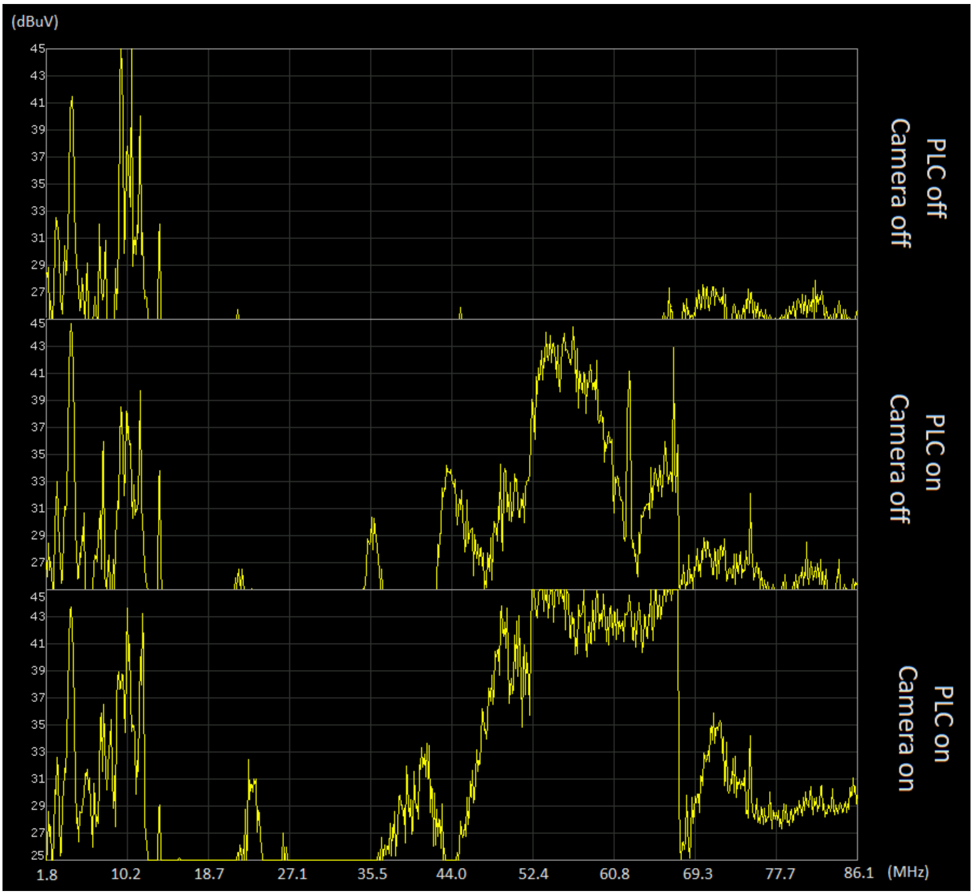


Figure 4.6 Results of preliminary EMC tests, dBμV vs frequency plot. The scale of the Y-axis is adjusted to give the waterfall diagram below a distinctive spectrum scale of the emissions. This results in some bottom and peak values to be cut off.

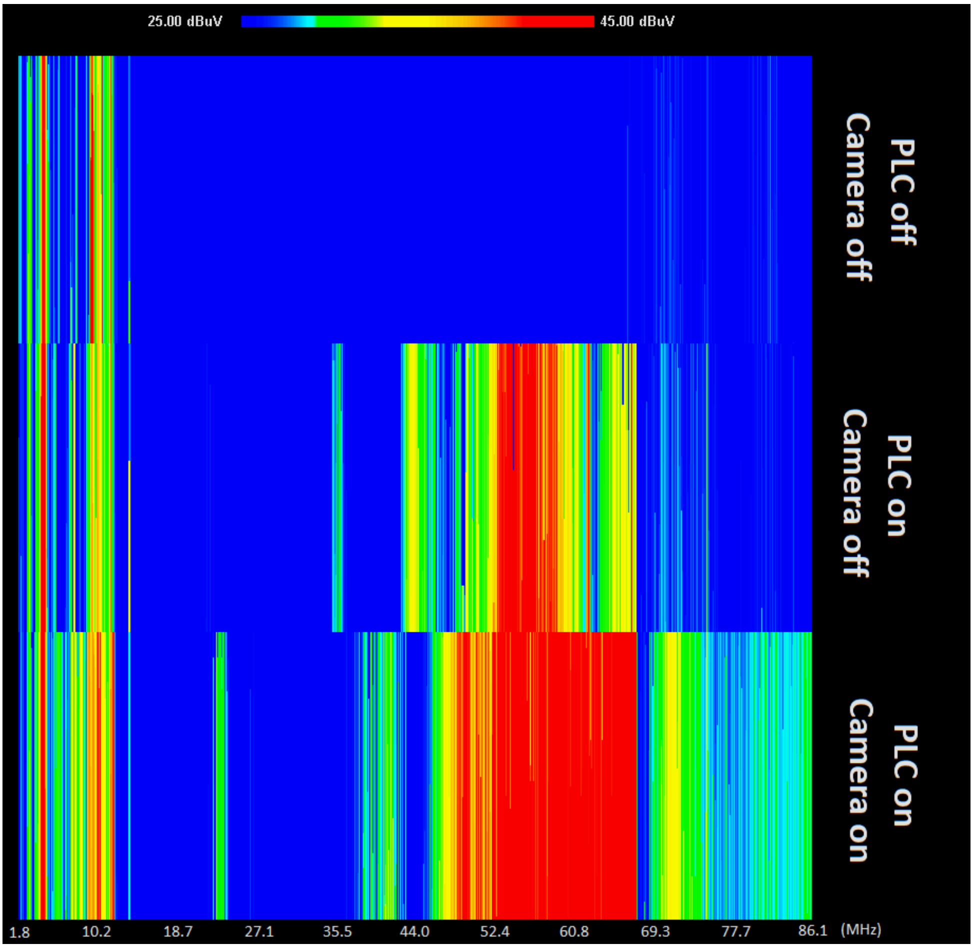


Figure 4.7 Results of preliminary EMC tests, waterfall diagram. On the x-axis you have the frequency range. On the y-axis you have time. This test were accumulated by max hold for 3 minutes, but this graph shows only the last seconds.

EMC chamber testing

This section is for the results of the EMC tests that were performed on the prototype together with the light rail. It was executed at Axis in-house EMC testing chamber. Marked in the graphs is a red line representing the maximum limit for radiation in a domestic environment. All values are true and compensated for the entire signal chain including antenna factor etc. Note that the prototype was always connected in the middle of the light rail. Only the five most interesting and relevant results are shown in this section, all the results from this test can be viewed in Appendix B.

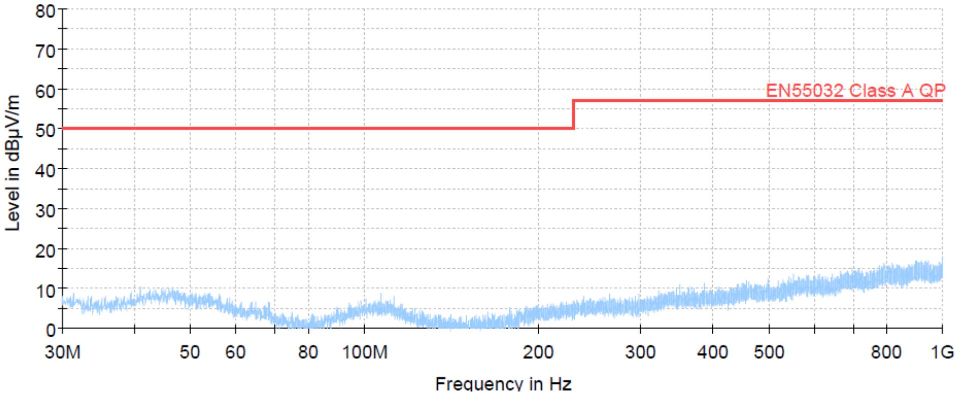


Figure 4.8 Empty chamber.

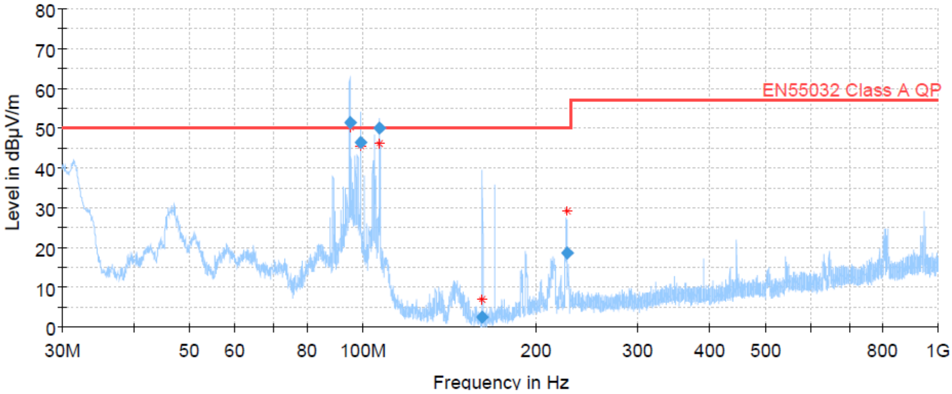


Figure 4.9 Empty chamber with power cables going in.

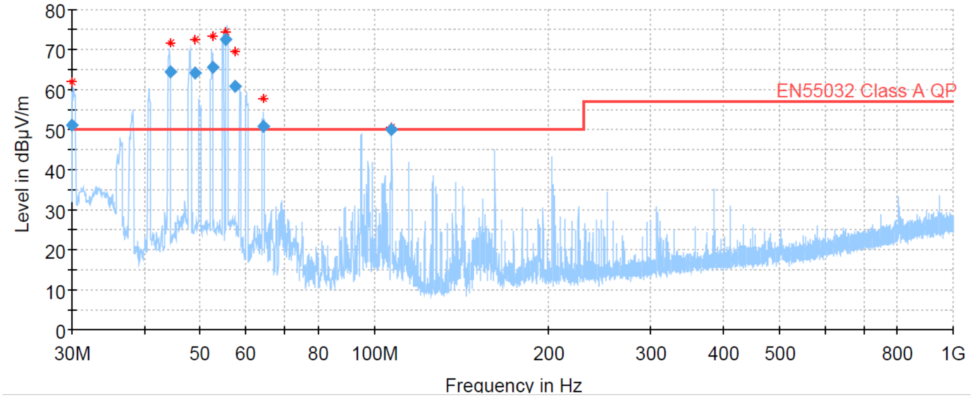


Figure 4.10 No cameras running, just the prototype on standby.

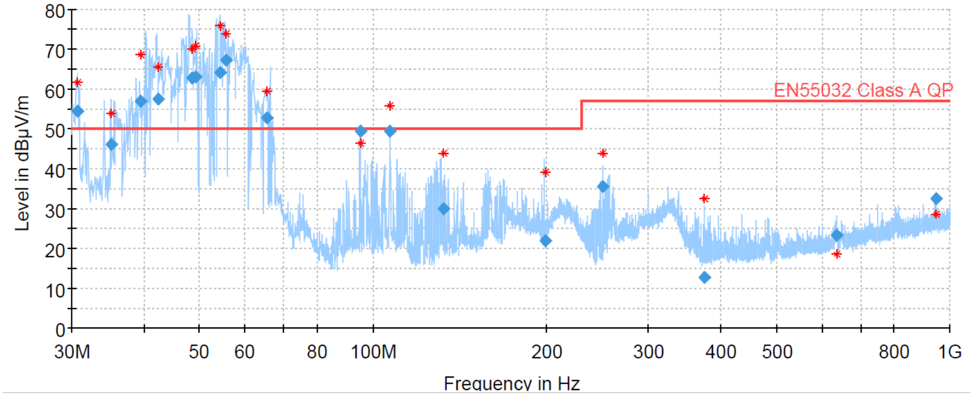


Figure 4.11 One camera running.

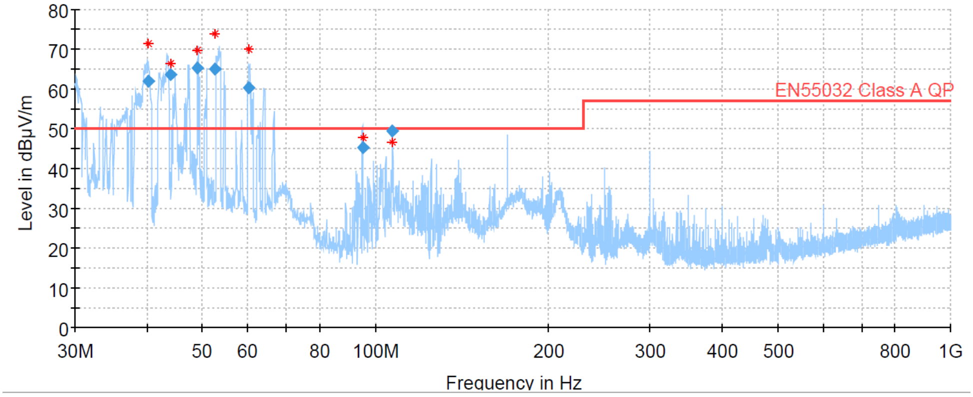


Figure 4.12 One camera running covered with aluminium foil.

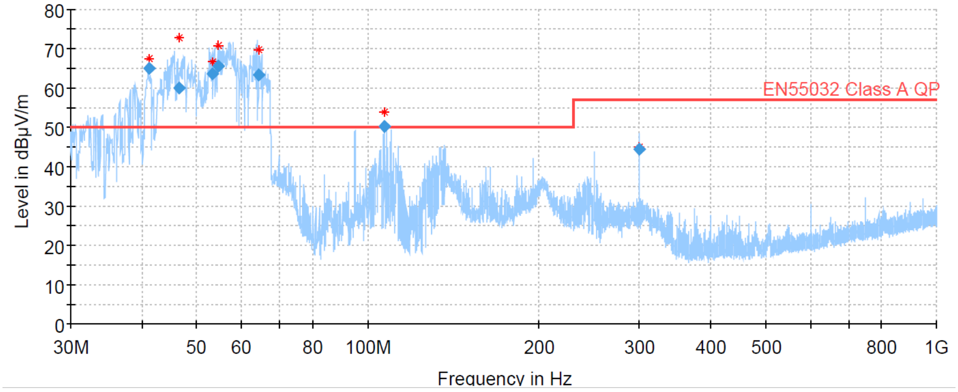


Figure 4.13 Two cameras running covered with aluminium foil.

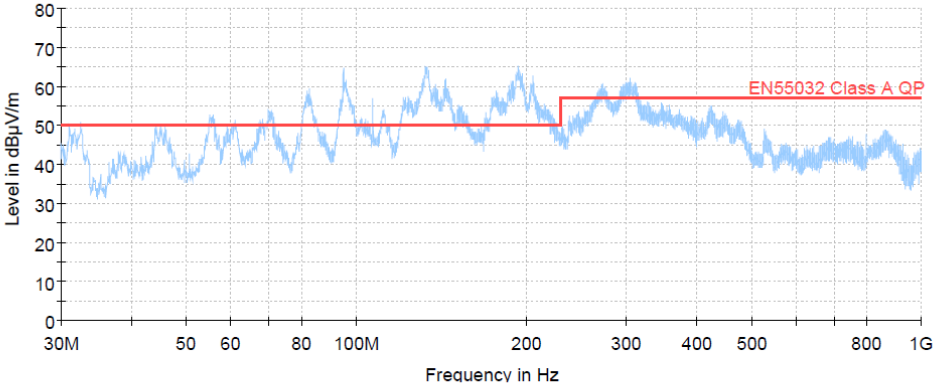


Figure 4.14 Two lamps.

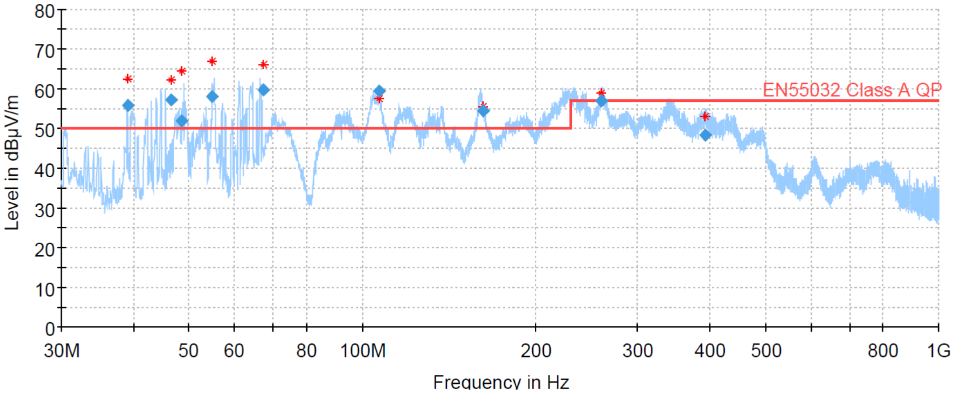


Figure 4.15 One camera running covered with aluminium foil and two lamps connected to the light rail.

4.5 Fixing EMC problems

Here are the results from the EMC tests where modifications were made in order to reduce the EMI.

Faraday's cage

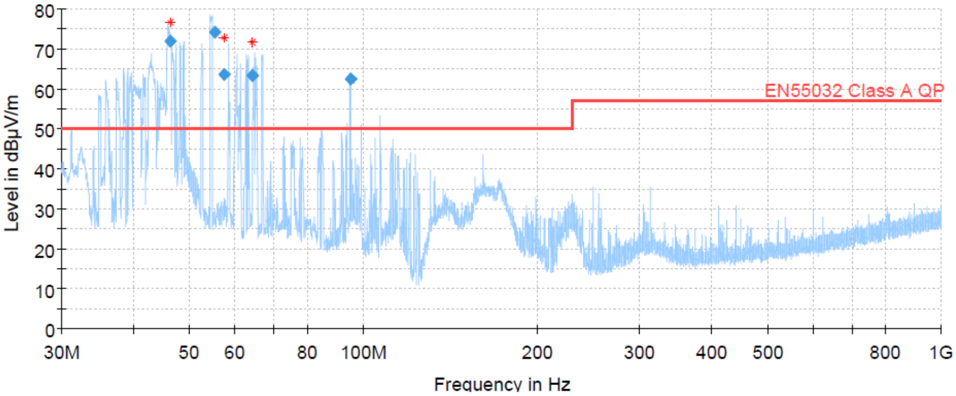


Figure 4.16 One camera running covered with aluminium foil and PLC unit in Faraday's cage.

EMC reduction filter

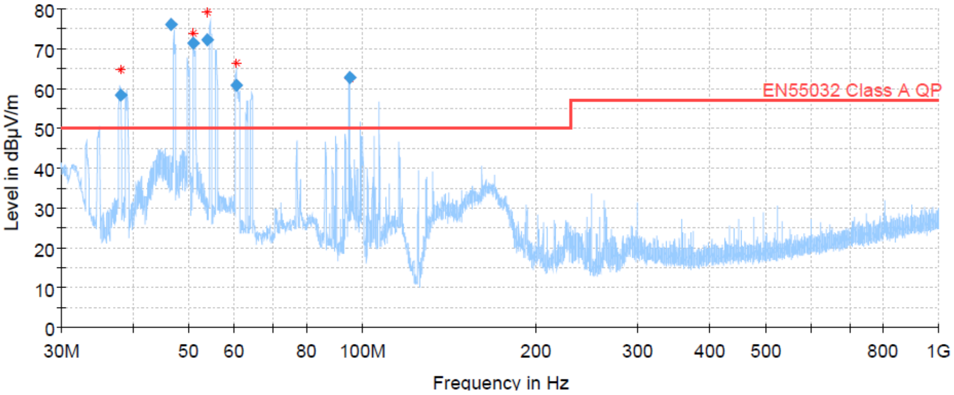


Figure 4.17 One camera running covered with aluminium foil and PLC unit in Faraday's cage and EMC reduction filter version 1.

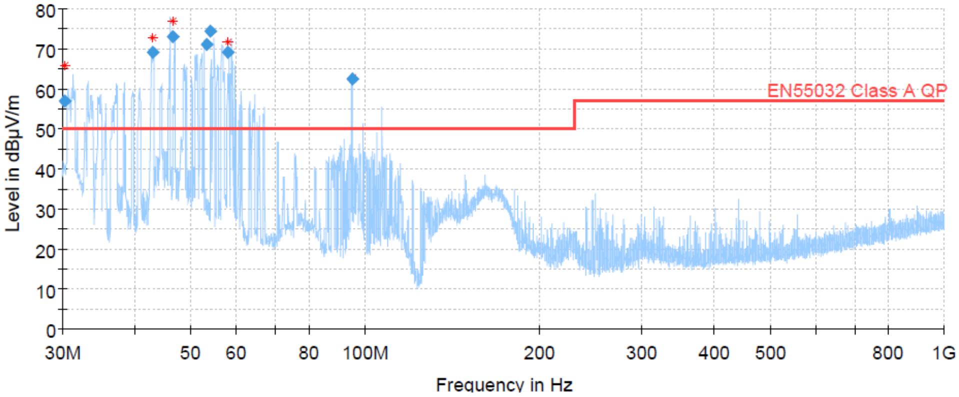


Figure 4.18 One camera running covered with aluminium foil and PLC unit in Faraday's cage and EMC reduction filter version 2.

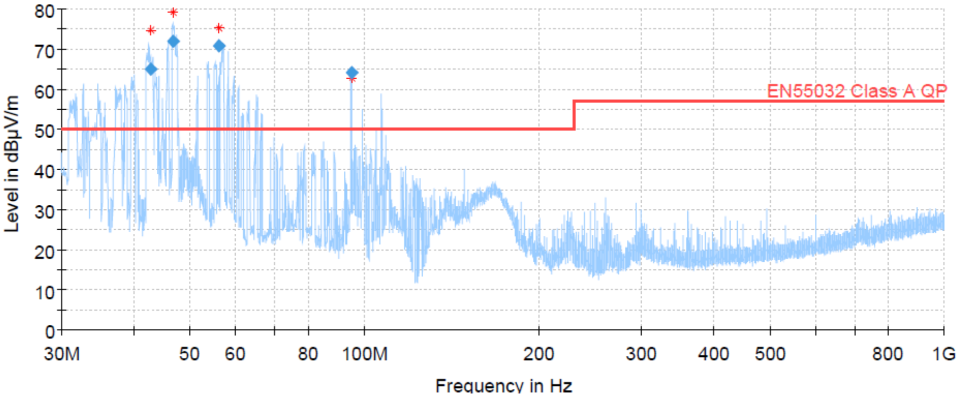


Figure 4.19 One camera running covered with aluminium foil and PLC unit in Faraday's cage and EMC reduction filter version 3.

5

Discussion

This chapter ties the whole thesis together and discusses the results, as well as the future, of our work. It begins with a section about the developing process of the prototype, followed by one on the light rail. The results from all the tests are then discussed. After this comes a section on the final design of the prototype. The results from the the two EMC tests are then discussed in its own two sections. A commonly asked asked question is then talked about in the section "Why not wireless cameras?". After this comes a section comparing 48 VDC to 230 VAC in light rail applications. Lastly future development is discussed.

5.1 Strategy and prototype development

The strategy chosen for this thesis was to modify an ethernet PLC device. The chosen device was the TP-Link TL-PA4010 which turned out to have a simpler PCB design to our advantage. Other PLC devices were complex and reverse engineering complex PCB was not the goal of this thesis. For time management a simpler product was the right way to go. As seen in Figure 4.1, the high voltage side was clearly highlighted when lit underneath and this made the reverse engineering process easier. Even though not fully understood, the circuit diagrams, see Figure 3.4 - 3.6, were a much needed tool in order to safely remove components from the PLC PCB. Even though a removed component can be reattached, the PCB itself may may be damaged from this process and not work properly. Even though precautions and carefulness were taken, six PLC devices were used in this project. The first two used worked as intended after the high voltage side was removed. The second two did work as intended when modified, but with a much lower speed between the units. Later, one component on one of the PCB burnt, the other one worked at full speed with the other devices. The reason for this was unknown and not investigated further. After moving the devices around and modifying them, another one broke. In total 3 devices were broken in the process. This is the result of using a PCB where it is not intended, out of its casing. These risk were known beforehand but due to previously mentioned reasons this route was still taken.

Light rail

A light rail in its simplest form is just two static metal rods with a fixed distance from each other. By using accessible materials this was shown in a very simple way. Unknowing about the material, just that it is some kind of metal, and with screwed on female contacts its performance was above our expectation. It had no issues during testing that we could relate to the rail itself, neither with one or two cameras. This also gave confidence that any light rail would work.

The off-the-shelf light rail for 230V applications performed as expected after previous test. Easy installation with solid attachment it does the job it was intended to do. It would have been more interesting to use a 48 V store bought light rail that was connected to the 230 VAC grid. This would have been a more accurate test to see if the electronics, most probably some switching circuit, would have an effect on the communication line and the total emissions. The 48 VDC lamp was ordered separately and as in Figure 4.4, the lamp bulb is larger then the intended 230 VAC bulb, however the functionality is the same.

48 VDC vs 230 VAC

The main reason this project used 48 VDC on the light rail, instead of the industry standard 230 VAC, was safety. At Axis, it is required to have a certain training to be allowed to work with high voltages, something we lacked. 48 VDC did however turn out to be a very good alternative. It has a few benefits over higher alternating voltages. First, of course, being the safety aspect. Another benefit is that PoE uses 48 VDC and therefore made it very easy to feed the PoE injector. It could just be attached straight onto the light rail. Not using mains voltage also has the advantage of isolating the light rail from the rest of the building. It would not be possible to jam the signal on the rail by connecting a jammer to a wall socket close to the light rail. Something that could be possible if the light rail shared the same wires as the mains wall circuitry. Having each light rail isolated from everything else also means that deploying multiple light rails in the same building will never be a problem. Remember that there is a limit to how many PLC units can be used on the same network. If all light rails are connected it means that this limit gets applied to the system as a whole, not just each individual light rail. A benefit of having them on the same network is that you would only need one base unit. The unit can connects to a computer and sends and receives the signals onto the network to all the camera units.

The main reason why you would want to deploy this technology on 230 VAC is simply because almost all light rails on the market runs on it. It was not a big issue for us since this thesis focused on proof of concept and creating a prototype to show that it is possible to send signals on a light rail. If this was to be developed into a real product it would probably be a good idea to have it run on 230 VAC to make sure it is compatible with all light rails.

5.2 Final Design of prototype

The final design contains 3 main component, PLC device, POE injector and PSU. These are then contained in a 3D printed housing. The housing is fastened to the modified light rail socket with a small screw at one of the edges. Unfortunately the 3D printed plastic is not strong enough to hold the device for a longer time, as it starts to bend after some time. This was first noted after having the prototype hanging in its housing for several days. This could be corrected however with the use of a heat gun. The light rail attachment also tends to come loose as the screw cannot be tightened too hard due to the risk of breaking the plastic.

There were always a heat concern as the PHY on the PLC PCB, see Figure 3.15, were getting warm. It got so warm you could not hold your finger on it for longer periods of time. In the original casing of the TP-Link TL-PA4010 there were no extra heat sink, or any source of cooling the chip. This indicated that air cooling should be enough for the PHY. In the 3D printed housing, Warren made sure to leave some extra air gap above the PHY to avoid any heating issue. The result of this were that the plastic on the outside becomes warm to the touch, but had no other effects. There were no long term testing done to the prototype to see how the heat would affect the housing. This because the goal of this thesis was to build a proof of concept.

The prototype was connected to the camera via an ethernet cable, this was cut to length for minimal design. This design feature could however be useful, with a longer cable, or with flexible length you could move the camera itself without disconnecting the prototype, or you could connect a camera that is not attached to the rail. This would mean that the setup would need simpler cable management than if the camera attachment were used without the prototype. This is a feature of the prototype and for a fully developed product with a slimmer design cable management would probably be removed. The goal as we see it, for a future product, is to have the PLC unit built into a light rail camera attachment. This would mean minimal design with no cable management.

Axis light rail camera attachment, see Figure 4.3 was a product that saved time and focus for this thesis. A universal mount was just what we needed. With some clear weaknesses with the light rail lamp socket and the 3D printed housing, making our own attachment could have been a difficult job. However, the camera attachment in the light rail chosen for this thesis does not provide a solid fitting. There is no risk for it falling down, but when testing on other light rail designs found here at Axis the attachment had a much more solid fit.

Overall we are very happy with the design of the housing and how the final prototype turned out. The design is clean and stylish. All components have a solid fit inside the housing and has no risk of damaging when transported or moved around. The housing itself is easy to open and close with only 4 screws to hold the lid solid in place. The design also gives easy access to the sync button and the ethernet output for easy connect. The housing would probably be smaller if a custom made PCB were developed for this applications. This makes us confident that this would be an attractive product that consumers could have hanging from their ceilings.

5.3 Testing of prototype

Power Consumption

There is not much to say about power consumption. Lamps and cameras will draw the same amount of power regardless of whether they are on a rail or not. The interesting part is then of course how much power our prototype draws in order to send the signal on the rail. This was found to be about 2 W which in relation to the camera and lights is small. The light rail that was used in this project had a limit that a single attachment only could draw 35 W, which leaves 30 W for the camera. This is definitely enough and it is not difficult to imagine this limit can be increased with another light rail.

Multiple Cameras

The ability to use multiple cameras is arguably essential for the concept of putting cameras on light rails. One of the main benefits of this solution over mounting the cameras in the ceiling individually is that with a light rail you only have to draw one pair of cables, the ones leading to the light rail. It saves at least one cable per camera in your system. Our prototype is built on a TP-Link ethernet PLC which has a limit of 16 devices per network. For us this means that the limit is 15 cameras per light rail, one device needs to be used as the base unit that connects a computer to the rail in order to access the cameras. One other limitation that is set by the TP-Link device is the physical length of the light rail. According to their data the limit is 300 meters but this was not verified. Connecting multiple prototypes is usually as easy as just connecting them onto the rail with the attachment. Sometimes you have to press the sync button that is on the units in order for them to establish a connection between each other. Keep in mind that the system has a 100 Mbps limit, which might be the reason why TP-Link sets the device limit to 16. There exist Gigabit PLC ethernet systems that allow for many more users but 15 cameras per light rail is already a decent amount. If you were to design the prototype from scratch we see no reason as to not being able to increase the limit substantially if you wanted to.

Ping tests

From the ping tests results, see Table 4.2, we only get two metrics to compare. The packet loss and the average ping time. As we can see there really is no significant difference in ping time between the test setups. It did not seem to matter what kind of light rail, or even if a light rail was used at all, in regards to how long time a ping took. The bottleneck here seems to be the prototype itself, the internal network components, and not the physical medium in which the signals gets transferred in. The same goes for the packet loss though there seems to be slightly more dropped packets in our final design than in the unmodified PLC units. It is still the same order of magnitude so the difference is not significant. The increase might be caused by the opening up of the PLC unit. Messing around with the bare PCB might have damaged it slightly and altered the signal path enough to make a difference. It might also just be a coincidence since the average ping time was steady.

Data speed tests

These tests tell the same story as the ping tests, that it did not really matter what kind of setup we used. From Table 4.2 we see that the download speed, upload speed, delay and TP-link speed stayed quite consistent between different test setups. If anything the results improved with our prototype over the unmodified units. This test itself is not the most reliable as we have no control over how our signals gets transferred through the internet to the test server. It did however give an indication that our prototype should work reasonably well. Worth mentioning again is that the system is capped at 100 Mbps so a download speed of around 94 Mbps is really good. Once again if the prototype was designed from circuit level gigabit ethernet could be used.

5.4 EMC testing

Prestudy

The preliminary EMC studies done at LTH gave us a good indication of which frequencies and at what magnitude we were to be expecting. The testing were done in a ordinary classroom and therefore outside noise could have affected the results. Therefore the first test in Figure 4.6 shown as the top most graph indicates the noise in the classroom between 1.8 MHz and 86.13 MHz. To make a fair comparison, the magnitude at these frequencies need to be taken into account. This can be seen at the lower frequencies from 1.8MHz to 15Mhz in all graphs and is considered outside noise.

When the PLC device is then turned on, a big increase in magnitude can be seen from 44 MHz to 70 MHz, see middle graph in Figure 4.6. The magnitude of the highest spikes reaches up over 40 dBμV. It is clearly shown that the PLC device itself is radiating emissions that can be picked up by the antenna. As mentioned before, these test are measured from 3 meter distances and should therefore be lowered with 10 dBμV in magnitude.

In the last graph in Figure 4.6 both the PLC device and the camera were on. Here we can see an even higher increase in magnitude in a broader frequency spectrum, around 35MHz to 86 Mhz. The highest peaks have also increased well above 45 dBμV. This indicates that the camera or the camera stream itself increases the total emission. Since no test were done on only the camera itself the emissions from it can not be compared. However it is most likely that the increase in emissions is due to the active camera stream. This because the frequency band that was increased, was exactly in the band that Homeplug AV2 uses to communicate on.

In Figure 4.7 a waterfall graph is shown from the same graphs discussed above. These graphs shows a more clear difference in the increasing emissions with the red color indicating a magnitude up towards 45 dBμV or higher. It also easier spots smaller magnitude increments on the whole frequency span. One thing to note, that was not clear before, is that the magnitude of emissions on the lower frequencies increases when the camera stream is active. If this is a coincidence from outside noise, or emission created by the prototype. The more tests that were done and presented in Appendix A indicates that when the camera stream is active the emission level rises, even at he lower frequencies.

Several test were done and some of these are presented in Appendix A. Some of the test were done with the PLC device on, camera stream on but it had different positions on the light rail. Middle in Figure 7.5, left in Figure 7.7 and right in Figure 7.7. Although the test results differ for one another, it is not convincing enough to conclude that the position of the PLC unit has an effect on the total emissions.

EMC chamber testing

Largely the EMC results came back as expected. From the preliminary studies we learnt that we would probably have a lot of emissions between 2 MHz and 86 MHz and that we should not count on passing the test. The chamber at Axis is an EMC testing chamber and as we can see in Figure 4.8, that it is very isolated and the noise floor is very low. However, we can see some areas in the noise floor that has a slight increase in known frequency bands. For example around 100 MHz we have the FM radio frequencies and in the higher frequencies, closer to 1 GHz it could potentially be the mobile network that plays its part.

The measurements were done at the standard frequencies of 30 to 1000 MHz but as we know from the preliminary studies, the most interesting range is around 2 to 86 MHz. One very important thing to note before going further into the results is that the EMC chamber got contaminated by EMI from power cables coming from the 48 VDC power supply outside the chamber. The radiation did not originate from the supply itself but the long cables going from outside to the inside allowed radiation from outside the chamber to get in. This is not ideal but we needed to drive the rail with 48 VDC and there was no other easy way of getting it into the chamber. This is not common practise and a filter should probably have been put on the cables going into the chamber. We can see these emissions in Figure 4.9 where the levels of EMI are already very high even though no electronics are running inside the chamber and the power supply outside is also turned off. The spikes at around 100 MHz and 160 MHz are present throughout the results but are not coming from the PLC unit. The frequency tops at around 100 MHz are suspiciously close to FM-radio stations and the wires going into the chamber are of length comparable to the wavelength of these.

Just turning our prototype on (attached to the rail) without any camera already gave emissions above the limits. This can be seen in Figure 4.10 where there are at least 10 peaks above the red line within the interesting range. There are also few other interesting peaks, some at very low frequencies and some at around 90 to 100 MHz which should be outside of the PLC protocols range.

When turning on the camera, Figure 4.11, a very noticeable increase in the 30 to 70 MHz range appears. This is excepted as now more data, the HD camera stream, is communicated on the rail. Not only are there more peaks but the peaks are much wider, indicating that there is much more power in these frequencies now compared to no camera. The noise floor from around 100 to 400 MHz is also pushed up a considerate amount. As mentioned, the PLC protocol should not use frequencies this high in its signaling. The increased amplitudes can instead be explained by either harmonics or other internal signals that escape from the PCB that do work in those frequency ranges.

Covering the camera with aluminum foil does result in a slight decrease in emissions, see Figure 4.12. The difference is not that significant and that was expected. The camera itself is not really the source of emissions, it should be the PLC unit. Using two cameras, Figure 4.13, did not affect the results much either.

Lastly, we have the most spectacular result, Figure 4.14. When connecting two LED lamps to the rail, with no other electrics running like cameras or PLC units, the emissions went through the roof. The noise floor even got raised above the maximum limit for a broad range of frequencies. It was actually rather surprising since it is a DC LED lamp with presumably no switching components. It should be noted that the lamps were very cheap, ordered from outside the EU, and did not promise anything about CE-markings, etc. Connecting a camera at the same as the two lamps, Figure 4.15, did not make things better.

Conducted emissions

EMC does not only include emissions from fields via the air. The emissions from the conducted paths must also be checked if you want to fully certify a product. We chose not to measure these as the only thing connected to the electricity grid in our case is the 48 VDC PSU that supplies the rail and this PSU is arbitrary in a proof of concept build. We used a lab bench power supply but that is of course not what a final product would use. The conducted emissions from this supply will be entirely dependant on the supply itself.

5.5 Fixing EMC problems

Like we have seen in previous EMC results the levels of radiation is high, passing the limits with over 30 dB at certain frequencies. An effort was made to lower these levels using two main methods.

Faraday's cage

Using a Faraday's cage did not effect the results much which was expected, see Figure 4.16. Our guess was that the radiation is coming primarily from the rails, unshielded metal cables with high frequency signals is a recipe for EMI. Even if the PLC unit itself is shielded, there are still unshielded cables coming from it going to the rail. Another idea was to enclose the whole rail. This would probably have lowered the emissions greatly but would also ruin the whole idea behind a light rail, which is to be able to easily install lamps anywhere along it.

EMC reduction filter

The second method was constructing three different filters to try and reduce the high frequency EM. From the results we see that only one of the versions seemed to show any significant improvements, version 1 from Figure 3.20. The idea is that the 48 VDC is blocked by the capacitor but the PLC signals pass trough. That signal then passes though a resistors where it is weakened, lowering parts of the signal and in turn lowers the EMI.

5.6 Future development

Why not wireless cameras?

During this thesis one particular question has come up several times. "Why not wireless cameras?". You could potentially use a wireless camera that is powered from the light rail and transfers the HD stream via WiFi to a base station located out of sight. This would then not be in need of a PLC unit and have the risk of sending HF signals over open rails that produces emissions over the limits.

There are three ways of connecting a camera wirelessly. The first way is to use radio to send analog signals. This is a method that has poor picture quality and can be easily disturb or picked up by unwanted users, for security this is not a good option. The second alternative is military grade, long range beam forming wireless transmission. This method requires clear sight from point to point and can be hard to achieve in most scenarios. The final one and most common one is WiFi cameras, these are very common on the retail market and can stream HD video with a good connection. [41]

Even though the communication is wireless, the camera is still in need of a power cable. In our case this could be solved from the ligh rail itself. When it comes to WiFi signals, you need a good connection in order to stream with high video quality. As commonly known, a WiFi signal may vary in quality depending on where the receiver is positioned, distanced far away or having disturbing objects like consecrate walls may lower the quality significantly. Having security cameras over WiFi could easily be disrupted with a signal jammer, even though these are highly illegal, they exist [42]. Wifi is also more susceptible to man in the middle hacking compared to wired security systems. Modern wired security systems will detect if a cable is cut and therefore know if it is being hacked. [41]

With all this in mind, this gives arguments for developing a stable wired security system that is both easily installed and adaptable to the consumers need.

Potential use cases

There is almost an unlimited number of use cases for this product. Anywhere you want to have lights as well as cameras. But admittedly, just because it is possible does not mean it is practical. The best place for this product would be a place where there already is a light rail and a need for cameras. An example of this could be a retail store, where light rails are already quite common and security cameras too. Firstly it is much easier to install the system, with multiple cameras on every light rail you can decrease the number of cables that needs to be used dramatically. Not only is this cheaper and easier from an installation point of view but also makes the cameras easier to control. You now have one ethernet cable connected to network with many cameras without the need for addition network peripherals like switches or routers. Apart from being easier and cheaper it is also possible to change the positions of the cameras with ease. Retail stores change the layout of the store from time to time, changing the position of the isles and so on. It is therefore advantageous to have the cameras movable as well so that you can make sure the cameras cover all the new angles. Retail store are of course only one example. Light rails are also common in offices and in industries but like we mentioned it might not be the solution for all security camera systems. In homes there is often not the need for multiple cameras in one room and light rails are not as common either. So to summarize this product does indeed target larger facilities.

There is a problem with this type of system that has not been discussed properly in this report yet. In order to attach the camera and PLC unit to a light rail you have to use the correct attachment. Not all light rails are of the same type. A decision has to be made whether to try and create an attachment that fits as many of the most common light rails as possible or design the system around one particular light rail. A variant of the first option is to make the product modular and sell the attachment itself separately. Making one attachment for each light rail manufacturer. They all have their pros and cons.

Semi universal attachment Making a semi universal attachment is of course better from a compatibility perspective. You can potentially install the system on an existing light rails and there would be no need to for new ones. This saves costs if the client already has light rails installed. The problem is then that even if the attachment fits many rails, it will probably be impossible to make them fit all of them.

Modular attachment This option might look very attractive at first glance, there is after all the potential of fitting the product to all light rails perfectly. The big downside is that you would have to cooperate with a lot of companies and that the actual manufacturing will be difficult. You now have tens or hundreds of different attachments to produce, expensive and very inefficient.

Creating a new light rail Creating a light rail specifically to work with the PLC camera system can in practice be implemented in two different ways. Either by working together with a light rail manufacturer and using one of their existing rails as the base, or by developing the light rail in house. These options ensures that the products work flawlessly as the system is designed for the purpose of working well together.

PCB and Protocols

One strategy not used in this thesis due to time limitations was to make our own PCB. This is a much more difficult job but could result in a better product. When making a PCB for a project it can be tailored into its specific needs and classification. For example in the result prototype, three main component were used, these could be put on the same PCB, increasing the speed while decreasing size, power and emissions.

Since the communication lines uses Homeplug AV2 protocol in the high frequency PLC range, EMC precautions should be considered from the start of developing an own PCB. With the known frequencies and its magnitude of emissions from EMC testing, see results section 4.4, we can see that some peaks needs to be lowered up to 25-30 dB. There are two main concerns discussed for the prototype we used, protocol and signal strength. These should be evaluated before constructing a PCB.

For our prototype and for TP-Link TL-PA4010 the protocol used was Homeplug AV2. This limits the frequency band to 2-86 MHz which could potentially not be optimal for some specific lengths of the light rail. By researching other potential protocols i.e. IEEE 1901 or others the frequencies used could be optimized for the specific need. There could also be a discussion about constructing a protocol to tailor it for this application, but this would require more knowledge about antenna theory than what this thesis covers.

The TP-Link TL-PA4010 original purpose is to send ethernet signals via the electrical grid. You plug in the device in one wall socket and extract the ethernet signal from another wall socket. How the electrical grid is routed and the length of the wired path is unknown. The TP-Link TL-PA4010 is specified up to 300 meters of electrical wiring. This also means that the signal strength needs to be high enough to reach that distance. Since the light rail would only be a fraction of that length, a few meters at most, the signal strength could potentially be lowered to decrease the magnitude of emission.

Other things to take into consideration during development is to use a short signal path with sufficient ground plane where high frequencies are present. The housing could be shielded and connected to protective ground in the rail.

Characteristic impedance and reflections

During the development phase of this project a discussion about characteristic impedance were made with colleagues at Axis. If it would be possible to do an impedance matching of the PLC units and the light rail it could possibly avoid reflections and signal degradation. However, since the PLC units were not designed by us, the input and output impedance is unknown and would be hard to measure. There was also a discussion made that the characteristic impedance could change as multiple PLC units were connected. If this project were to continue this should be something to consider as it could play a big roll in maximizing signal integrity and avoid reflections.

6

Conclusions

The results of this Master Thesis show that it is indeed possible to transfer video communication and power on a 48 VDC light rail. More specifically a prototype were constructed to demonstrate this proof of concept. This was realized by using a PLC to ethernet device with a PSU and a POE injector. With this prototype, the test shows that a steady camera stream with high quality over the light rail could be achieved. It also shows that it is possible for a multi camera option on the same light rail, theoretically up to 15 devices for this prototype. EM radiation testing were also performed on the prototype in order to evaluate emission frequencies and magnitude.

From the results of EM radiation testing done both at the LTH and in Axis in-house testing chamber it indicates emission levels above the Class A standard. It shows a high level of emissions specifically in the Home Plug Av2 frequency range, 30-86 MHz which is generated by the prototype. Some measures were done to decrease these emissions, both with faraday's cage and filters. As the results shows one of the filter applications indicates that it is possible to reduce the emissions. From this, a conclusion could be made that it might be possible to reduce the emission levels to pass the EMC restrictions. In order achieve this a tailored PCB for this application would probably be the best way to go, taking into consideration reducing emission levels from the beginning of development.

.

Bibliography

[1] Siemens. *Power line carrier communication for digital transmission grids*. https://www.siemens.com/download?DLA18_691. 2020 (accessed February 16, 2021).

[2] HomePlug Powerline Alliance. *Faqs*. http://www.homeplug.org/about/faqs/. 2014-03-31 (accessed November 19, 2020 using web.archive.org).

[3] Axis Communications. *Axis t91a33 lighting track mount*. https://www.axis.com/products/axis-t91a33-lighting-track-mount. (accessed January 27, 2021).

[4] *Discussion with colleague at axis communication*. November 10, 2020.

[5] IEC. *Electromagnetic compatibility*. https://www.iec.ch/emc/explained/EMC. (accessed October 26, 2020).

[6] SWEDAC. *EMC, elektromagnetisk kompatibilitet*. https://www.swedac.se/amnesomraden/emc-elektrisk-kompabilitet/. (accessed October 26, 2020).

[7] European Comission. *Electromagnetic compatibility (emc) directive*. https://ec.europa.eu/growth/sectors/electrical-engineering/emc-directive_en. (accessed November 11, 2020).

[8] electronics notes. *Emi electromagnetic interference: the fundamentals*. https://www.electronics-notes.com/articles/analogue_circuits/emc-emi-electromagnetic-interference-compatibility/what-is-emi-basics-tutorial.php. (accessed February 9, 2021).

[9] Backyard Brains. *Diy faraday cage*. https://backyardbrains.com/experiments/faraday. (accessed February 9, 2021).

[10] GAMRY Instruments. *Faraday cage: what is it? how does it work?* https://www.gamry.com/application-notes/instrumentation/faraday-cage/. (accessed February 9, 2021).

[11] European Commission. *Electromagnetic compatibility (emc)*. https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards/electromagnetic-compatibility_en. (accessed November 11, 2020).

[12] Your Europe. *CE marking*. https://europa.eu/youreurope/business/product-requirements/labels-markings/ce-marking/index_en.htm. (accessed November 11, 2020).

[13] ASQ. *What is CE marking?* https://asq.org/quality-resources/ce-marking. (accessed November 11, 2020).

[14] Svenska Institutet för Standarder. *CE-märkning*. `https://www.sis.se/standarder/ce-markning/`. (accessed November 11, 2020).

[15] Cypress. *Power line communication*. `https://www.cypress.com/applications/power-line-communication`. (accessed November 20, 2020).

[16] Circuit Digest. *What is power line communication (plc) and how it works*. `https://circuitdigest.com/article/what-is-power-line-communication-plc-and-how-does-it-work`. (accessed November 20, 2020).

[17] A. Majumder and James Caffery. *Power line communication: an overview*. `https://www.researchgate.net/publication/3227750_Power_line_communication_An_overview`. November 2004 (accessed November 25, 2020).

[18] IEEESA. *Ieee 1901.2-2013 - ieee standard for low-frequency (less than 500 kHz) narrowband power line communications for smart grid applications*. `https://standards.ieee.org/standard/1901_2-2013.html`. (accessed November 20, 2020).

[19] eiwellspring. *Power line communication frequencies*. `http://www.eiwellspring.org/plc/PLCfrequencies.htm`. (accessed November 20, 2020).

[20] Federation of American Scientists. *Frequency modulation*. `https://fas.org/man/dod-101/navy/docs/es310/FM.htm`. (accessed November 25, 2020).

[21] How stuff works. *How broadband over powerlines works*. `https://computer.howstuffworks.com/bpl.htm#pt2`. (accessed November 25, 2020).

[22] IEEE Xplore. *1901.1-2018 - ieee standard for medium frequency (less than 12 MHz) power line communications for smart grid applications*. `https://ieeexplore.ieee.org/document/8360785`. (accessed December 1, 2020).

[23] IEEE Xplore. *1901.2-2013 - ieee standard for low-frequency (less than 500 kHz) narrowband power line communications for smart grid applications*. `https://ieeexplore.ieee.org/document/6679210`. (accessed December 1, 2020).

[24] IEEE SA. *Power line communications standards committee*. `https://sagroups.ieee.org/plcsc/`. (accessed December 1, 2020).

[25] IEEE SA. *Ieee 1905.1-2013 - ieee standard for a convergent digital home network for heterogeneous technologies*. `https://standards.ieee.org/standard/1905_1-2013.html`. (accessed December 1, 2020).

[26] Wikipedia. *1905.1 home network (does not show ac powerline or moca connectivity)*. `https://en.wikipedia.org/wiki/IEEE_1905#/media/File:1905_home_network_-_multi_devices_graphic.jpg`. (accessed December 1, 2020).

[27] Creative Commons. *Attribution-sharealike 3.0 unported (cc by-sa 3.0)*. `https://creativecommons.org/licenses/by-sa/3.0/`. (accessed December 1, 2020).

[28] Johan Sköld Erik Dahlman Stefan Parkvall. *5G NR, The next generation wireless access technology*. Academic Press, 2018.

[29] Göran Lindell. *Introduction to Digital Communications*. LTH, 2006.

[30] Morty Eisen. *Introduction to poe and the ieee802.3af and 802.3at standards*. `https://www.ieee.li/pdf/viewgraphs/introduction_to_poe_802.3af_802.3at.pdf`. 2009 (accessed October 16, 2020).

[31] Cisco. *What is power over ethernet (poe)?* `https://www.cisco.com/c/en/us/solutions/enterprise-networks/what-is-power-over-ethernet.html`. 2020 (accessed October 9, 2020).

[32] IEEE. *802.3-2005*.

[33] IBM. *Osi model*. `https://www.ibm.com/support/knowledgecenter/sv/SSCVHB_1.1.0/glossary/npi_osi_model.html`. 2017 (accessed January 29, 2021).

[34] Cloudflare. *What is the osi model?* `https://www.cloudflare.com/learning/ddos/glossary/open-systems-interconnection-model-osi/`. (accessed march 15, 2021).

[35] Texas Instrument. *Our company*. `https://www.ti.com/about-ti/company/overview.html`. (accessed January 14, 2021).

[36] Kjell & Company. *Tp-link tl-pa4010kit homeplug 600mb/s 2-pack*. `https://www.kjell.com/se/produkter/natverk/tradlost-natverk/homeplug/tp-link-tl-pa4010kit-homeplug-600mbs-2-pack-p97255`. (accessed January 19, 2021).

[37] Clas Ohlson. *Tracklight belysningssystem Northlight*. `https://www.clasohlson.com/se/Tracklight-belysningssystem-Northlight/p/Pr364290000`. (accessed January 14, 2021).

[38] AliExpress. *Led lampen gu10 spotlight*. `https://www.aliexpress.com/item/4000068999455.html`. (accessed January 26, 2021).

[39] tp-link. *How many powerline adapters can be added to the same network?* `https://www.tp-link.com/us/support/faq/434/`. (accessed January 27, 2021).

[40] Adamantios @ Wikipedia. *An rf anechoic chamber*. Licensed under create common `https://creativecommons.org/licenses/by-sa/3.0/`. Original Link:`https://en.wikipedia.org/wiki/Anechoic_chamber#/media/File:Radio-frequency-anechoic-chamber-HDR-0a.jpg`. 2009 (accessed January 24, 2021).

[41] SCW. *Wifi security cameras: pros and cons*. `https://www.getscw.com/ip-camera/wifi-enabled`. (accessed February 03, 2021).

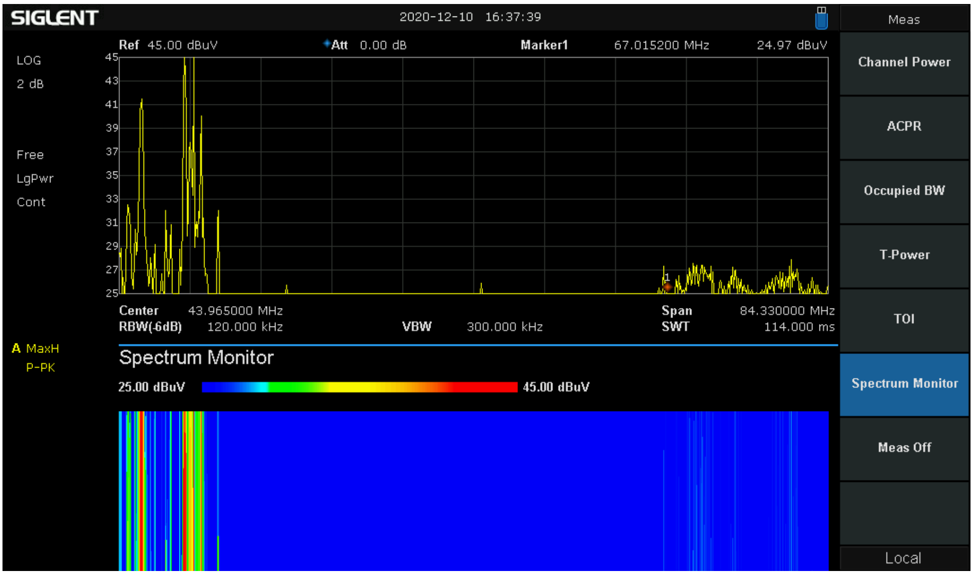
[42] PTS. *Förbud mot störsändare*. `https://www.pts.se/sv/privat/radio/utrustning/forbud-mot-storsandare/`. (accessed February 03, 2021).

7

Appendix A

Preliminary EMC study

The following test results were performed with the Siglent - SSA3021X Spectrum analyzer. All amplitude values must be subtracted by 10dB to compensate for the tests being performed at 3 meters instead of the standard 10 meters. The spectrum range measured was 1.8 MHz - 86.13 MHz, because these are the frequencies that the PLC protocol uses. The images contains one regular spectrum vs amplitude plot and one waterfall-graph. The latter is an accumulation of the maximum amplitudes at each frequency. Horizontally we still see the frequency but vertically is time. The colors change according to the maximum amplitude that was been recorded at that specific frequency. The tests were run for 3 minutes to accumulate maximum values. An external Power supply unit was used to drive the light rail with 48 VDC, noted PSU in the images. If nothing else is mentioned, the PLC unit is connected in the middle of the light rail.



2020-12-10 16:37:39

Ref 45.00 dBuV Att 0.00 dB Marker1 67.015200 MHz 24.97 dBuV

LOG 2 dB

Free LgPwr Cont

Center 43.965000 MHz Span 84.330000 MHz

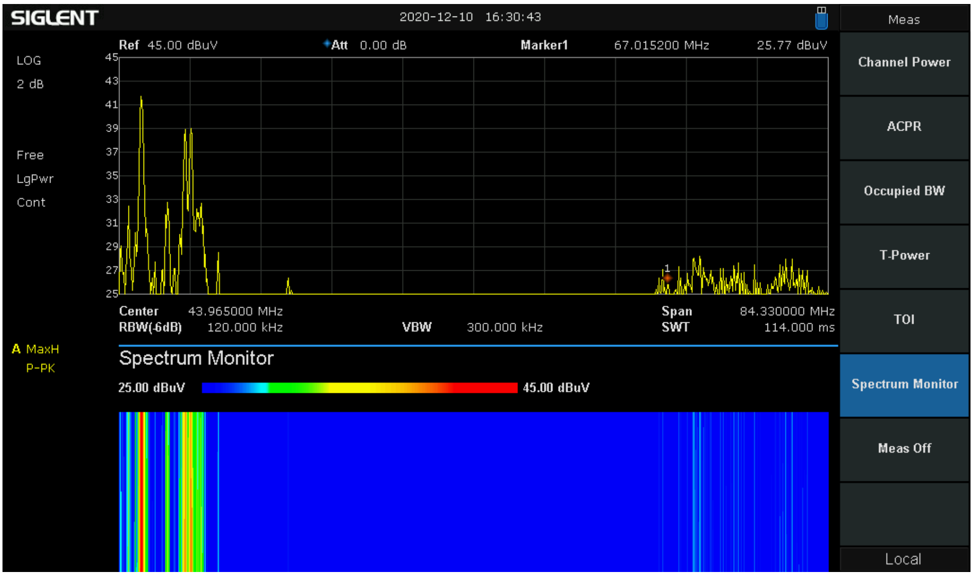
RBW(-6dB) 120.000 kHz VBW 300.000 kHz SWT 114.000 ms

A MaxH P-PK

Spectrum Monitor

25.00 dBuV 45.00 dBuV

Figure 7.1 PLC off, PSU off, Camera disconnected, Camera stream off.



2020-12-10 16:30:43

Ref 45.00 dBuV Att 0.00 dB Marker1 67.015200 MHz 25.77 dBuV

LOG 2 dB

Free LgPwr Cont

Center 43.965000 MHz Span 84.330000 MHz

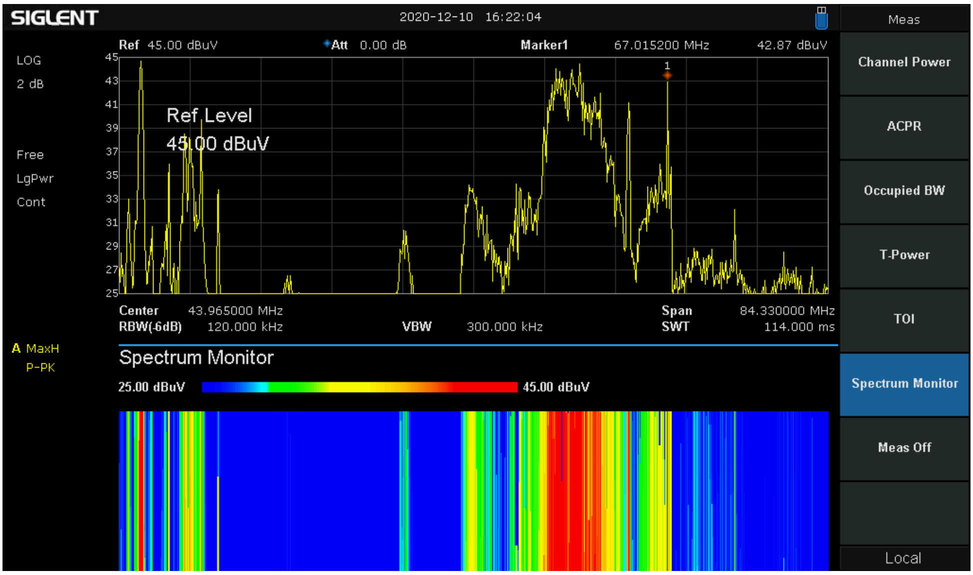
RBW(-6dB) 120.000 kHz VBW 300.000 kHz SWT 114.000 ms

A MaxH P-PK

Spectrum Monitor

25.00 dBuV 45.00 dBuV

Figure 7.2 PLC off, PSU on, Camera disconnected, Camera stream off.



2020-12-10 16:22:04

Ref 45.00 dBuV Att 0.00 dB Marker1 67.015200 MHz 42.87 dBuV

LOG 2 dB

Free LgPwr Cont

Ref Level 45.00 dBuV

Center 43.965000 MHz Span 84.330000 MHz

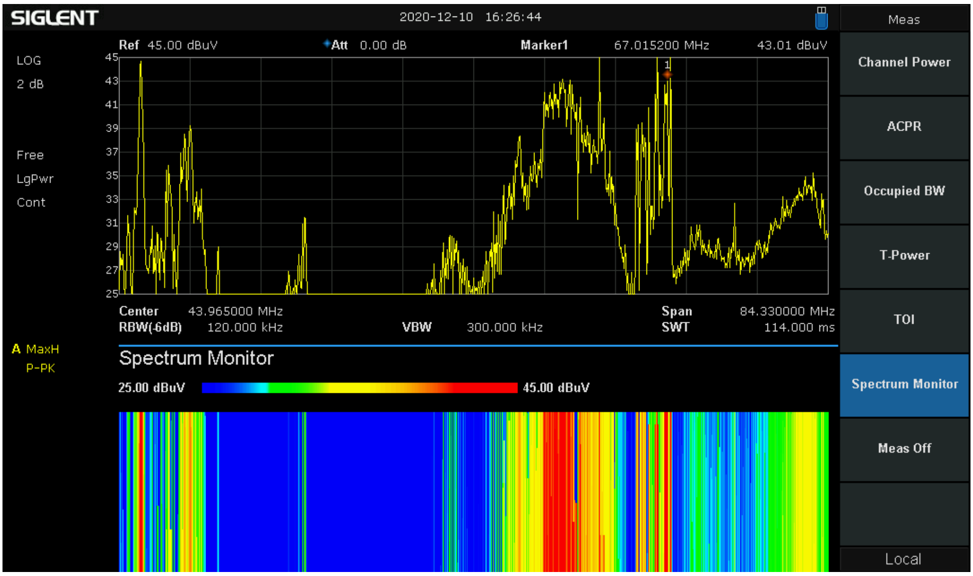
RBW(-6dB) 120.000 kHz VBW 300.000 kHz SWT 114.000 ms

A MaxH P-PK

Spectrum Monitor

25.00 dBuV 45.00 dBuV

Figure 7.3 PLC on, PSU on, Camera disconnected, Camera stream off.



SIGLENT 2020-12-10 16:26:44

Ref 45.00 dBuV

Att 0.00 dB

Marker1 67.015200 MHz 43.01 dBuV

LOG 2 dB

Free LgPwr Cont

Center 43.965000 MHz

RBW(-6dB) 120.000 kHz

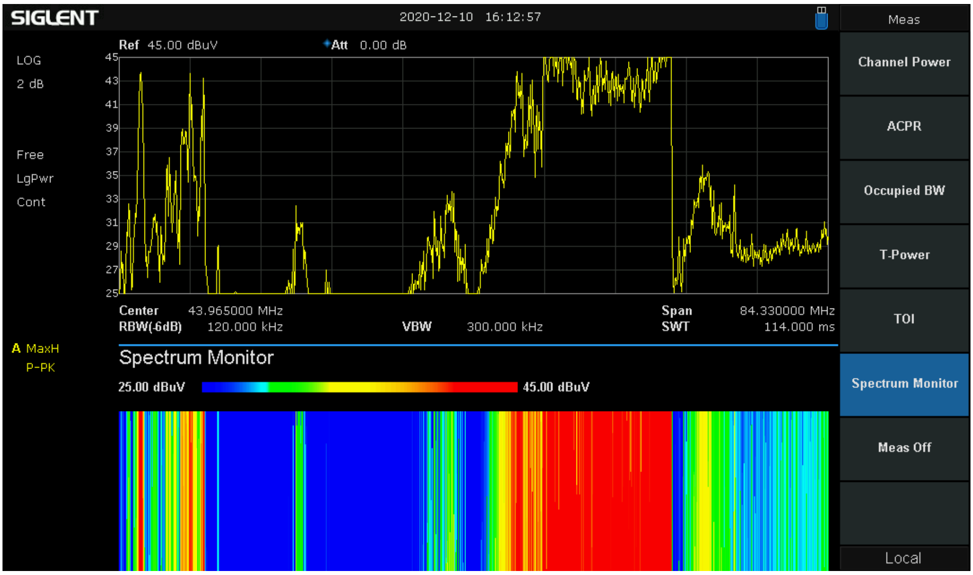
VBW 300.000 kHz

Span 84.330000 MHz

SWT 114.000 ms

A MaxH P-PK

Figure 7.4 PLC on, PSU on, Camera connected, Camera stream off.



SIGLENT 2020-12-10 16:12:57

Ref 45.00 dBuV

Att 0.00 dB

LOG 2 dB

Free LgPwr Cont

Center 43.965000 MHz

RBW(-6dB) 120.000 kHz

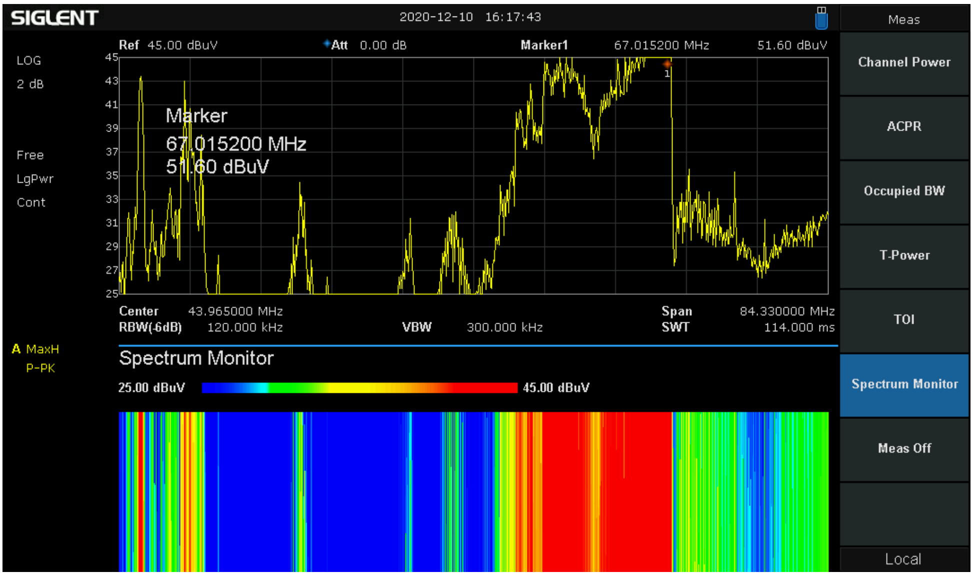
VBW 300.000 kHz

Span 84.330000 MHz

SWT 114.000 ms

A MaxH P-PK

Figure 7.5 PLC on, PSU on, Camera connected, Camera stream on.



2020-12-10 16:17:43

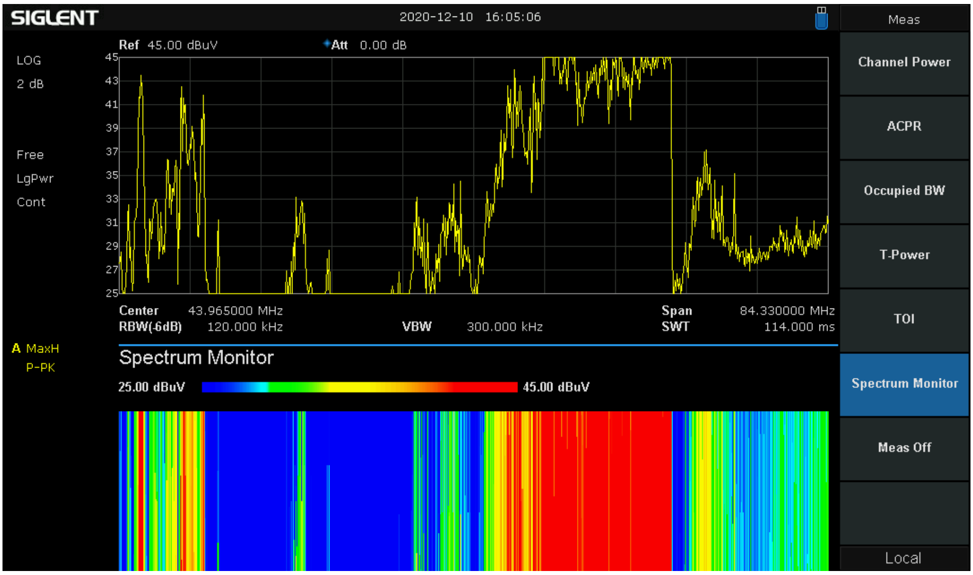
Ref 45.00 dBuV Att 0.00 dB Marker1 67.015200 MHz 51.60 dBuV

Marker
67.015200 MHz
51.60 dBuV

Center 43.965000 MHz
RBW(-6dB) 120.000 kHz
VBW 300.000 kHz
Span 84.330000 MHz
SWT 114.000 ms

Spectrum Monitor
25.00 dBuV
45.00 dBuV

Figure 7.6 Same as Figure 7.5 but with PLC unit on the left side of light rail.



2020-12-10 16:05:06

Ref 45.00 dBuV Att 0.00 dB

Center 43.965000 MHz
RBW(-6dB) 120.000 kHz
VBW 300.000 kHz
Span 84.330000 MHz
SWT 114.000 ms

Spectrum Monitor
25.00 dBuV
45.00 dBuV

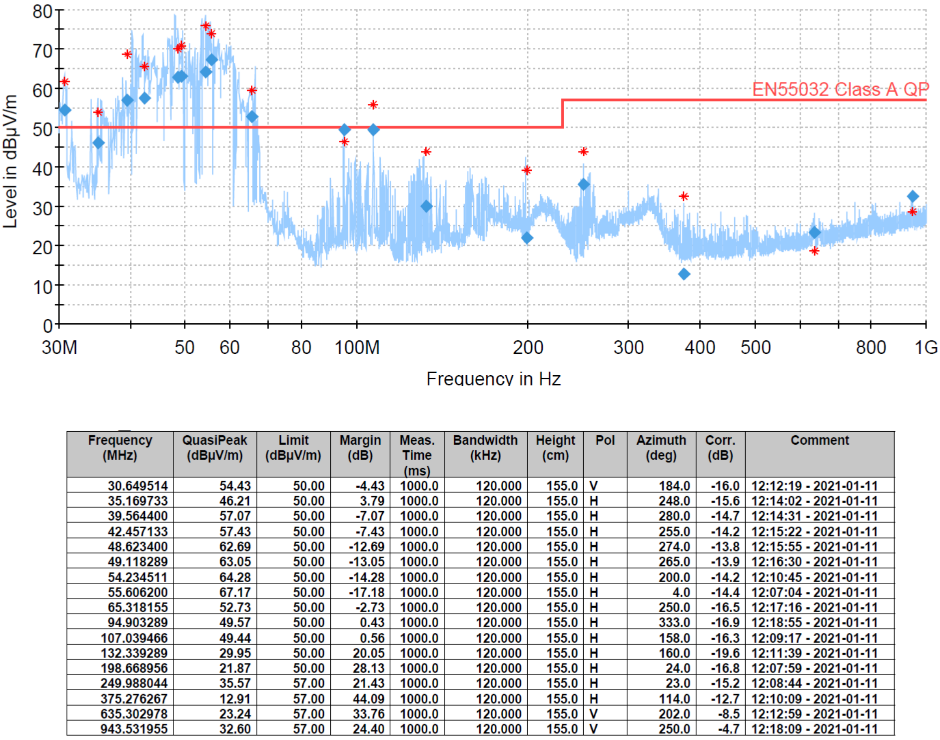
Figure 7.7 Same as Figure 7.5 but with PLC unit on the right side of light rail.

8

Appendix B

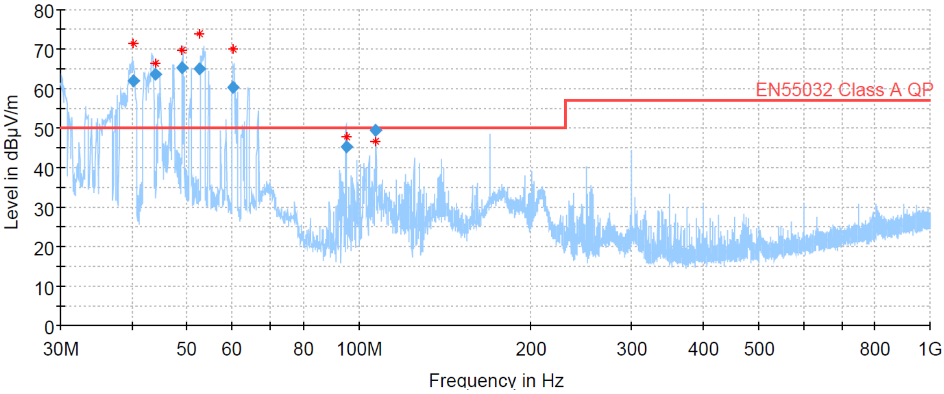
EMC study

In this appendix all the results from the Axis EMC tests are presented. Note that the camera(s) were always streaming their feed during the tests and that if nothing else is mentioned the prototype was connected in the middle of the light rail and the camera(s) were covered with aluminum foil.



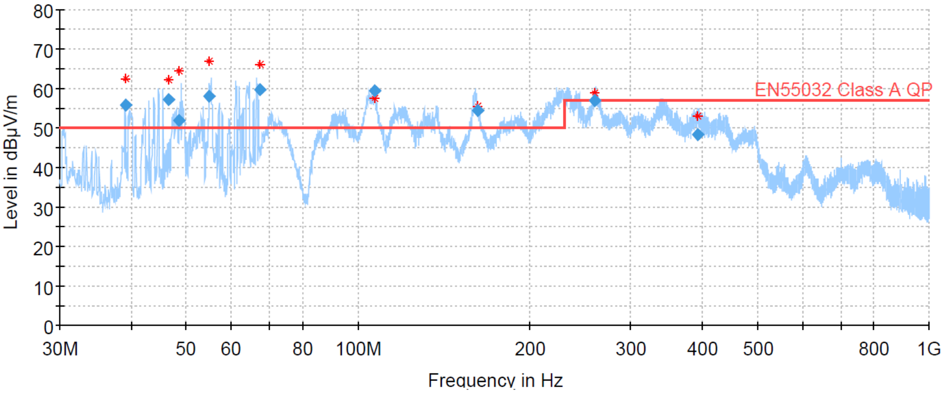
Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
30.649514	54.43	50.00	-4.43	1000.0	120.000	155.0	V	184.0	-16.0	12:12:19 - 2021-01-11
35.169733	46.21	50.00	3.79	1000.0	120.000	155.0	H	248.0	-15.6	12:14:02 - 2021-01-11
39.564400	57.07	50.00	-7.07	1000.0	120.000	155.0	H	280.0	-14.7	12:14:31 - 2021-01-11
42.457133	57.43	50.00	-7.43	1000.0	120.000	155.0	H	255.0	-14.2	12:15:22 - 2021-01-11
48.623400	62.69	50.00	-12.69	1000.0	120.000	155.0	H	274.0	-13.8	12:15:55 - 2021-01-11
49.118289	63.05	50.00	-13.05	1000.0	120.000	155.0	H	265.0	-13.9	12:16:30 - 2021-01-11
54.234511	64.28	50.00	-14.28	1000.0	120.000	155.0	H	200.0	-14.2	12:10:45 - 2021-01-11
55.606200	67.17	50.00	-17.18	1000.0	120.000	155.0	H	4.0	-14.4	12:07:04 - 2021-01-11
65.318155	52.73	50.00	-2.73	1000.0	120.000	155.0	H	250.0	-16.5	12:17:16 - 2021-01-11
94.903289	49.57	50.00	0.43	1000.0	120.000	155.0	H	333.0	-16.9	12:18:55 - 2021-01-11
107.039466	49.44	50.00	0.56	1000.0	120.000	155.0	H	158.0	-16.3	12:09:17 - 2021-01-11
132.339289	29.95	50.00	20.05	1000.0	120.000	155.0	H	160.0	-19.6	12:11:39 - 2021-01-11
198.668956	21.87	50.00	28.13	1000.0	120.000	155.0	H	24.0	-16.8	12:07:59 - 2021-01-11
249.988044	35.57	57.00	21.43	1000.0	120.000	155.0	H	23.0	-15.2	12:08:44 - 2021-01-11
375.276267	12.91	57.00	44.09	1000.0	120.000	155.0	H	114.0	-12.7	12:10:09 - 2021-01-11
635.302978	23.24	57.00	33.76	1000.0	120.000	155.0	V	202.0	-8.5	12:12:59 - 2021-01-11
943.531955	32.60	57.00	24.40	1000.0	120.000	155.0	V	250.0	-4.7	12:18:09 - 2021-01-11

Figure 8.1 One uncovered camera.



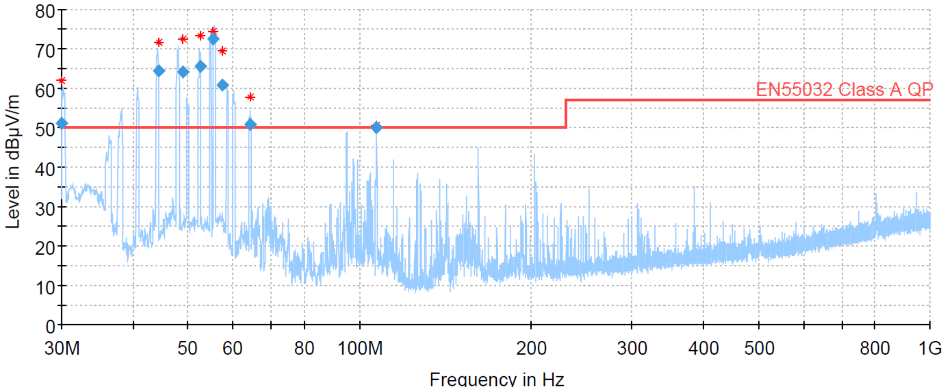
Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
40.332822	61.98	50.00	-11.98	1000.0	120.000	155.0	V	248.0	-14.5	13:46:39 - 2021-01-11
43.951623	63.53	50.00	-13.53	1000.0	120.000	155.0	V	250.0	-14.0	13:47:08 - 2021-01-11
49.081244	65.36	50.00	-15.36	1000.0	120.000	155.0	V	68.0	-13.8	13:44:33 - 2021-01-11
52.639311	64.89	50.00	-14.89	1000.0	120.000	155.0	H	94.0	-14.1	13:45:08 - 2021-01-11
60.126266	60.32	50.00	-10.32	1000.0	120.000	155.0	H	22.0	-15.1	13:44:05 - 2021-01-11
94.900489	45.35	50.00	4.65	1000.0	120.000	155.0	V	292.0	-16.9	13:47:34 - 2021-01-11
106.995333	49.33	50.00	0.67	1000.0	120.000	155.0	V	192.0	-16.3	13:45:55 - 2021-01-11

Figure 8.2 One camera.



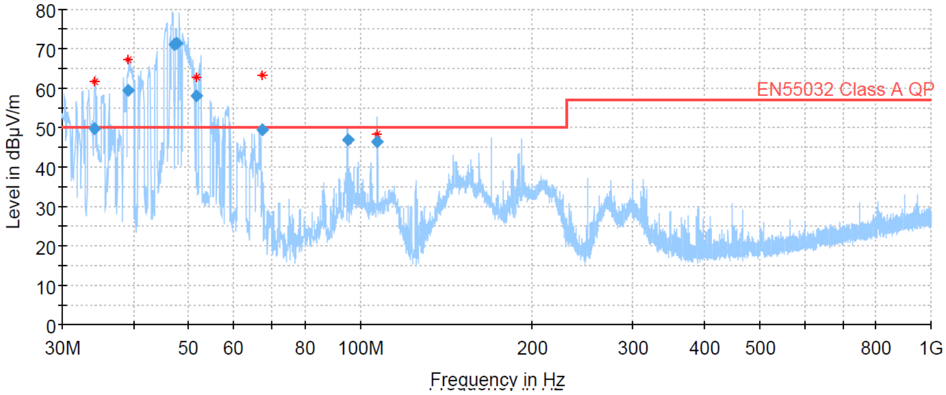
Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
39.146266	55.87	50.00	-5.87	1000.0	120.000	155.0	H	327.0	-14.7	14:17:12 - 2021-01-11
46.557333	57.34	50.00	-7.34	1000.0	120.000	155.0	V	228.0	-13.8	14:15:26 - 2021-01-11
48.614111	51.87	50.00	-1.87	1000.0	120.000	155.0	H	249.0	-13.8	14:16:09 - 2021-01-11
54.677867	57.97	50.00	-7.97	1000.0	120.000	155.0	V	110.0	-14.3	14:13:21 - 2021-01-11
67.133667	59.70	50.00	-9.70	1000.0	120.000	155.0	H	274.0	-17.2	14:16:39 - 2021-01-11
106.997511	59.46	50.00	-9.46	1000.0	120.000	155.0	H	22.0	-16.3	14:11:43 - 2021-01-11
161.644067	54.58	50.00	-4.58	1000.0	120.000	155.0	V	129.0	-19.3	14:13:56 - 2021-01-11
259.340244	57.01	57.00	-0.01	1000.0	120.000	155.0	H	-14.0	-15.1	14:12:34 - 2021-01-11
393.520623	48.24	57.00	8.76	1000.0	120.000	155.0	V	160.0	-12.3	14:14:48 - 2021-01-11

Figure 8.3 One camera and two lamps.



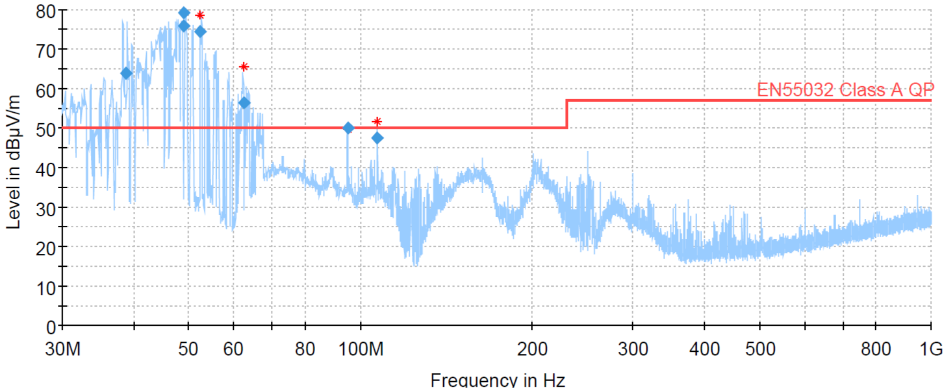
Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
30.002875	51.12	50.00	-1.12	1000.0	120.000	155.0	V	22.0	-16.0	14:39:33 - 2021-01-11
44.484689	64.34	50.00	-14.35	1000.0	120.000	155.0	V	76.0	-14.0	14:40:13 - 2021-01-11
49.078378	64.29	50.00	-14.29	1000.0	120.000	155.0	H	154.0	-13.8	14:41:34 - 2021-01-11
52.583600	65.62	50.00	-15.62	1000.0	120.000	155.0	V	338.0	-14.1	14:43:39 - 2021-01-11
55.261911	72.37	50.00	-22.37	1000.0	120.000	155.0	V	198.0	-14.4	14:42:09 - 2021-01-11
57.490555	60.94	50.00	-10.94	1000.0	120.000	155.0	V	12.0	-14.7	14:38:45 - 2021-01-11
64.154623	50.72	50.00	-0.72	1000.0	120.000	155.0	H	256.0	-16.2	14:42:59 - 2021-01-11
107.041333	49.88	50.00	0.12	1000.0	120.000	155.0	V	68.0	-16.3	14:40:50 - 2021-01-11

Figure 8.4 No cameras, just prototype on standby.



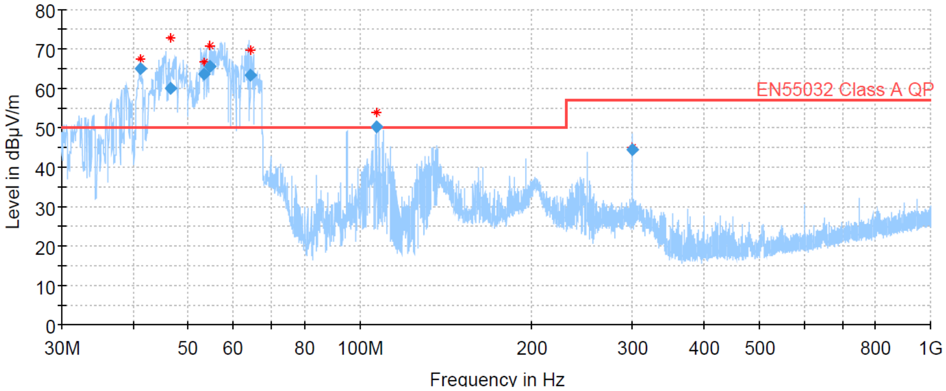
Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
34.190178	49.82	50.00	0.18	1000.0	120.000	155.0	H	248.0	-15.9	15:01:30 - 2021-01-11
39.185556	59.44	50.00	-9.44	1000.0	120.000	155.0	H	228.0	-14.7	15:02:08 - 2021-01-11
47.200889	71.18	50.00	-21.18	1000.0	120.000	155.0	V	159.0	-13.8	14:59:57 - 2021-01-11
47.692800	71.29	50.00	-21.29	1000.0	120.000	155.0	H	246.0	-13.8	15:02:39 - 2021-01-11
51.446200	58.13	50.00	-8.13	1000.0	120.000	155.0	V	160.0	-14.0	15:00:41 - 2021-01-11
67.404466	49.43	50.00	0.57	1000.0	120.000	155.0	V	292.0	-17.3	15:04:09 - 2021-01-11
94.884222	47.03	50.00	2.97	1000.0	120.000	155.0	V	282.0	-16.9	15:04:50 - 2021-01-11
106.991866	46.39	50.00	3.61	1000.0	120.000	155.0	V	202.0	-16.3	15:03:31 - 2021-01-11

Figure 8.5 One camera, prototype attached closest to the feed of the light rail.



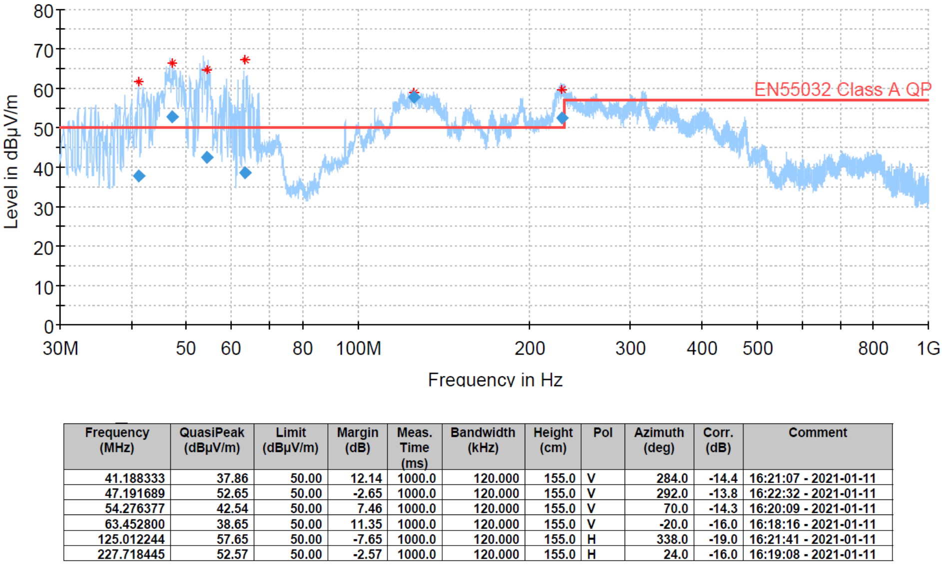
Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
38.868222	64.02	50.00	-14.02	1000.0	120.000	155.0	V	-14.0	-14.8	15:38:12 - 2021-01-11
49.037200	79.04	50.00	-29.04	1000.0	120.000	155.0	V	338.0	-13.8	15:41:52 - 2021-01-11
49.087044	75.71	50.00	-25.71	1000.0	120.000	155.0	V	338.0	-13.8	15:42:22 - 2021-01-11
52.383023	74.37	50.00	-24.37	1000.0	120.000	155.0	V	110.0	-14.1	15:39:35 - 2021-01-11
62.343823	56.32	50.00	-6.32	1000.0	120.000	155.0	V	158.0	-15.7	15:41:15 - 2021-01-11
94.890355	49.91	50.00	0.09	1000.0	120.000	155.0	V	30.0	-16.9	15:39:03 - 2021-01-11
106.960133	47.64	50.00	2.36	1000.0	120.000	155.0	H	154.0	-16.3	15:40:19 - 2021-01-11

Figure 8.6 One camera, prototype attached furthest from the feed of the light rail.



Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
41.160578	64.98	50.00	-14.98	1000.0	120.000	155.0	V	338.0	-14.4	16:05:56 - 2021-01-11
46.539245	59.91	50.00	-9.91	1000.0	120.000	155.0	V	158.0	-13.8	16:02:59 - 2021-01-11
53.323977	63.70	50.00	-13.70	1000.0	120.000	155.0	V	219.0	-14.2	16:05:24 - 2021-01-11
54.576200	65.67	50.00	-15.67	1000.0	120.000	155.0	V	183.0	-14.3	16:03:56 - 2021-01-11
64.198333	63.22	50.00	-13.22	1000.0	120.000	155.0	V	158.0	-16.2	16:03:29 - 2021-01-11
106.958933	50.18	50.00	-0.18	1000.0	120.000	155.0	H	204.0	-16.3	16:04:42 - 2021-01-11
300.017066	44.36	57.00	12.64	1000.0	120.000	155.0	H	68.0	-14.3	16:02:18 - 2021-01-11

Figure 8.7 Two cameras.



Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
41.188333	37.86	50.00	12.14	1000.0	120.000	155.0	V	284.0	-14.4	16:21:07 - 2021-01-11
47.191689	52.65	50.00	-2.65	1000.0	120.000	155.0	V	292.0	-13.8	16:22:32 - 2021-01-11
54.276377	42.54	50.00	7.46	1000.0	120.000	155.0	V	70.0	-14.3	16:20:09 - 2021-01-11
63.452800	38.65	50.00	11.35	1000.0	120.000	155.0	V	-20.0	-16.0	16:18:16 - 2021-01-11
125.012244	57.65	50.00	-7.65	1000.0	120.000	155.0	H	338.0	-19.0	16:21:41 - 2021-01-11
227.718445	52.57	50.00	-2.57	1000.0	120.000	155.0	H	24.0	-16.0	16:19:08 - 2021-01-11

Figure 8.8 Two cameras and two lamps.

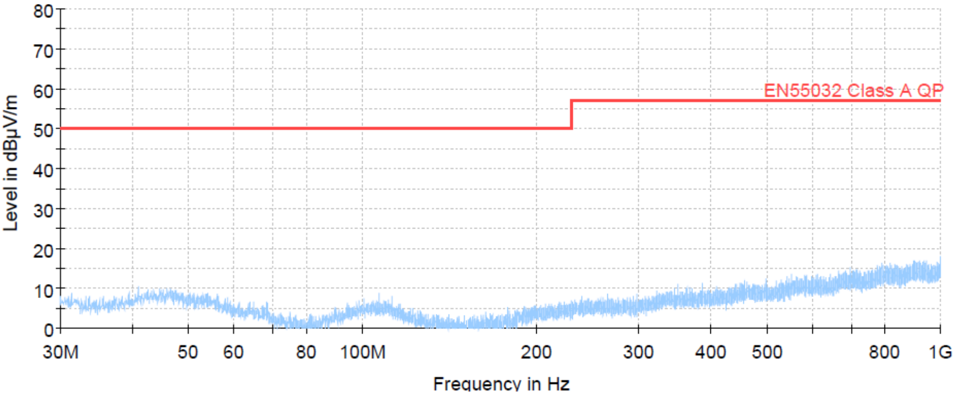
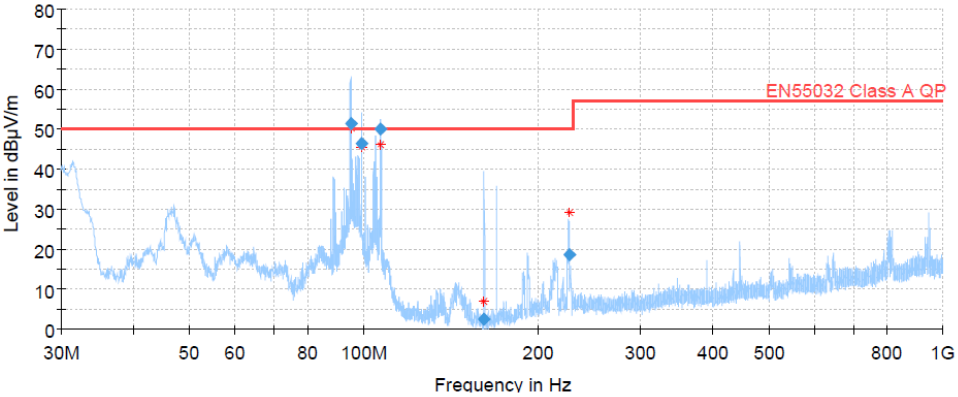


Figure 8.9 Noise floor of EMC chamber.



Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
94.893822	51.42	50.00	-1.42	1000.0	120.000	155.0	H	68.0	-16.9	14:02:03 - 2021-02-10
99.094089	46.42	50.00	3.58	1000.0	120.000	155.0	H	48.0	-16.4	14:02:41 - 2021-02-10
107.013889	50.09	50.00	-0.09	1000.0	120.000	155.0	V	101.0	-16.3	14:03:26 - 2021-02-10
161.453933	2.51	50.00	47.49	1000.0	120.000	155.0	H	-22.0	-19.3	14:01:33 - 2021-02-10
226.238956	18.71	50.00	31.29	1000.0	120.000	155.0	V	69.0	-16.1	14:04:17 - 2021-02-10

Figure 8.10 Only power cables going in to the chamber.

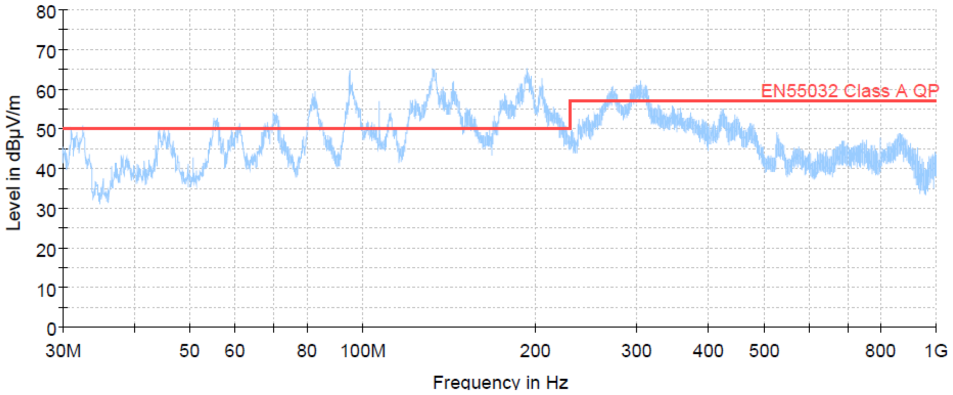
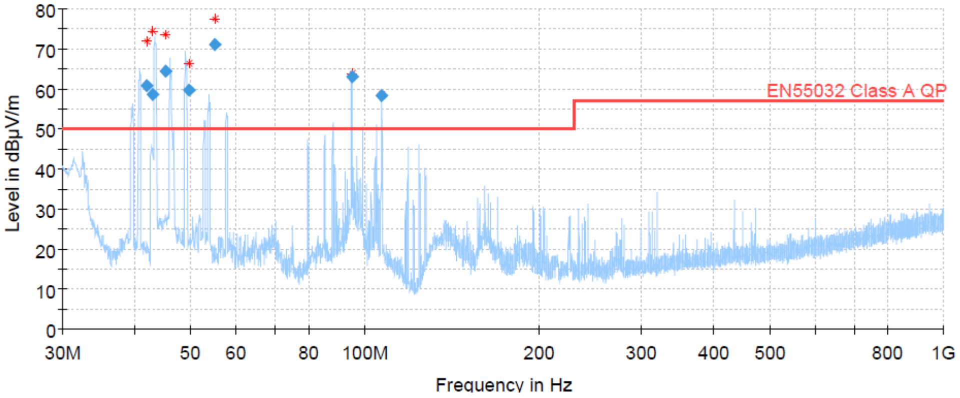
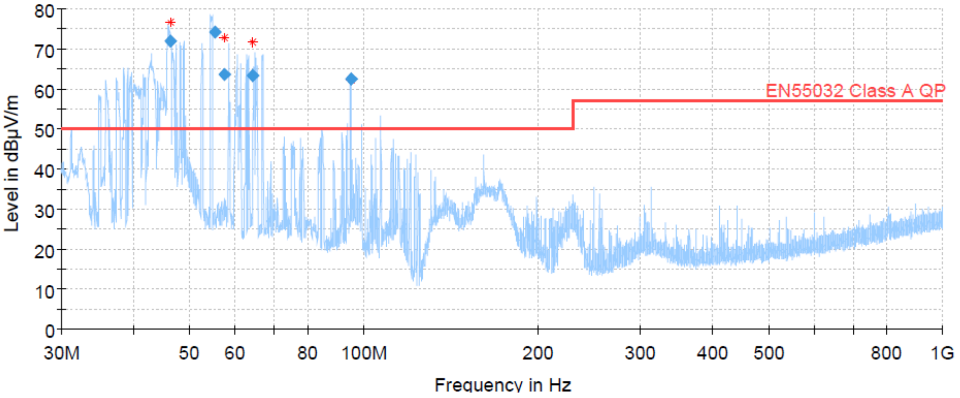


Figure 8.11 Two lamps.



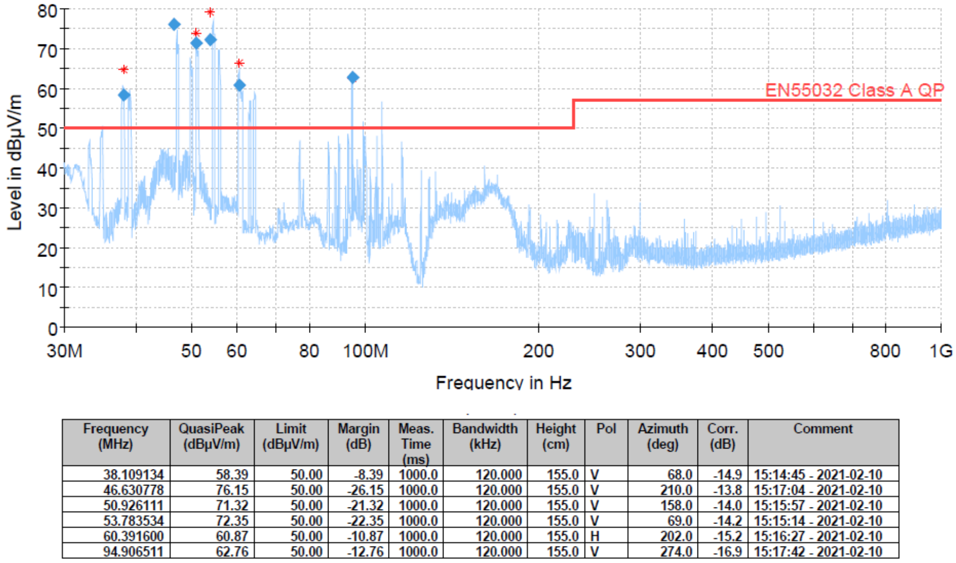
Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
42.043023	60.89	50.00	-10.89	1000.0	120.000	155.0	V	293.0	-14.3	14:35:05 - 2021-02-10
43.033377	58.58	50.00	-8.58	1000.0	120.000	155.0	H	326.0	-14.1	14:34:17 - 2021-02-10
45.339022	64.57	50.00	-14.57	1000.0	120.000	155.0	V	292.0	-13.9	14:33:44 - 2021-02-10
49.575845	59.69	50.00	-9.69	1000.0	120.000	155.0	V	248.0	-13.9	14:33:23 - 2021-02-10
54.930333	71.16	50.00	-21.16	1000.0	120.000	155.0	V	158.0	-14.3	14:32:53 - 2021-02-10
94.941955	63.06	50.00	-13.06	1000.0	120.000	155.0	V	68.0	-16.9	14:32:23 - 2021-02-10
107.011733	58.30	50.00	-8.30	1000.0	120.000	155.0	V	295.0	-16.3	14:35:36 - 2021-02-10

Figure 8.12 PLC on inside a faraday's cage but no camera.



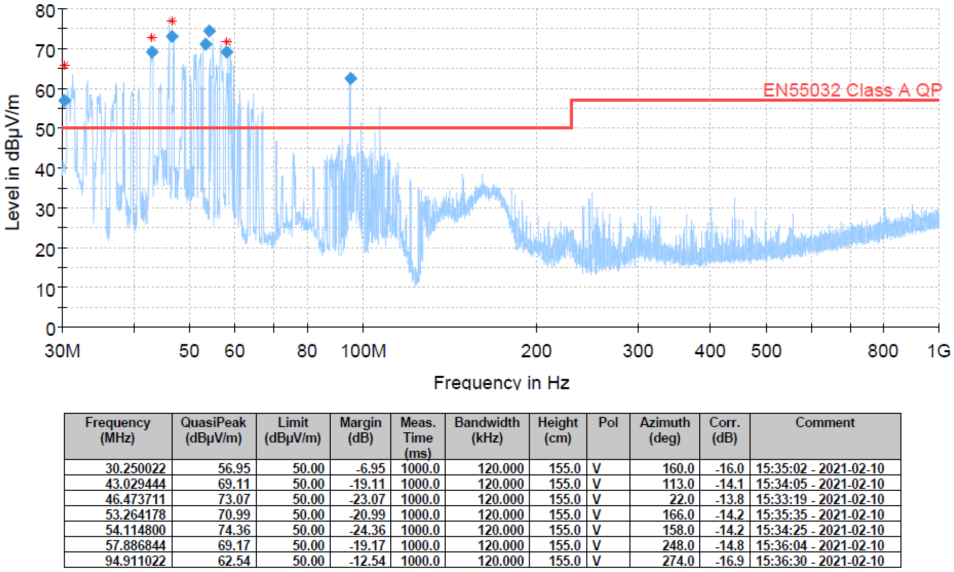
Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
46.372044	71.98	50.00	-21.98	1000.0	120.000	155.0	V	158.0	-13.8	14:57:55 - 2021-02-10
55.240845	74.21	50.00	-24.21	1000.0	120.000	155.0	V	22.0	-14.3	14:55:27 - 2021-02-10
57.531889	63.59	50.00	-13.59	1000.0	120.000	155.0	H	40.0	-14.7	14:56:04 - 2021-02-10
64.078333	63.39	50.00	-13.39	1000.0	120.000	155.0	H	22.0	-16.1	14:56:42 - 2021-02-10
94.908222	62.49	50.00	-12.49	1000.0	120.000	155.0	V	22.0	-16.9	14:57:20 - 2021-02-10

Figure 8.13 PLC on inside faraday's cage with camera.



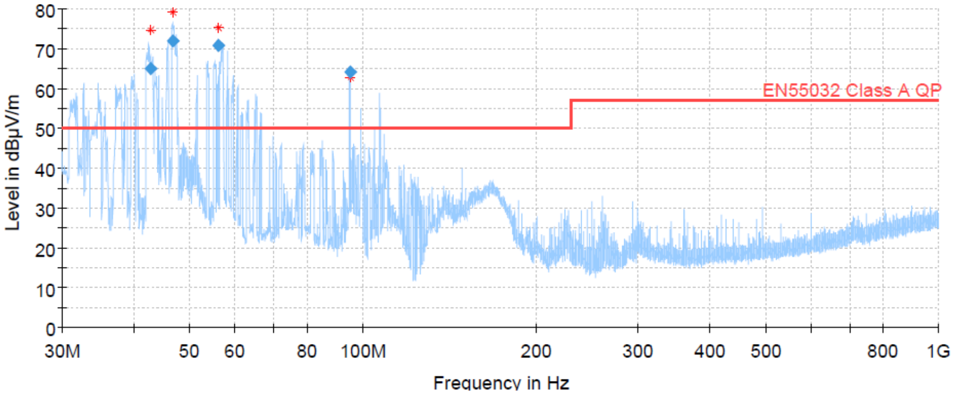
Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
38.109134	58.39	50.00	-8.39	1000.0	120.000	155.0	V	68.0	-14.9	15:14:45 - 2021-02-10
46.630778	76.15	50.00	-26.15	1000.0	120.000	155.0	V	210.0	-13.8	15:17:04 - 2021-02-10
50.926111	71.32	50.00	-21.32	1000.0	120.000	155.0	V	158.0	-14.0	15:15:57 - 2021-02-10
53.783534	72.35	50.00	-22.35	1000.0	120.000	155.0	V	69.0	-14.2	15:15:14 - 2021-02-10
60.391600	60.87	50.00	-10.87	1000.0	120.000	155.0	H	202.0	-15.2	15:16:27 - 2021-02-10
94.906511	62.76	50.00	-12.76	1000.0	120.000	155.0	V	274.0	-16.9	15:17:42 - 2021-02-10

Figure 8.14 Same as Figure 8.13 but with EMC reduction filter version 1.



Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
30.250022	56.95	50.00	-6.95	1000.0	120.000	155.0	V	160.0	-16.0	15:35:02 - 2021-02-10
43.029444	69.11	50.00	-19.11	1000.0	120.000	155.0	V	113.0	-14.1	15:34:05 - 2021-02-10
46.473711	73.07	50.00	-23.07	1000.0	120.000	155.0	V	22.0	-13.8	15:33:19 - 2021-02-10
53.264178	70.99	50.00	-20.99	1000.0	120.000	155.0	V	166.0	-14.2	15:35:35 - 2021-02-10
54.114800	74.36	50.00	-24.36	1000.0	120.000	155.0	V	158.0	-14.2	15:34:25 - 2021-02-10
57.886844	69.17	50.00	-19.17	1000.0	120.000	155.0	V	248.0	-14.8	15:36:04 - 2021-02-10
94.911022	62.54	50.00	-12.54	1000.0	120.000	155.0	V	274.0	-16.9	15:36:30 - 2021-02-10

Figure 8.15 Same as Figure 8.13 but with EMC reduction filter version 2.



Frequency (MHz)	QuasiPeak (dBµV/m)	Limit (dBµV/m)	Margin (dB)	Meas. Time (ms)	Bandwidth (kHz)	Height (cm)	Pol	Azimuth (deg)	Corr. (dB)	Comment
42.777666	65.05	50.00	-15.05	1000.0	120.000	155.0	V	234.0	-14.2	15:49:09 - 2021-02-10
46.795956	72.06	50.00	-22.06	1000.0	120.000	155.0	V	158.0	-13.8	15:48:31 - 2021-02-10
55.996133	70.88	50.00	-20.88	1000.0	120.000	155.0	V	102.0	-14.5	15:48:05 - 2021-02-10
94.898889	64.22	50.00	-14.22	1000.0	120.000	155.0	V	264.0	-16.9	15:49:44 - 2021-02-10

Figure 8.16 Same as Figure 8.13 but with EMC reduction filter version 3.