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DESIGN AND IMPLEMENTATION OF A BI-DIRECTIONAL VISIBLE LIGHT COMMUNICATION TESTBED

Thesis author	Pekka Kamsula
Thesis supervisor	Marcos Katz
Thesis advisor	Juha-Pekka Mäkelä
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ABSTRACT

This work defines a bi-directional visible light communication (VLC) testbed design and implementation process using Universal Software Radio Peripheral (USRP) software defined radios (SDR) and open-source software. The visible light communication design uses LED light sources for wireless communications purposes. The testbed combines light, infrared and radio frequencies as wireless media to be utilized in a hybrid wireless communication system.

Bi-directional communication at 12.5 Mbps bit rate was successfully achieved and only limited by a sample rate of the USRP system. The achieved communication distance was in the range of 0.5 to 7 meters depending on the used optics. A TCP-IP communication and access to the Internet was also established by using light and infrared communication links. The Internet connection was also established by using power line communication for providing data to the lighting through the existing power line cables. The results in the work were obtained by using a GMSK modulation. Also, GFSK, QPSK, 8-PSK, 16-QAM and OFDM modulation were initially tested for future study.

Key words: Visible light communication, software defined radio, open-source software, testbed implementation, Li-Fi

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TIIVISTELMÄ

Työssä suunnitellaan ja rakennetaan kaksisuuntainen kokeiluympäristö valon käyttöön langattomassa tiedonsiirrossa käyttäen ohjelmistoradioita ja avoimen lähdekoodin ohjelmistoja. Kokeiluympäristössä voidaan tutkia ja käyttää valon, Infrapunan ja radioaaltojen taajuusalueita tiedonsiirtoon. Valon tiedonsiirrossa käytetään valaistuskäyttöön suunniteltuja LED valaisimia sekä valaistukseen että tiedonsiirtoon.

Työssä saavuttiin laitteiston näytteistystaajuuden rajoittama kaksisuuntainen 12,5 Mb/s tiedonsiirtonopeus ja käytetyn optiikan ominaisuuksista sekä tiedonsiirtonopeudesta riippuvainen tiedonsiirtoetäisyys 0,5 – 7 metriä. Järjestelmään ohjelmoitiin valo- ja infrapunalinkin avulla toimiva TCP-IP yhteys Internetiin. Internet yhteys valaisimelle onnistuttiin siirtämään myös käyttäen sähköverkon valmiita kaapelointeja. Työn tulokset saavuttiin käyttäen GMSK moduloitua signaalia. Myös GFSK, QPSK, 8-PSK, 16-QAM ja OFDM modulaatioiden toimivuus testattiin tutkimuksen jatkoa varten.

Avainsanat: valo, langaton tiedonsiirto, ohjelmistoradio, Li-Fi

TABLE OF CONTENTS

FOREWORD

The aim of this work is to provide instructions for designing and implementing a visible light communication testbed with using software defined radios. The work focuses on to utilize the testbed for future researches of the visible light communication and combining it to the radio and infrared communications for the research of hybrid networks.

The design and implementation process started from the scratch in late 2013. The first simple implementation was made after the few weeks from the start by transmitting sound through the light channel. After the beginning the research proceeded step by step to the final testbed. The software implementations required the most of the time during the project.

Several people were participated to this work during the project and I would like to thank them. At the first, I would like to thank the thesis supervisor Professor Marcos Katz and the thesis advisor Doctor of Science Juha-Pekka Mäkelä for the time and contribution served to this project. Thanks also go to students Burim Derveni, Alexander McBride, and Jeffrey Proko from the Drexel University, who contributed to write the publication from the testbed to the 5G conference. Thanks to Muhammed Saad Saud from the Centre for Wireless Communications for cooperation and improvements of the testbed implementation.

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Pekka Kamsula

LIST OF ABBREVIATIONS AND SYMBOLS

AC	alternating current
AGC	automatic gain control
APD	avalanche photo detector
BER	bit error rate
BLH	blue light hazard
BPSK	binary phase shift keying
CAGR	compound annual growth rate
CPC	compound parabolic concentrator
CBR	constant bit rate
CRC	cyclic redundancy check
DC	direct current
DMT	discrete multitone modulation
DTIRC	dielectric totally internal reflecting concentrator
EMI	electromagnetic interference
EVM	error vector magnitude
FDM	frequency division multiplexing
FFT	fast Fourier transform
FOV	field of view
GFSK	Gaussian frequency shift keying
GMSK	Gaussian minimum shift keying
HD	high-definition video
IARC	International Agency for Research on Cancer
IEEE	Institute of Electrical and Electronics Engineers
IM/DD	intensity modulated direct detected
IR	infrared
ISM	industrial, scientific and medical radio bands
LED	light emitting diode
Li-Fi	light fidelity
LOS	line of sight
MIMO	multiple input multiple output
NLOS	non-line of sight
OFDM	orthogonal frequency-division multiplexing
OOK	On-Off keying
PAM	pulse-amplitude modulation
PC	personal computer
PPM	pulse-position modulation
PSK	phase-shift keying
PWM	pulse-width modulation
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
RCLED	resonant-cavity light emitting diode
RF	radio frequency
RONJA	Reasonable Optical Near Joint Access
SDR	software defined radio
SER	symbol error rate
SNR	signal to noise ratio

UP-VLC	Ultra-Parallel Visible Light Communication project
USRP	universal software radio peripheral
VBR	variable bit rate
VLC	visible light communication
VLCC	Visible Light Communication Consortium
WDM	wavelength division multiplexing
WHO	World Health Organization
WLAN	wireless local area network
$H_f(S,R)$	impulse response from the transmitter S to the receiver R
X_f	impedance
C	capacitance
F	frequency
π	pi

1. INTRODUCTION

Current trend of wireless communication with ever increasing demand for higher throughput and ubiquitous coverage is setting high demand for spectrum utilization of the radio frequency communication. It is predicted that mobile data traffic will grow at a compound annual growth rate (CAGR) of 61 percent from 2013 to 2018 [1]. This direction calls for alternative means for finding extra capacity and even extra capability communication methods in the future. The visible part of the spectrum provides about 400 THz unregulated, unlicensed and safe medium that can be used for communications purposes. The available spectrum is over 1000 times larger than the entire radio frequency spectrum [2].

Interest of wireless visible light communication (VLC) has increased concurrently with development and utilization of light emitting diode (LED) technology. A LED can provide a very high modulation bandwidth for communication purposes simultaneously with an energy efficient illumination. The LEDs are widely utilized for indoor lighting, automotive and public street lights after the light intensity of the LEDs were developed in sufficient intensity levels. Legislations on the sustainable and efficient use of energy have also speeds up the usage of the LED lamps [3] [4]. This direction will free up the market for the LED technology providing a platform to implement VLC technology. The market for VLC technology is estimated to reach more than 9 billion dollars by year 2020, at a CAGR of 87.31 % from year 2014 to 2020 [5].

The VLC technology has been announced to the “Top 100 radical technologies of the future for Finland” by the “Committee for the Future” in the Parliament of Finland [6]. This testbed work will be the first published VLC implementation in the Finland meaning the VLC technology is quite new and it could provide numerous opportunities for the research. The VLC technology is related to the more researched infrared (IR) telecommunication technology. The IR communication is used and standardized as it has been part of Institute of Electrical and Electronics Engineers (IEEE) 802.11 wireless local area network (WLAN) standard [7]. Infrared system can reach over Gbps data rates [8]. Over 10 Gbps data rates have also been reported and standardizations made during past years [9] [10].

This research provides instructions for a novel VLC testbed implementation in the software defined radio (SDR) platform using open-source software. Uni- and bi-directional communications are established integrating the light, IR and radio frequencies (RF) to a hybrid network technology. A light fidelity (Li-Fi) internet connection was achieved at data rate of 12.5 Mbps [11]. The Li-Fi communication was also implemented in the infrastructure of office using power line communication (PLC) technology. The results of this research were presented and the testbed was described in a VLC article in the newspaper named Kaleva [12]. The results were published in the “1st International Conference on 5G for Ubiquitous Connectivity” and the real time video stream demonstration was being promoted numerous times on several events to hundreds of interested people during the project [13].

The rest of the thesis is organized as follows: In Chapter 2, the main characteristics of VLC technology, history of optical communication and comparison with other wireless technologies are presented. Standardization and safety regulations related to the test bed have been observed. In Chapter 3, the design of the testbed was discussed. Chapter 4 presents the results and implementation process. Chapter 5 focuses on the discussion and making the conclusions of the project.

2. VISIBLE LIGHT FOR WIRELESS COMMUNICATION

Visible light provides about 400 THz unlicensed and secure and radio-free media for wireless communications. The bandwidth of visible light is over 1000 times wider than all the previously used radio frequencies together which allows enormous capacity for communications purposes [2]. A human eye is sensitive only to the visible light part of the electromagnetic spectrum between ultraviolet and infrared spectrum. The whole spectrum between wavelengths of 380 to 780 nanometers can be used for the VLC. Figure 1 shows the location of the visible light spectrum as a part of the whole electromagnetic spectrum [14].

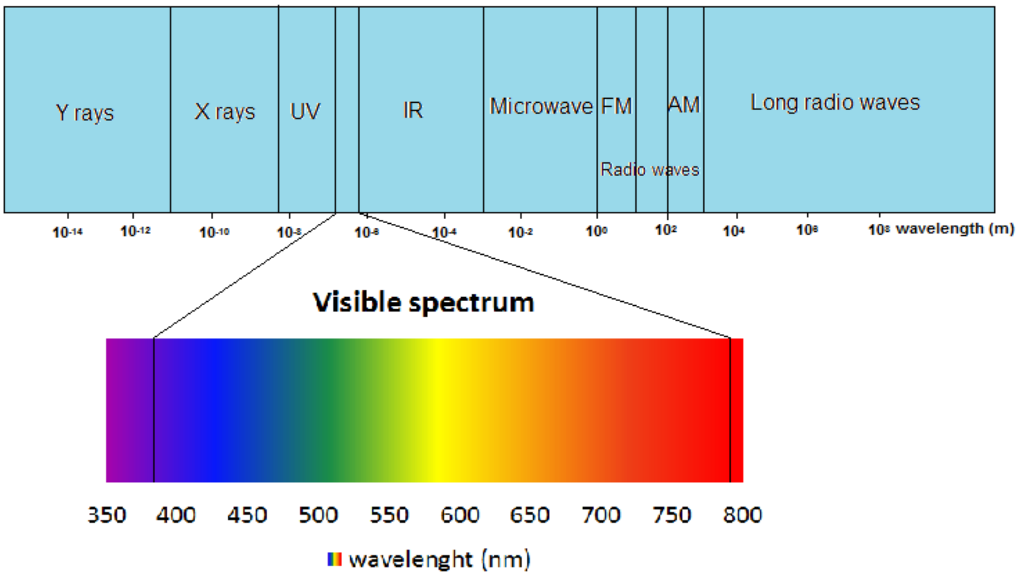


Figure 1. Visible light part of the electromagnetic spectrum.

The basic idea of the VLC is to add an information data into the light intensity changes and detecting the changes on the receiver side. That is called as intensity modulated direct detected (IM/DD) method [2]. The used modulation frequency is usually much higher than that the human eye can detect and therefore it does not cause noticeable flickering in the lighting. Both the baseband signals and passband modulation schemes can be used with the VLC.

The light cannot penetrate opaque objects as walls which make it highly locale and directed communication media. An advantage of the directive light is the ability to make interference free communication cells called also as atto-cells [11]. One drawback of this is the need for high number of the light communication base stations for providing larger coverage to the communication. Considering on the need for numerous light sources, an idea is to harness current lighting infrastructure to the communications purposes. The combination of the lighting and the communication infrastructure would be cost efficient and consume less energy than the lighting and the communication utilized separately [15]. Communication optimized VLC links can also be implemented for higher data rates by using lasers diodes or some dedicated light sources [16]. The dual-use VLC with commercial lighting equipment used for both lighting and communications is the type of the VLC studied in this work.

2.1. Evolution of visible light communication

Communicating by visible light medium has a long history even though the current LED based VLC technology was invented in 21st century. The pre-history of VLC was based on the use of sunlight, fire or different kind of lamps for transmitting information. For example sunlight was reflected by mirrors, fire was used in beacon fires and lighthouses, lamps are used as nowadays in lighthouses and in direct Morse coded communication. The first sophisticated wireless communication equipment was the photo phone invented by Alexander Graham Bell in year 1880. The photo phone used vibrating mirrors for sending sound on a beam of sunlight. [2]

It took over a century to develop components and technologies for use of a high data rate VLC. The development of LED has provided enhancements to the light intensities and modulation bandwidths for the VLC. One of the first LED based VLC communication system was made in year 2001 when Twibright labs open-source project Reasonable Optical Near Joint Access (RONJA) presented a long range bi-directional optical communication link. A 1.4 km link was achieved at a data rate of 10 Mbps using red light. [16]

The first significant step for evolution of the LED based VLC was the establishment of Visible Light Communication Consortium (VLCC) in Japan in 2003. In this consortium, Japanese technology companies aimed to standardize and promote the VLC technology. They have proposed three Japan Electronics and Information Technology Industries Association (JEITA) standards: CP-1221 visible light communication system, CP-1222 visible light ID system and CP-1223 visible light beacon system. CP-1221 and CP-1222 were published in year 2007 and JEITA CP-1223 six years later in 2013 [17]. More standardization was proposed in 2011 when Institute of Electrical and Electronics Engineers (IEEE) published IEEE 802.11.7 standard for the visible light communication [10]. The standard defines physical (PHY) and medium access control (MAC) layers of visible light communication system. The proposed data rates of communication were sufficient to support audio and video multimedia services. Implementation of IEEE 802.11.7 standard was demonstrated with universal software radio peripheral (USRP) devices in 2013 with data rates up to about 100 kbps [18].

Between 2008 and 2010, European Union funded OMEGA project made efforts for developing global standard for home networking by integrating different communication technologies [19]. VLC and IR communication were included in the research and the design of their VLC prototypes was shared in their home pages. They achieved 100 Mbps speed with the uni-directional VLC link transmitting Ethernet frames.

The best known public VLC presentation was given in 2011 when Professor Harald Haas demonstrated his team's work: “Wireless data from every light bulb” at Technology Entertainment Global conference [20]. A high quality real-time video broadcast over VLC link was demonstrated in the presentation. A video of the presentation has been great success. It has been viewed over 1.5 million times in internet.

A 1 Gbps transmission over a phosphorescent white LED by using rate-adaptive discrete multitone (DMT) modulation was demonstrated in IEEE photonics journal in 2012 [21]. 1.4 Gbps data rate was achieved in one channel using RGB LED and exploiting an optimized DMT modulation. By exploiting the wavelength division multiplexing (WDM) and three color channels, authors achieved 3.4 Gbps data rate at standard illumination level [22]. In 2014, Ultra-Parallel Visible Light Communication (UP-VLC) project achieved 3 Gbps data transmission speed using a single color gallium nitride micro-LED [23]. However, the distance between the transmitter and the receiver in these studies were only few centimeters but the results show the potential of VLC technology for high speed wireless communication.

One example for software based VLC testbed was proposed in 2011 [24]. In the testbed, a real-time video stream over three meter link distance were demonstrated using the USRP devices and GNU Radio software with bitrate of 1 Mbps. Authors also succeeded in testing orthogonal frequency division multiplexing (OFDM) with using binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) modulations in data rates up to 2 Mbps.

In the future, markets for VLC technology is estimated to reach almost 10 billion dollars by year 2020, at a CAGR of 87.31 % from year 2014 to 2020. Commercialization of the VLC technology is expected to start taking place from year 2015. The major players of technology are listed: pureLiFi Ltd. (United Kingdoms) [25], Bytelight (United States) [26], Oledcomm-France LiFi (France) [27], Nakagawa Laboratories (Japan) [28], Outstanding Technology (Japan) [29], LightPointe Communications (United States) [30] and fSONA Networks (Canada) [31] among others. [5]

2.2. Comparison visible light to RF and IR communications

VLC communication has some advantages over the traditional radio frequency and infrared communication. The major advantage of the VLC is the 400 THz unlicensed and almost unlimited frequency band for communication. The IR has as wide frequency bandwidth as the VLC, but whole RF band is only 300 GHz wide, strictly limited and regulated [2]. Utilizing higher RF frequencies has also a drawback of diminished link distances that affects the suitability of these frequencies in certain applications like high mobility usage. Another advantage of the VLC is low power consumption and low implementation costs when using illumination lamps of infrastructure for VLC. IR and RF communications require own base stations and energy consumption therein.

The biggest difference between RF to IR and visible light communications is propagation through obstacles. The RF can provide connection through obstacles while the VLC and IR can serve secure and safe high speed connections to the users in a determined area. This is because the coverage and mobility are limited in VLC and IR communications. The RF also suffers from electromagnetic interference (EMI) whereas VLC and IR may suffer from ambient lighting.

When comparing the health risks of the technologies, the RF may have more potential health risks than IR and VLC. Combining several studies, International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) has classified in radiofrequency electromagnetic fields as possibly carcinogenic to humans [32]. The thermal effect of RF frequencies to human is also well known but the risks and causes of it have not been conclusively proved [32]. The VLC technology has one known health risk known as blue light hazard (BLH) which can be caused by a high intensity blue light emitted from light sources [33]. The risk is not relevant when using normal light levels and color temperatures. Risks from the IR are resulted from the heating effect of the invisible radiation absorbed to the human skin and eyes [34].

RF and IR communications have had longer standardization and research history which has resulted to several standards. Particularly, the radio frequency communication is the most standardized wireless communication media. IR communication has been part of 802.11 WLAN standard, but use of it have not become popular [7]. VLC has been a part of the standards in recent past years [10] [17]. A summarized comparison between the wireless technologies is shown in Table 1.

Table 1. Comparison between VLC, RF and IR communication

	VLC	**RF**	**IR**
Bandwidth	Unlicensed, ~400 THz	Regulated, limited, <300 GHz	~400 THz
Electromagnetic interference EMI	No	Yes	No
Power consumption	Low	Medium	Low
Mobility	Limited	Yes	Limited
Standards	802.15.7	Several, matured	802.11
Coverage	Narrow	Wide	Narrow
Health risks	BLH	Several	Thermal
Implementation cost	Low	Low-Medium	Medium

2.3. The visible light communication channel

The visible light communication channel can be defined as an optical channel, in which the communication based on a light intensity modulation and a direct detection is occurring [35]. The channel can be modeled similarly to the more studied infrared communication channel [36]. The information is transmitted by modulating the light intensity $I(t)$ in response to an electrical current signal $x(t)$. This can be modeled as

$$I(t) = gx(t), \tag{1}$$

where the g is an optical gain of the transmitter. The direct detection can be modeled as an output electrical photocurrent $y(t)$ received from light intensity. The channel response $h(t)$ from $I(t)$ to $y(t)$ is approximated

$$y(t) = rg \cdot x(t) \otimes h(t) + n(t), \tag{2}$$

where $\otimes$ denotes convolution, r is the sensitivity of the detector and $n(t)$ the noise in the process. A line-of-sight (LOS) channel model was characterized with the path loss and received optical power by simulations and measurements in [37]. The ideal LOS channel impulse response is flat and the signal is a time delayed delta function which represents amplitude degradation of the transmitted signal. In indoor, VLC multiple reflections of light by the room surface broaden the diffuse channel impulse response which requires a good design of the modulation schemes and the usable data rates of the VLC system [38]. Common materials have different reflection factors to the visible light [39] which should be considered in the system design. For example, a white paint reflects from 75 % to 85 % of the directed light, but a red brick only 10 % to the 15 % providing a huge variety of signal reflection channels.

Non-line-of-sight (NLOS) channel model measurements were presented in [38], where the impulse and the corresponding frequency response of an indoor NLOS VLC channel were experimentally measured by using a short pulse and a frequency sweep techniques. The channel impulse response can be presented as the sum of rays after any number of reflections

$$h_c(S,R) = \sum_{k=0}^{\infty} h_c^k(S,R), \tag{3}$$

where $h_c(S,R)$ represents the impulse response of the rays undergoing *k-th* order reflection from the transmitter S to the receiver R.

A VLC through non-line-of-sight (NLOS) propagation channel is also feasible and is proved to work also in this work. The VLC signal can be transmitted indirectly by reflecting it via ceilings or walls. The indirect propagation of the transmitted light widen the coverage of the communication area, but the NLOS channel could also cause some disadvantages like signal attenuation and multi-path propagation which causes intersymbol interference (ISI) to the communication [38]. The attenuation can be reduced by providing more light power to achieving the similar light condition than with the LOS channel. The problems with the ISI can be reduced by using some sophisticated modulation methods such as OFDM modulation.

Preferred lighting levels in an office environment have been studied in [40]. The study concludes that in normal office work, the light level should be about 500-700 lux depending on the work type. Workers were satisfied with the lighting level of 400 lux but under that level, the mood of the working became lower. Also, the lighting level over 1000 lux is not recommended because of glare, reflection or other visual problems. This gives limits to the VLC in the office environment. The light level of dual-use lighting should be from 400 to 1000 lux. For the illumination it means the light output of 400 to 1000 lumens for an illuminated one square meter surface area as the equation of lux is the measured lumens in a square meter area.

The color spectrum of the light is also an important factor in the dual-use illumination and communications. The illumination, based on sourcing the white light, should contain all wavelengths of the visible light for providing the best visual effect to the human eye. The imbalance or a lack of colors can be seen as a distorted hue in the observed image. In the real life, the perceived white light usually consists of different portions of the light colors as shown in the Figure 3 presented in Section 2.4. Despite of the imbalanced white light, the human eye has also different response to the colors. A draft of the human eye responsivity curve is presented in a Figure 2 [41].

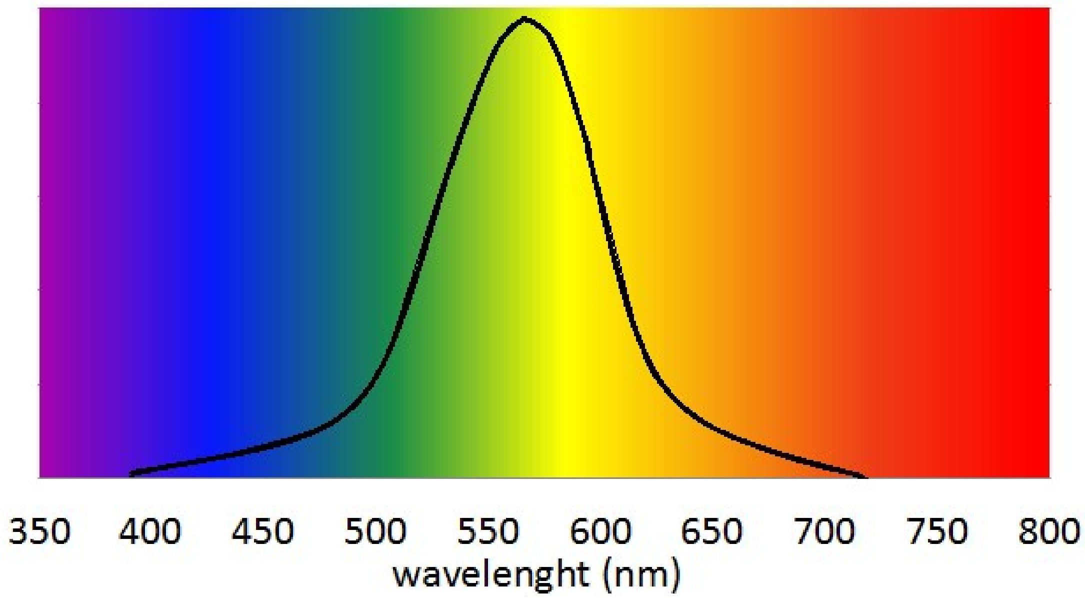


Figure 2. The visible light responsivity of the human eye.

The human eye is most responsive to the green and yellow wavelengths of light. The red and blue response is much lower which favors to use it in the VLC. If using the green to yellow section, the color shifts, intensity changes and high brightness's were observed easier than in the blue or red colors. [41]

2.4. Ambient light and noise on the VLC channel

Sources of natural and artificial light superimposed together produce ambient light which is detected as a noise in a VLC detector. The nature of the ambient light is quite stationary and therefore it can be optically or electrically filtered away from VLC communication. Identifying the light sources and the impacts of the ambient light is very important in designing VLC receiver.

The most disturbing natural light source is the sun emitting light in all wavelength of visible light spectrum. An intensity level of the sunlight can be very high in a wide dynamic range. Because the nature of the sun light is constant, the light does not contain interference frequencies to the VLC. The sunlight produces only stationary shot noise to detector and it is observed as a stable DC voltage in the receiver. This kind of noise can be easily filtered away from the detected signal. The only real problem from the sunlight is its ability to saturate the detector and therefore the increased requirements of the detectors dynamic range in different lighting conditions. Furthermore, the sun emits also infrared and ultraviolet wavelengths which are acting as wavelength of visible light producing shot-noise to receiver. Because the silicon based detectors are more responsive to infrared wavelengths than visible light, the infrared radiation can cause more noise to the VLC receiver [42].

The most common artificial lights used nowadays in indoor lighting are fluorescent and LED lights. The popularity of the tungsten lamps is diminishing. The spectrums of the light sources are shown in Figure 3.

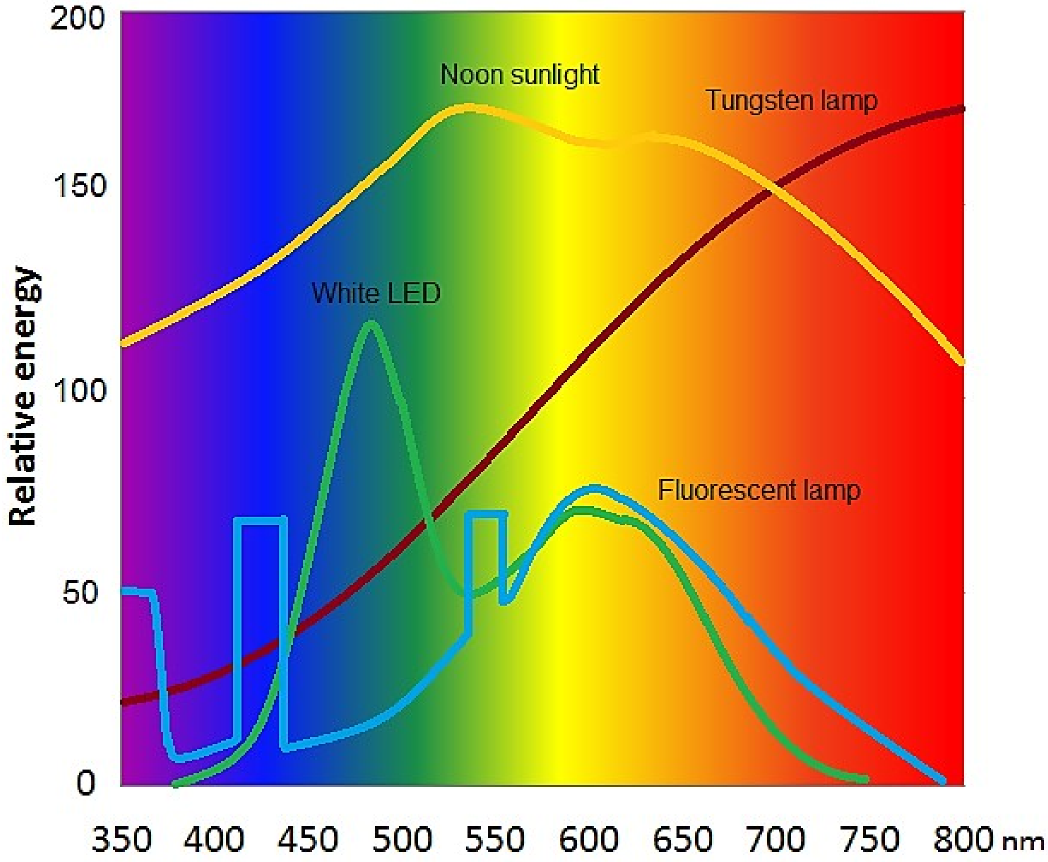


Figure 3. Visible light spectrum of the common light sources.

Background light produced by natural and artificial light induces shot-noise to the photo detection which is increasing the background current in the receiver. This background current can be reduced by using optical or electrical filtering [44]. More about filtering will be explained in the Chapter 3.

Interfering signals from incandescent and fluorescent light sources have been measured in [44]. An incandescent lamp emits sinusoid with a frequency of 100 Hz when using 50 Hz power supplies. The harmonics can be measured below 2 kHz frequencies, but only frequencies lower than 800 Hz carriy significant energy. A conventional fluorescent lamp produces a distorted sinusoid signal and its harmonics from 50 Hz to 20 kHz frequencies. A fluorescent lamp geared by electronic ballast produce very broad interference from 50 Hz and 100 Hz to 1 MHz frequencies. [44]

2.5. Safety regulations for the visible light communication testbed

Electrical installations are strictly regulated in Finland. Only very low voltage installations fewer than 50 volts alternating current AC and 150 volts direct current DC are allowed to people who know the risks of the electricity [45]. According to regulation and minimizing the risks caused from the electricity, the highest voltage level used in test bed are regulated to 50 volts. Usable current level has no regulation even it could be more harmful than the high voltage. A too high current level could burn components and wires. To avoiding risks of current, it will be limited to one Ampere. Limiting the current and voltage levels to safe area, the maximum output of testbed will be 50 watts. Safety regulations have to be followed in implementation process. Main hazards in this testbed are caused by electricity, heat and light. These hazards and risks must be identified and analyzed before the testbed implementation.

Photobiological safety of lamps and lamp systems is regulated in ISO/IEC standard IEC 62471 [46]. The standard classifies the LED lights to four risk levels shown in Table 2.

Table 2. The hazard levels of the LED lighting [46]

Risk	**Group**	**Risk definition**
Exempt	None	No photobiological hazard
RG-1	Low risk	No photobiological hazard under normal behavioral limitation
RG-2	Moderate risk	Does not pose a hazard due to aversion response to bright light or thermal discomfort
RG-3	High risk	Hazardous even for momentary exposure

The company CREE has made standard measurements and classifications to the several LED components [46]. One LED emitting blue light has set to the RG-3 risk level and the other components are classified to RG-2, RG-1 and exempt levels. The risks from the LEDs are caused by the BLH from blue light emitted from the LED components. The blue light could cause potential eye safety issue called photo retinitis and photochemical damages to the retina. Retinal thermal injuries can also result if used high intensity levels of light. [33]

White LED light does not emit more blue light than lights using other technologies at the same color temperature which means the LED technology as safe as earlier lighting technologies. 2700 Kelvin warm white LED emits blue light at same level than halogen bulb. 4000 Kelvin cool white and 6500 Kelvin Daylight LED emits much more blue light and are more hazardous for that reason. The warmer color temperature includes less blue light than colder ones; hence the warmer color temperatures are preferred in practice. [33]

Different wavelengths of electromagnetic spectrum have different effects to the human body. Main issues are skin and eye effects. Thermal effect is caused by infrared radiation and skin effects from ultraviolet radiation [47]. LED light does not emit significantly infrared or ultraviolet wavelengths; hence the only real issue when using normal light level is the blue light hazard. [33]

3. DESIGNING A VISIBLE LIGHT COMMUNICATION TESTBED

A visible light communication testbed provides a platform for investigating, measuring and developing the VLC technology. Several visible light testbed installations have been proposed around the globe during the last few years. The reported testbeds usually demonstrate a small distance uni-directional link to the purpose of enhance data rates of the VCL link [21] [23]. These testbeds have been utilized by sourcing accurate information signals from a signal generator to the VLC link and receiving it with a high speed oscilloscope or a spectrum analyzer. In the present work, the design of the testbed is made for having versatility to the real life communication demonstrations rather than achieving high signal frequencies.

A VLC testbed is modeled, as shown in Figure 4, consisting on the parts from data source through the light channel to the data sink. The model is also providing the structure and parts for the testbed designing process.

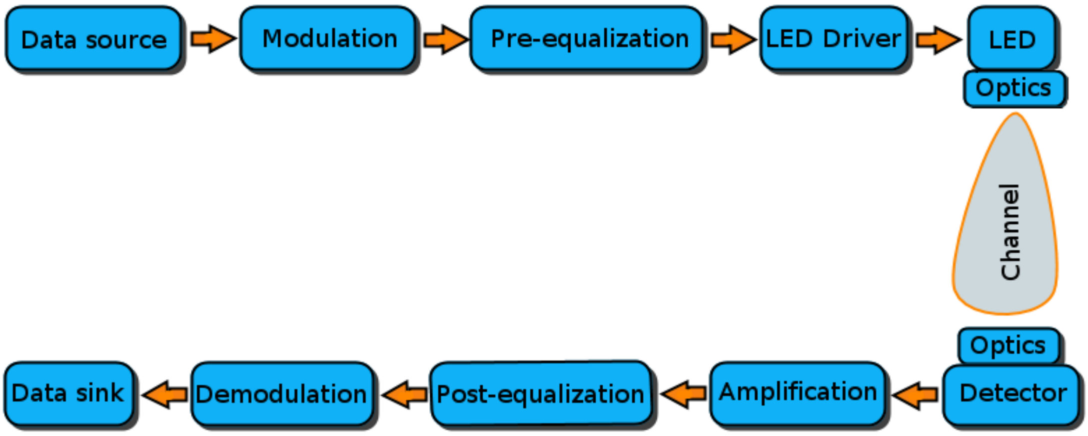


Figure 4. A model of a VLC link.

The design process is partitioned into smaller parts for having a more explicit structure for the research. The all parts are designed separately to be as good as possible and tested in order to avoid birth bottlenecks.

The design process started in defining the requirements of the testbed and selecting an appropriate platform to the implementation. The main criteria for designing the testbed are:

1. Scalability
    a. Variations with the LED types and quantity
    b. Variations of modulation schemes available
    c. Connectivity to different software
    d. Connectivity to other communication media
2. Usability
    a. Easy to modify mainly with software
    b. Easy to connect to different equipment and networks
3. Cost efficiency
4. Ability to present real life scenarios with the VLC technology
5. Bi-directionality

To fulfilling the stated criterions, the testbed was implemented with USRP SDR devices [48] which are providing a versatile and cost efficient platform for the system designing. The system designs can be modified and duplicated easily and the used parameters like frequencies, amplification and filtering are simply controllable in the real time with the software [49]. Also, plenty of open-source software examples are available in GitHub [50]. The use of the USRP devices allows implementing the bi-directional communication link with a minimum number of external components. The USRP devices can handle lots of functions during the communications sessions without need for adjusting them manually. At the beginning, the automation helps the use of devices and software, before the skills and knowledge about them has been increased.

During the several designing sessions, a proposal structure of the testbed was developed. The designed straightforward structure of the desirable VLC testbed is shown in Figure 5. The block diagram of the bi-directional VLC testbed shows the components needed for utilizing and implementing the testbed.

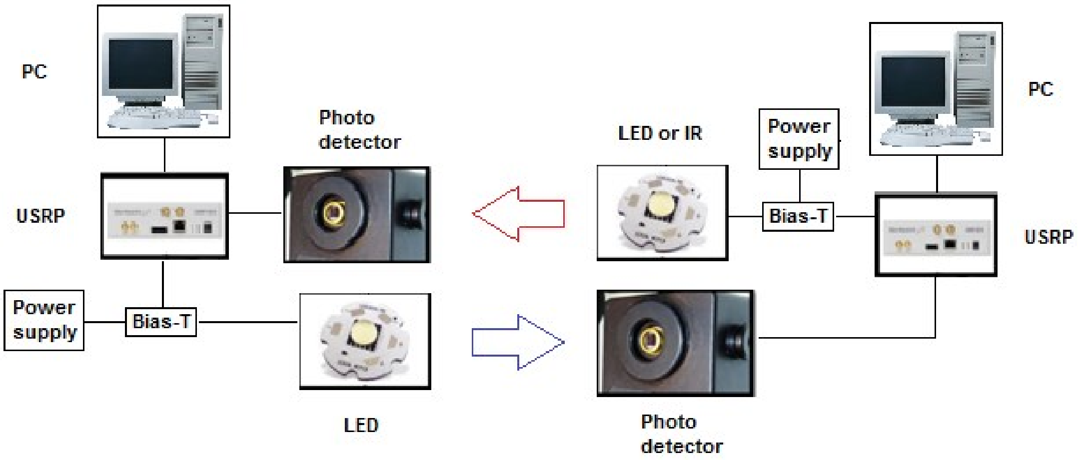


Figure 5. A structure of a bi-directional visible light communication testbed.

As seen from Figure 5, the design of the VLC test bed is quite simple, because the signal processing and connectivity are handled in the USRP devices and personal computers. The only external components are LEDs, detectors and LED driver circuits. The LED driver circuits consist on power supplies connected to Bias-T circuits. The use of external power supply allows a wide dynamical range for utilized voltage and current levels providing sufficient power levels to the almost all kind of LED components. Mostly, the other major changes of the testbed will be made in the software design and its parameters.

The main structure of the testbed, presented in Figure 4 and Figure 5, is the basis for the designs and implementations in this testbed. The Chapter 3 follows the system models by presenting the main components and its functions to the VLC. The components are separated in sections for having clear structure to the presentation. At first, the VLC transmitter is defined in the Section 3.1. After that, the structure of the receiver is presented in Section 3.2. The signal processing is separated into Section 3.3, where the USRP devices and software are explored from the viewpoints of the whole communication system including the signal processing in the transmitter and the receiver ends of the communication link.

3.1. VLC transmitter

A VLC transmitter is basically a light intensity modulated light source, whose purpose is to transform the information data to the light signal using an applicable modulation method. The transformation from the electrical signal to the light should be as linear as possible in order to achieve the optimal conditions for the transmission. The nonlinearity caused by the LED and LED driver can be straighten with pre-equalization technologies. A structure of a basic VLC transmitter is defined in Figure 6.

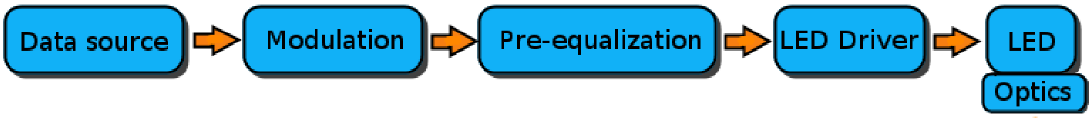


Figure 6. Main parts of the VLC transmitter.

As seen from the structure, the transmitter contains six parts from the data source to the transmitter optics which are transmitter optics, LED, LED driver, pre-equalization, modulation and data source. The data source, modulation and pre-equalization are implemented in the USRP device and the LED driver, the LED and the transmitter optics with external components. The pre-equalization can also be implemented with external circuits.

In this section, functionality and designs of the LED, the LED driver, the modulation schemes and the transmitter optics are presented. Propositions for the future use of the testbed are provided with suggested components to be added for enhancing the functionality of the testbed.

3.1.1. Light emitting diode

A light emitting diode (LED) is the main component of the dual-use VLC combining the lighting functionality and the wireless communication. A LED can provide a very high modulation bandwidth for the communication purposes simultaneously with an energy efficient illumination. Since the light power of the LED has been improved during the 21st century, the LED has become a common component of the illumination devices. LEDs are widely applied for indoor lighting, automotive and public street lights. Energy efficiency legislations have also speed up the usage of the LED lamps.

A LED component is a type of a diode made out of semiconductor material which is emitting specific wavelengths of the light. The color of the emitted light depends on the used materials and the structure of the LED. For illumination purposes, a white light, with several wavelengths of the light, is required. There are two main ways to produce white illumination light by using LED components. The most common and cheaper way is to use a phosphor coated blue LED. The other way is to use multi-color LEDs like a RGB LED which combines primary colors to produce white light. The phosphor coating over the blue LED spreads the spectrum of the generated blue light to other colors and the observed light is white. The other way is to use multi-color LEDs. A multi-color LED could emit for example red, blue and green light, where the mixture of these light sources is perceived as white light. [51]

The LED component demands correct power conditions when producing the visible light. The LED remains off under the on-voltage threshold level but over the level, the emitted light intensity increases almost in a linear way consuming more current to flow through the component. The operation of the VLC based on this linearity dependence of the power and the light output of the LED. The linearity of a LZC-00MC40 LED light output dependence on the forward current is shown in Figure 7 [52].

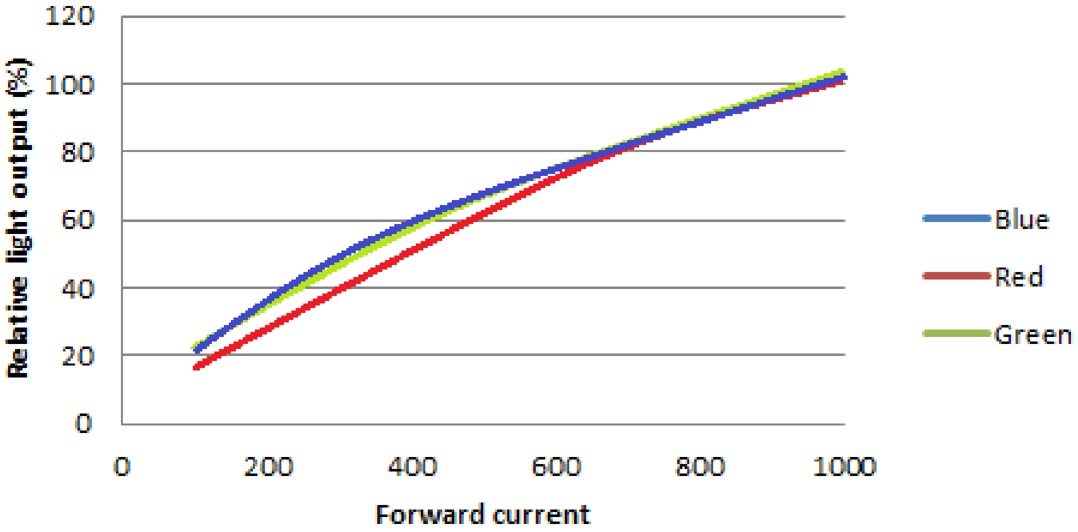


Figure 7. Relative light power vs. forward current of a RGB LED.

The relative light output will increase nearly in a linear way by the forward current in the all three colors of the LED. There is maximum 10 % light output difference between the colors in lower current levels. The variation can be seen as a color shift and imbalance of the white light output. To avoid the color imbalance, used current levels should be adjusted separately or about 750 mA current as the manufacturer of the component recommends [52]. In this research, the design of the testbed will be constructed to allow over 750 mA current levels in order to have this component utilized.

The relative light output linearity should be found also in the forward voltage behavior of the LED as the VLC information data signal is modulated into the voltage differences. Because no figures from voltage-light output dependency were provided in the manufacturer data sheet, the relationship between the light output and the forward voltage should be induced from the information of the Figure 7 and Figure 8 [52].

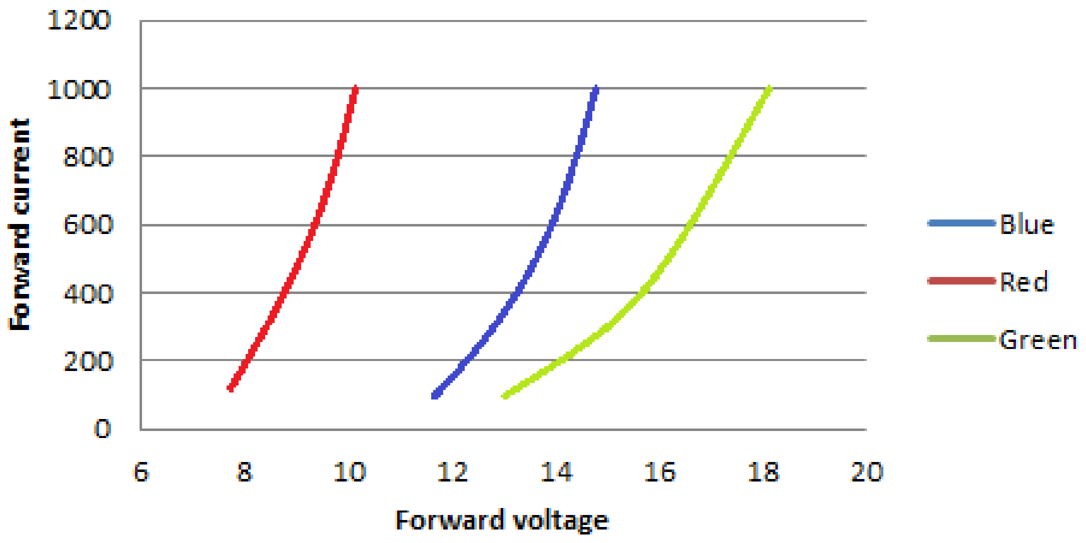


Figure 8. Forward current vs. forward voltage of the RGB LED.

Forward current versus forward voltages curve of the LZC-00MC40 RGB LED in Figure 8 shows how the correlation has some linearity between the current and voltage when using voltage above the threshold level. The linearity is better when using current level over 400 mA. It is preferred to use the typical recommended 750 mA current level explained earlier for providing a good linearity also to the voltage modulation. Without the linearity, only a simple modulation schemes like the On-Off Keying (OOK) or some pulse modulations can be used. More advanced modulations are requiring accurate linearity or a near linear operation to function [53].

Temperature of the LED component has some negative effects to the output intensity of the LED which should be noticed when designing a VLC system. The first major thing is that the relative light output intensity degreases concurrently with warming of the LED component. For example, the light output of the LZC-00MC40 RGB LED decreases about 70 % with red, 20 % with green and 10 % with blue light when the temperature of the component was increased from 20 °C to 120 °C [52]. This should be into account when designing a VLC detector and its detection range. The detector should be designed to work with a LED which has reached the operational temperature and its light output intensities. Another warming defect of the LED is wavelength shifting which could have impacts when using narrow band optical filters. Wavelength shifts of the LZC-00MC40 RGB LED could be few nanometers making it not being as serious to the VLC as the intensity degradation. A temperature of the LED in normal use depends on the cooling of the LED, used power levels, surrounding temperature and the component itself.

As the bandwidth of normal LED illumination components was limited to about tens of MHz, faster components were invented for achieving higher data rates [2]. Three main types of a higher bandwidth LED components are a resonant-cavity LED (RCLED), an edge-emitting LED and a micro LED. The RCLED has been used for plastic fiber communication providing a very wide modulation bandwidth. Data rates achieved with the RCLEDs have been over 1 Gbps, but the weakness of the component is a low visible light intensity making it unusable for the higher distance use of the free space communication [54]. The edge-emitting LED has a better output intensity than the RCLED and it can provide data rates over hundreds of Mbps [54].

The micro LEDs are microscopically small and emitting only a little light in one component, but adding them to array the output intensity will be increased to sufficient levels for the VLC. The widest bandwidth of the VLC has also been proposed using micro LEDs [9]. The micro LEDs will be the most promising component to add in the testbed, but the price of it is too high leaving it out of this project.

3.1.2. LED driver hardware

The purpose of a LED driving hardware is to correctly bias the transmitter LED and drive it in linear voltage - optical power region. Another main purpose is providing fast rise and fall times to the LED which is influencing the maximum bit rate of the VLC system. Also, power dissipation and data signal attenuation must be considered and minimized.

In the literature, the most widely used led driver is a Bias-T circuit, in which the idea is based on adding bias voltage to the data signal and sourcing the combination to the transmitter LED [2]. In some works, various transistor circuits were designed to amplify the signal to the sufficient LED driving levels [24]. In this testbed, the Bias-T circuit was selected to due to its versatility. The circuit was also designed and implemented for achieving higher allowable current levels and ability to modify the circuit in the future. All founded commercial circuits were allowing only lower current levels or the design was made to the higher frequency ranges. The designed circuit is also suitable to be added to protect outputs of the USRP devices from the LED biasing voltages and current. Figure 9 defines the type of the modeled Bias-T circuit.

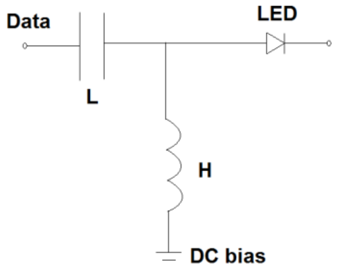


Figure 9. Bias-T circuit

The circuit is based on biasing a LED to the normal lighting intensity level by using a constant voltage and adding the information data signal to it from signal source. The biasing level is also in the middle of linear region of LEDs output.

The added inductor and the capacitor in the circuits are protecting the power source and data source from the disturbing signals. The capacitor blocks direct current (DC), but allows an alternating current (AC) data signal pass through. Inductor blocks AC data signal and protect power supply without influencing DC bias voltage. The impedance X_f of the designed capacitor can be calculated as

$$X_f = \frac{1}{2\pi f C}, \tag{4}$$

where the F is frequency and C is the capacitance. When frequency $f = 0$, the impedance $X_f = 0$ and it means open circuit to DC. The DC can flow through the capacitor without any attenuation [55]. The capacitor of Bias-T circuit was made by connecting Minicircuits DC block BLK-89 to the output of the USRP device. DC block has low insertion loss 0.01 dB under 100 MHz frequency range. The maximum DC input voltage is 50 volts which was sufficient for this application. [56]

An inductor was connected to the output of the power supply. The selection of appropriate inductor is quite simple. The maximum direct current should not exceed allowable current level. Self-resonance frequency should not be in used frequency band. In this testbed, the inductor PE-53816S was used. Inductance of the inductor is 17 µHenry, the maximum DC current 1.02 Ampere and the maximum DC resistance 0.1 Ohms. [57]

The Bias-T circuit in VLC testbed specifies the maximum usable voltage and current levels. The maximum voltage will be 50 volts limited by the DC block. The maximum current level will be 1.02 Ampere limited by the inductor. To obey the both limits, the maximum power output of the testbed will be about 50 W. The voltage and current limits could be adjusted by changing the values of the capacitor and the inductor.

3.1.3. Pre-equalization

Modulation bandwidth of the transmitter LED can be enhanced by using pre-equalization method [58]. The modulation bandwidth of a phosphor coated white LED was increased from 1 MHz to 12 MHz by utilizing pre-equalization techniques in [59]. One reason of the pre-equalization is an ability to enhance linearity LED in electrical to light intensity conversion. For enhancing the linearization an analog or a digital predistortion method can be utilized [53]. The technology can be also implemented in this testbed for improving the modulation bandwidth and linearity.

3.1.4. Modulation schemes

The information in VLC system can be transmitted by using both the baseband signals and the passband modulation schemes providing a novel implementation platform for matured wireless communication technology. A selection of the modulation scheme should be made by considering the need for data rates, signal strength and the cost of the communication equipment for example. There is no perfect modulation scheme available for the all VLC systems, but each of those has some particular advantages. A short review of the modulation schemes is provided in this section leading to presenting the methods selected and implemented to this testbed.

With the earlier VLC systems the baseband modulations such on-off keying (OOK), pulse-position modulation (PPM), pulse-amplitude modulation (PAM), pulse wide modulation (PWM) as the variations of them were mostly used [11]. The data rates were at the beginning like in the JEITA standards about some kbps or at the most some Mbps limited by bandwidth of the transmitter LED and restricted by the ability of multipath interference suppression [17] [38]. After several improvements of the post- and pre-equalization and the modulation methods, the data rates have been increased to over 100 Mbps with the basic modulation schemes in laboratory environment [60]. The highest VLC data rates have been achieved by using more advanced modulation methods like the OFDM and the DMT with some multiplexing method or with the multiple input multiple output (MIMO) techniques [9] [21] [61].

In this work, a Gaussian minimum shift keying (GMSK) modulation was chosen as a main modulation technique mainly for the six reasons mentioned below:

1. easy implementation in software
2. spectral efficiency
3. signal non-linearity
4. self-synchronizing capability
5. widely used in wireless communication like in the GSM standard
6. immunity to amplitude variance and noise

The first reason for selecting the GMSK to main modulation to the VLC testbed was implementation time and cost, while the modulation was already coded in the GNU Radio and the Python programs allowing an easy implementation in the system [49]. The second reason was spectral efficiency of the modulation which allowed adding more data to the LED bandwidth limited communication channel. The third reason was that the requirement for signal linearity was not tight which mean the non-linearity of the LED did not harm the communication. The fourth advantage of the GMSK was self-synchronizing capability which allowed variations for timing of the communication. The fifth benefit was that the GMSK is widely used in different RF standards and the knowledge of it is matured. The sixth advantage of the GMSK was the immunity to amplitude variance and noise as none of the information was carried as in amplitude variance.

Several measurements were done during the implementation to check the adequacy of the GMSK to the VLC. The most accurate measurements were obtained from calculating an error vector magnitude (EVM) with using an Agilent E4446A PSA Series spectrum analyzer equipment and Agilent 89600 VSA 16.0 software to receive GMSK modulated test signals. From the results the EVM was about 4 % in good communication conditions when the signal was transmitted from the VLC transmitter of this testbed. When measuring the VLC link with a signal transmitted from signal generator the results were even better due to increased signal power not available from USRP. Figure 10 presents a constellation diagram of received GMSK signals in GNU Radio software received in USRP device. The alignment of the constellation points shows the accuracy of the detection.

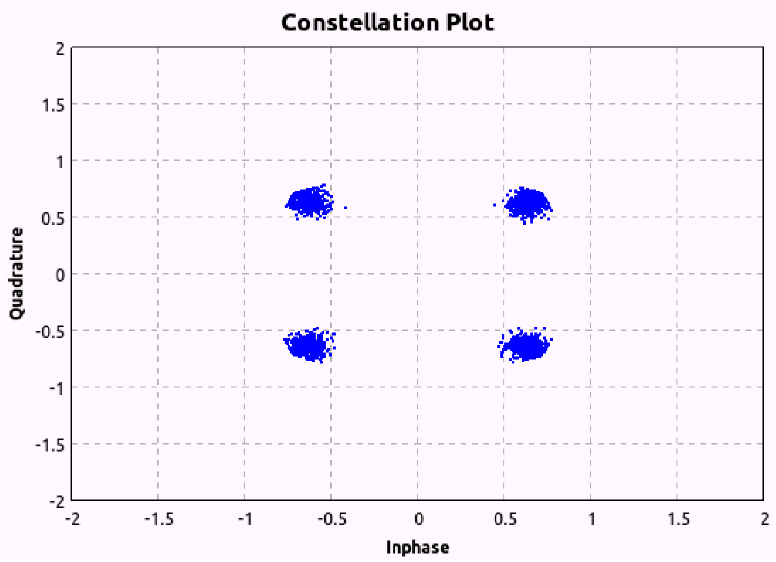


Figure 10. Received constellation points of a GMSK modulated signal.

The GMSK signal carries only one bit per symbol even it has four constellation points which limits the maximum data rates of the communication. Considering the advantages and measurements of the GMSK modulation, modulation methods with higher modulation levels should be utilized for achieving higher data rates. For example a quadrature phase shift keying (QPSK) signal carries two bits per symbol in the four constellation points allowing twice as much data capacity as the GMSK. Eight-phase-shift keying (8-PSK) carries three bits per symbol and sixteen-quadrature amplitude modulation (16-QAM) four bits per symbol. Comparison between modulation methods will be left in the future work, because the measurement needs accurate adjustments, proper software parameters and systematic measurements for getting true and correct results. The focus of this work is to report and implement the modulation methods for the scalable measurement platform. From this point, the working modulation methods tested and implemented in the VLC testbed have been GMSK, GFSK, BPSK, QPSK, 8-PSK, 16-PSK, 16-QAM and also OFDM with BPSK carrier modulation.

Basically, OFDM and similar discrete multitone (DMT) modulation divides the information data into several parallel data streams and channels which all are modulated separately at low symbol rates with some conventional modulation scheme like QPSK or BPSK. The produced orthogonal sub-carriers are then aligned into the available bandwidth. This method allows a better bandwidth usage and reduction to the inter-symbol interference, but requiring the linearity for communication. The DMT differs from the OFDM as the DMT uses baseband signals and it is adaptive for the used communication channel. A VLC system can use both of these methods. [53] There has been some research for modifying the energy efficiency of the traditional OFDM implemented in the VLC channel. The proposed unipolar OFDM modulation method has been explained in paper [62] where they also resolved the need for bias voltages and the problems caused by the bias level drift.

3.1.5. Transmitter optics

A light beam of transmitter LED can be modified by using optical lenses, mirrors, diffusers, filters and spatial modulators for providing improvements to the light conditions leading to the better communication quality and signal power of the VLC link. Internal optics of the LED components providing usually a wide light beam which can be improved by adding an external fore lens to the LED as it is done for the LED component added to illumination light bulbs. The most common transmitter optics based on compressing a wide beam LED light to narrower beam for increasing the light intensity on the detection area. For this purpose, many types of optics can be used. The lens can also be used in the opposite way for making light beam wider providing better coverage and mobility to the receiver.

In this work, commercial lighting infrastructures and light bulbs were used as the light source, which were providing matching transmitter optics to the VLC use. The intensity and the light beam of the tested light sources were similar to commercially designed and manufactured which relates the results from this testbed to the real life. Some experimental studies were still carried out by using narrow beam optics. The results showed the tremendous improvements of the communication distance and the data rates.

An active optical beamforming is an effective way to enhance the mobile VLC link. Adjusting directive communication light beam to the perfect alignment for the receiver will improve signal strength and signal to noise ratio (SNR) leading to faster data rates and quality of the communication. The benefits of the technology are getting better data rates and coverage by using a minimum light power and a number of light sources. Recently, research on an active optical beam forming using spatial modulators was proposed by Kim Sung-Man [63]. In the research, they achieved significant improvement in the data rate, transmission distance and the SNR of VLC.

3.2. VLC receiver

Receiving the VLC information signal based on the direct detection which is meaning the transmitted light intensity changes were detected and converted into the electrical data signals. The received data signals should be as linear as possible in order to implement more sophisticated modulation schemes like OFDM. For that reason, all the parts of the VLC receiver, presented in Figure 11, should work in linear manner for the accurate detection. The structure of the VLC receiver can be separated into six parts from optics to the data sink.

Figure 11. Main parts of the VLC receiver.

This section explains the main parts of the VLC receiver separated into four sections: “Receiver optics”, “Light detection”, “Signal amplification” and “Electrical signal filtering and post-equalization”. The “receiver optics” section is explaining the optical components used in VLC and providing some examples to be utilized into the testbed. In the “Light detection” section, component types for the light detection are explored and the detectors used in this testbed are specified. The "Signal amplification" section is presenting the amplifier types used with the VLC and in this testbed. The "Electrical signal filtering and post-equalization" section is explaining the main ideas of filtering and post-equalization used in VLC.

3.2.1. Receiver optics

Lenses, mirrors and optical filters were used to improve the light detection and to filter interfering signal. The lenses and mirrors were set to focus transmitted light to the detector increasing received optical power and improving the signal to noise ratio. The optical filters were mainly added to reduce ambient and disturbing light before detection. Optics is the main part of VLC and the proper use of it is especially important. The main idea to enhance light detection is to provide enough light intensity on the surface of light detection area using condensing lenses, mirrors or some sophisticated optical elements. The best optics for the detection depends on the intended use and requirements of a link distance, a light power and a horizontal offset without forgetting the price of the optics. The selection of the optics is usually compromise. Enhancing one feature could make the other aspect worse.

There are some optical weaknesses which should be recognized when designing a VLC receiver. The biggest problem caused by the optics is when light is off-focused on the detector causing a focal point misalignment. When transmitted light is not in full alignment with the center line of optics, as seen in Figure 12, the light rays will not focus into the detector area and the communication will be severely degraded.

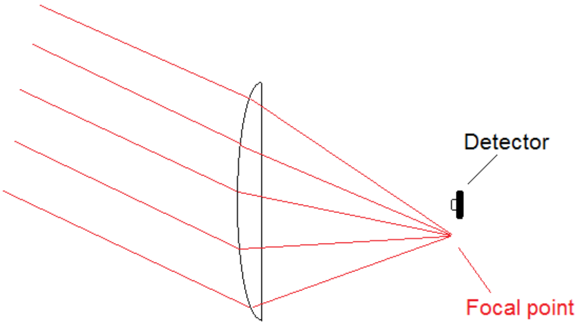


Figure 12. Misalignment of the focus point.

Other optical weaknesses are spherical and chromatic aberration caused by refraction variation of light rays. Spherical aberration caused by incoming light rays end up converging at different points after passing through a spherical lens or reflected from a concave mirror. Spherical aberration could be minimized by using aspheric lenses, multi lens systems, parabolic mirror or parabolic concentrators [64]. Conventional class lens suffers from chromatic aberration which means that the different wavelengths of light converge at the different focal points [65]. Mirrors do not suffer from chromatic aberration. In Table 3, the optical weaknesses are collected [64] [65].

Table 3. Spherical and chromatic aberration of the optical elements

	spherical aberration	**chromatic aberration**
Spherical lens	Yes	Yes
Aspherical lens	No	Yes
Fresnel lens	Yes	Yes
Concave mirror	Yes	No
Parabolic mirror	No	No
Parabolic concentrator	No	No

Shaped mirrors are efficient optical elements which can be used in the VLC receiver. The mirrors do not suffer from chromatic aberration, but the spherical aberration may occur if parabolic shapes are not used. A concave or parabolic mirror collects light to the detector placed on the focal point as shown in the Figure 13. The shape of the parabolic mirror would be the best optical intensity focuser in the VLC use, but a drawback of using parabolic mirrors is the price of them. The parabolic shapes are expensive to manufacture. [64]

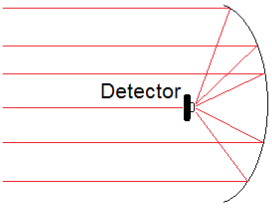


Figure 13. A concave mirror.

One example of concave mirror based VLC detector developed and patented by company named Visilink. The structure of detector is very simple. A concave mirror focuses light to a small sizes photo diode which is located in the focal point of the concave mirror. The small sized photo diode has a small electrostatic capacitance which improves detectors response time. The low electrostatic capacity reflection photo detector LEC-RP0508 has 50 MHz response time and photo sensitive is equivalent about 15 A/W. [29]

One weakness of using optics in VLC is optical transmission losses which are caused by optical elements itself and by losses of the between different optical elements. The losses inside the optics are usually known but for example, the transmission loss between class and air is about 4 % resulting in high losses when combining several optical elements [64]. To avoid the air space losses, the gap between elements can be filled with optical cement or even water [64]. One way to minimize the air space losses in the VLC is to coat a lens with a filtering material.

One good alternative of the optical element to the VLC receiver is introduced in United States Patent 6829442 [66]. The receiver, structure shown in Figure 14, combines a large fore lens and a compound parabolic concentrator (CPC) integrating the good optical features together. The large fore lens collects the light rays from a large detection area by focuses it to the CPC which will providing larger field of view (FOV) resulting the wider horizontal offset for the receiver.

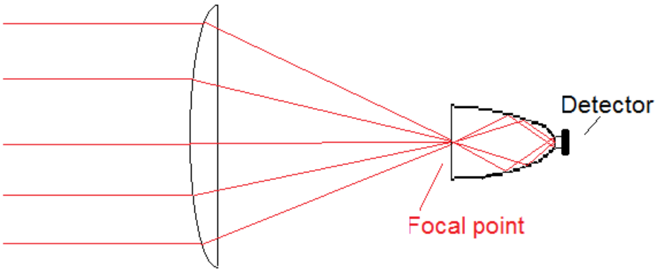


Figure 14. Structure of an optical receiver [66].

A possibly good optical shape for the VLC receiver is also shown in Figure 15. The dielectric totally internally reflecting concentrator (DTIRC) provides even higher concentration than CPC and the equal FOV. The DTIRC can be manufactured in small sizes, single piece and compact structures. [67]

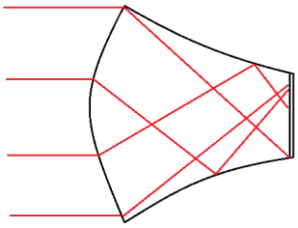


Figure 15. Dielectric totally internally reflecting concentrator [67].

When comparing the different types of receiver optics, the selection for this VLC testbed will be made between non-imaging optics DTIRC and CPC with large fore lens. By covering the optics with an adequate optical filter the structure will be even improved to the VLC.

Optical filtering provides considerable benefits for light detection by reducing the impacts of ambient and interfering lights of the optical channel. The filtering always weakens the detected signal power, but it will allow use of the more responsive detectors and the optics with a higher concentration factor. Research has been made on the effectivity of the filtering away the background current caused by ambient light [44]. In the research the ambient light filtering were measured at different light conditions and the results are shown in Table 4 [44]. The measurements were done using a long pass absorption optical filter with a cut-off wavelength at 800 nm.

The filtering is considerably reducing the background current converted to detector from spot noise caused by ambient light. A narrow band optical filter reduces the ambient light allowing better detection of the light carrying the information signal.

Table 4. Background current for different illumination conditions [44]

	Without optical filter	**With optical filter**	**Filter reduction**
Direct sun light	5100 uA	1000 uA	5.1
Indirect sun light	740 uA	190 uA	3.9
Incandescence light	84 uA	56 uA	1.5
Fluorescent light	40 uA	2 uA	20

In earlier research work, the bandwidth of the phosphorous white LEDs was enhanced by detecting filtered blue light instead of the whole white light emitted from a LED. The consequence of the phosphor coating of the LED is that the intensity changes of the LED became slower limiting the maximum data rates achieved in the VLC link. Using an optical blue band pass filter the slow phosphor generated yellow light was filtered away from the channel and the fast blue light component could be detected. This is a way to enhance performance of a phosphor LED based VLC system, but its impact depends on used modulation method. [68]

The blue filtering was also implemented in this testbed for measuring the benefits of it to the VLC communication. The use of blue filter reduced incoming light so much that the communication became impossible to achieve in higher distances when using the photodiode detectors. When using an avalanche detector the use of blue or some other filter will be preferred for avoiding saturation of the sensor. Some research has also been made showing that blue filtering is not needed at all [68]. The results were similar to those obtained during this project.

3.2.2. Light detection

A light detection is based on the ability to convert light intensity changes into electricity. Different types of electrical light sensitive components can be used in VLC. The best components have a fast response time to light level changes, a high responsivity to light power and a wide dynamical range of detecting light in different intensity levels. It is always a compromise to find optimal component for designed VLC system. In this study, three different types of detector were used. First, a silicon based photodiode detectors were tested. The second type of tested detector was avalanche photodiode based detector and the third tested detector type was a solar panel. Recently, a usage of the mobile phone cameras as the VLC detector has been reported in the literature. A study presents a technique for sending data from solid-state luminaries to rolling shutter cameras on mobile devices [71]. The achieved data rates were quite low but sufficient to the indoor localization for example. This type of detection was omitted due to lack of interface options to the rest of the system.

Silicon based photodiodes are inexpensive components and the bandwidth and responsivity were sufficient in VLC use. The Thorlabs photo detector PDA36A-EC was mainly utilized in this project [42]. Because the USRP device limited the maximum bandwidth to the 12.5 MHz, the bandwidth of the detector was sufficient. Detectors proven bandwidth is 10 MHz, but it is still working adequately in the 12.5 MHz frequency band. Also, PDA10A was implemented into the testbed providing the wider bandwidth but less sensitivity [69]. The main specs of the detectors and differences between them are presented in a Table 5.

Table 5. Specification of photodiode detectors used in the testbed

Photo detector	**PDA10A**	**PDA36A**
Wavelength Range	200 - 1100 nm	350 - 1100 nm
Detector Size	diameter 1.0 mm	3.6 mm x 3.6 mm
Gain	Fixed: 10 kV/A with Hi-Z Load, 5 kV/A with 50 Ω Load	8 x 10 dB Steps
Bandwidth Range	DC - 150 MHz	DC - 10 MHz

The biggest difference between the photo detectors is usually shown in a responsivity curve provided by the manufacturer. Responsivity to particular light area should be sufficient to visible light detection. If the responsivity of detector is minimal in the measured area, the interfering light could be dominate and prevent the signal detection. Figure 16 shows the response curves provided from the PDA36A and the PDA10A detector [42] [69]. In the figure, the response of detector was related to the relative light output of a LZC-00MC40 RGB LED [52]. The figures show the PDA10A PIN diode is about 130 % and the PDA36A about 60 % more responsive to red than blue wavelengths of light which suggests to use the red rather than the blue light to VLC. Still, both detector have peak wavelengths on the infrared area meaning the IR filtering should be need for reducing the noise produced from the infrared radiation. In this testbed, the infrared is filtered by coating the receiver lens with optical filtering material.

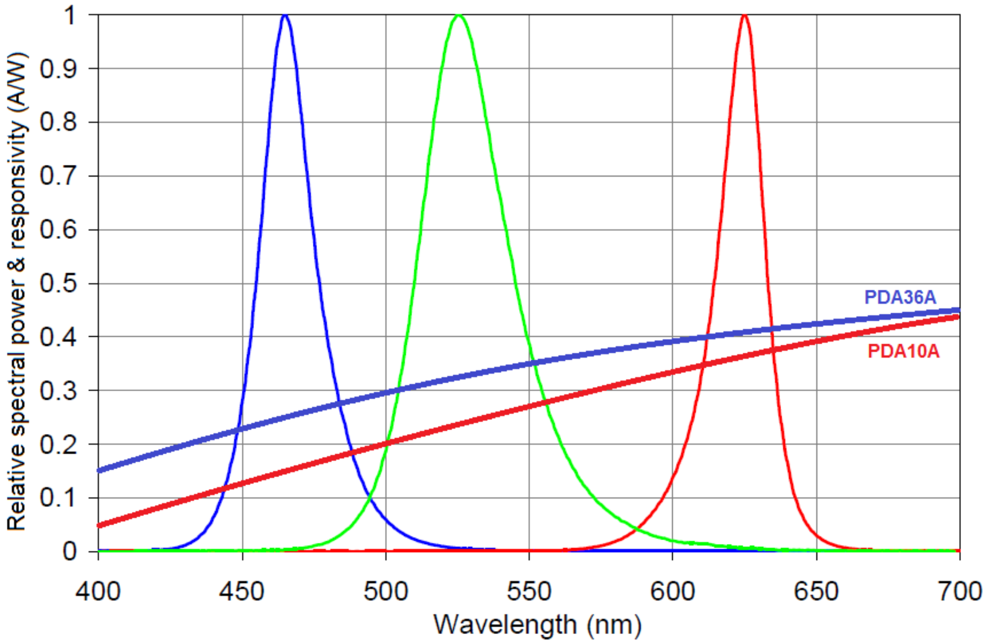


Figure 16. Photo detectors PDA36A and PDA10A responsivity to and relative light output of a LZC-00MC40 RGB LED.

A much better responsivity and a wider bandwidth were provided by the avalanche photo detectors (APD). The avalanche diodes are so responsive that it can be manufactured in minimal size and still getting enough gain to detect light for the VLC. The small size leads to minimal internal capacitance which makes the component faster with faster response time. A drawback of APD is its high price.

A Thorlabs avalanche photo detector APD110A2, responsivity shown in Figure 17, was also implemented in this testbed. The highest responsivity of the detector is 25 A/W in 700 nm wavelength which means over 50 times enhancement compared to the photodiode detectors used in the testbed. [70]

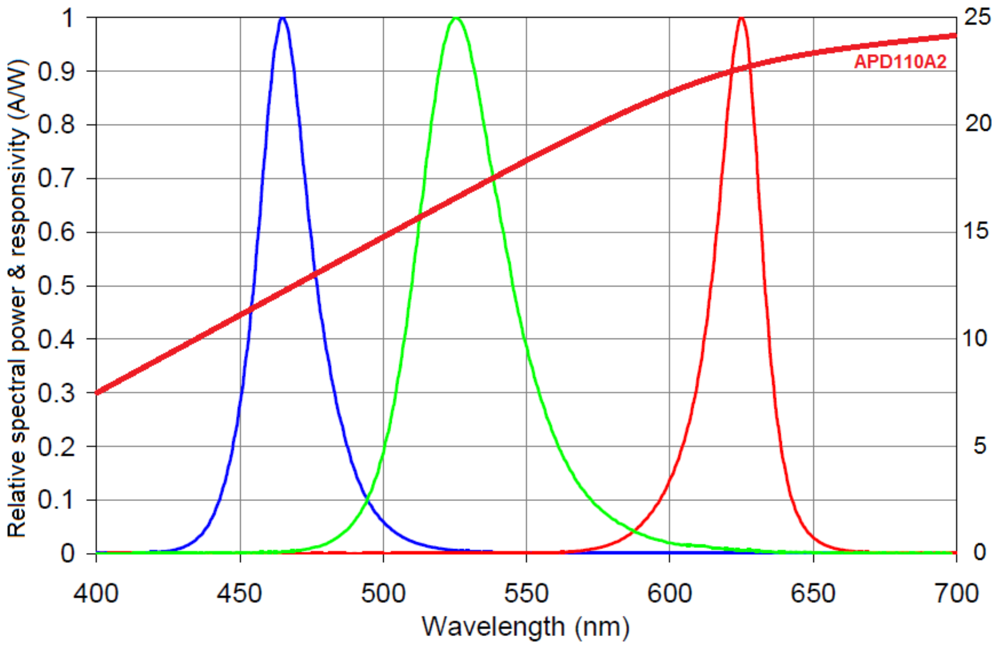


Figure 17. APD detector APD110A2 response curve and relative light output of a LZC-00MC40 RGB LED.

Other main specifications on the APD are shown in Table 6 [70]. One weakness of the APD is the saturation even from the ambient light. It would be necessary to use some optical filters to avoiding saturation and enhancing a dynamical detection range of the detector. The filtering could even be adaptive to adjust itself to changing lighting conditions. This, however, is a challenging to implement.

Table 6. Specification of an APD11A2 detector

Photo detector	**APD110A2**
Wavelength Range	200 - 1000 nm
Detector Size	diameter 1.0 mm
Gain	Fixed: 100 kV/A with Hi-Z Load, 50 kV/A with 50 Ω Load
Bandwidth Range	DC - 50 MHz

One interesting case of the VLC detection is to use solar panels not only harvesting the energy but also detecting the VLC information signals. One solar panel was tested during the project. Data rates around 1 Mbps were successfully achieved with the GMSK modulation proving the feasible detection and a future use of them. The idea could be used to combine VLC detection to the energy harvesting as the VLC can be combined to the lighting which allowing to design energy efficient communications.

3.2.3. Signal amplification

Detected communication signal can be amplified for a proper demodulation. Amplification can be made in three different places in the testbed. The first place is to use amplifiers inside the detectors. The second way is to use internal hardware of the USRP device. Third place is to use an external amplifier connected between the detector and the USRP.

The most common signal amplification type is transimpedance amplification. A transimpedance amplifier can be implemented with an operation amplifier with a feedback resistor. The amplification gain can be changed by switching the feedback resistor of the circuit. [64]

PDA36A-EC switchable gain photo detectors are used in testbed. In the detectors a low noise transimpedance amplifier is embedded in the packet of photo detector. The amplifier gain can be adjusted from 0 dB to 70 dB in 10 dB increment steps. It has a drawback when using the detectors amplifier. Gain setting adjustment affects to the bandwidth of the detector as shown in Table 7. Increase of gain narrows the bandwidth which rejects the use of gain setting. That means usable gain settings in this testbed could be 0, 10 or 20 dB. [42]

Table 7. Gain settings of a PDA36A detector

Gain	**Bandwidth**
0 dB	10 MHz
10 dB	5.5 MHz
20 dB	1 MHz
30 dB	260 kHz
40 dB	150 kHz
50 dB	45 kHz
60 dB	11 kHz
70 dB	5 kHz

Another amplified detector PDA10A has been used in the testbed. It has a fixed amplification gain 10 kV/A or 5 kV/A depending on a load resistance [69]. The APD110A2 detector has 100 kV/A gain to a high impedance output and 50 kV/A to the 50 ohm output [70].

Using software for adjusting amplification in the USRP device is the most practical way to implement receiver amplification in the testbed. GNU Radio and Python software have parameters to adjust the amplification values which adjusting the embedded programmable amplifiers in the USRP devices. Adjustment range is about 0 dB to 31.5 dB in NI-USRP-2920 devices and an automatic gain control (AGC) can be also use [72]. The AGC allows the software to adjust gain setting during the communication, which enhance the mobility in the testbed.

For better amplification in mobility cases, an adaptive external amplifier could be used. The adaptive amplifier changes the amplification when input of signal is changing. It also could be used to filter interfering DC component of the signal. One simple idea is to add an adaptive minimum voltage detector for tracking minimum voltage level of signal and a differential amplifier to remove the voltage [73]. When using the circuit and OOK modulation, the receiver was insensitive to sunlight and indoor fluorescent light [73].

3.2.4. Electrical signal filtering and post-equalization

Some electrical filtering issues have been implemented in the testbed. The idea is to reject interfering signals and pass only the data signal. In the testbed there can be use internal filters of the USRP or some external filters. The internal filters are easy to adjust with software, but it uses resources of computer and USRP. The external filters do not demand computers resources, but adjusting the value of frequencies means changing the components.

The most effective way to enhance the received signal is to filter DC component from it. It can be made by adding a high pass filter or a blocking capacitor to the system. The blocking effect of capacitor has been explained in the LED driver hardware section. The high pass filter blocks the signal under cutoff frequency and passes all higher frequencies. These easy methods cannot be used with some modulations which have significant DC components like OOK [73]. When using continuous modulation like the GMSK, this method can be used and was used in this testbed.

Interfering low frequency signals from artificial lights can be also filtered with a high pass filter. To implement this kind of filter into the VLC testbed, the cutoff frequency of filter could be adjusted to near 1 MHz. When using a Basic-RX daughterboard in receiver, the frequencies lower than 1 MHz will also be attenuated [74].

The post-equalization can be used to help synchronization and demodulation by enhancing the detected signal. In [75], authors achieved 10 Mbps data rates when using a common 1 MHz bandwidth phosphor coated white LED with and the OOK modulation and 0.1 meter distance after implementing a basic RC-equalization with a pre-distortion scheme. Data rates over 100 Mbps have been also achieved by using some post-equalization schemes to enhancing the OOK demodulation [60].

In this work, a post-equalization scheme was measured with comparing the EVM percent to the symbol rate from with and without the post-equalization received GMSK modulated signals. The results are shown in the Figure 18.

From the measured results shown in Figure 18, the post-equalization improved the EVM values significantly by providing even over 15 dB enhancements to the signal detection. The EVM rate was from 65 to 70 % lower with post-equalization than without it in all tested symbol rates.

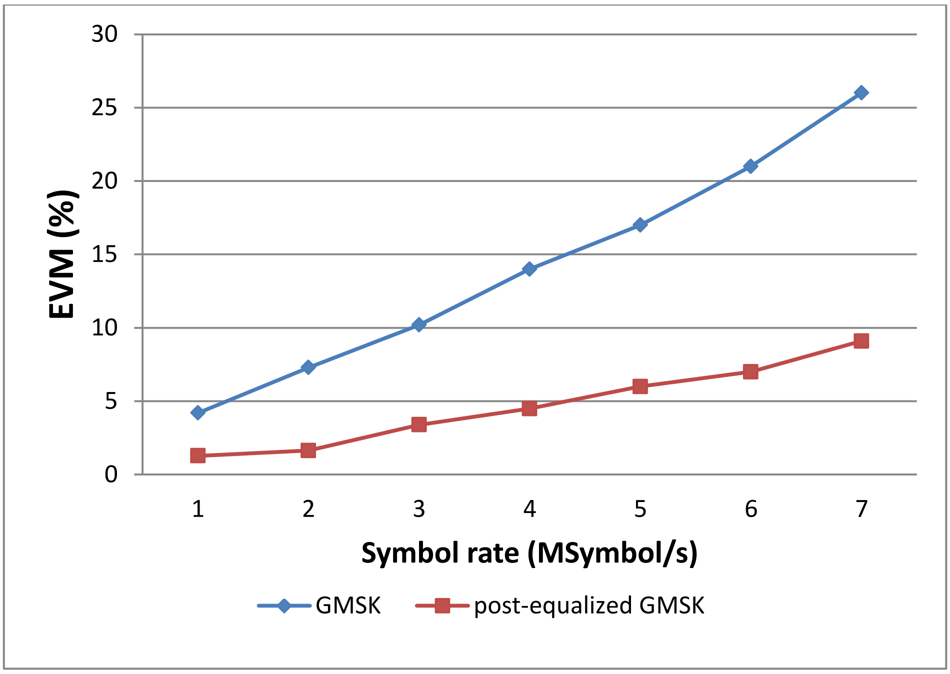


Figure 18. EVM measurements for non-equalized and post-equalized GMSK modulated signal.

3.3. Signal processing

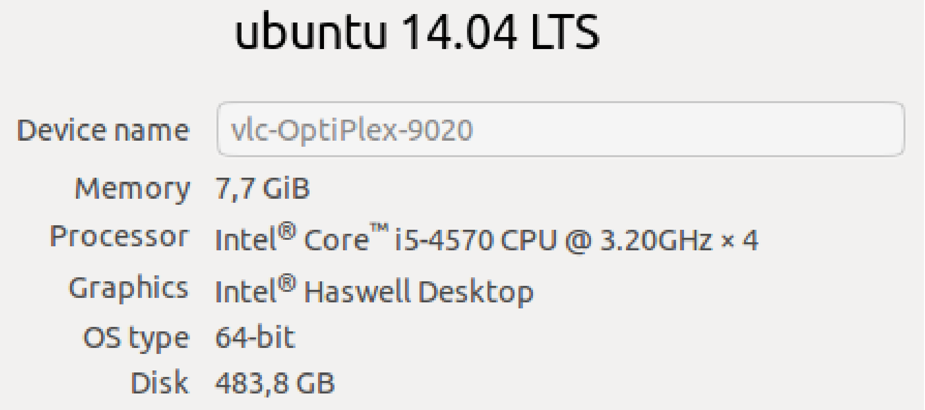
Signal processing is always needed when sending or receiving any digital information data signals. In this testbed, the signal is processed by using the USRP device connected to the personal computer in the both transmitter and receiver side. The hardware and software of the used signal processing in the testbed is defined and explained separately in next sections. Also, the maximum theoretical data rates provided by the equipment are defined.

3.3.1. Signal processing hardware

The physical signal processing is handled by using Dell OptiPlex 9020 computers connected to a USRP N210 and a NI-USRP 2920 software defined radio (SDR) devices through 1 Gbps Ethernet connections. The Dell computers are basic business class desktop computers with i5 quad core processors and 8 GB system memory [76]. The USRP devices are networked series SDR equipment with embedded FPGA processors [72] [48]. The USRP N210 and the 2920 devices are physically similar equipment between each other only manufactured by different corporations [48] [72]. The device software is different, but still interchangeable. The both equipment were updated to use the same software provided by Ettus Research [77].

The use of the SDR equipment requires a lot of processing power from the host PC, especially when utilizing high sampling rates. The use also requires a fast 1 Gbps Ethernet connection between the PC and the USRP without any delays from external switches or routers to transmit and receive the communication samples. After developing the testbed with some older dual core computers and with the limiting effect of them, the newer computers were utilized to improve the results.

The utilized Dell OptiPlex 9020 computers were running Ubuntu 14.04 LTS operating systems. The main details of the OptiPlex 9020 computer are summarized in Figure 19 explaining the hardware needed to get the results from the testbed.



ubuntu 14.04 LTS

Device name: vlc-OptiPlex-9020

Memory: 7,7 GiB

Processor: Intel® Core™ i5-4570 CPU @ 3.20GHz × 4

Graphics: Intel® Haswell Desktop

OS type: 64-bit

Disk: 483,8 GB

Figure 19. Main details of a Dell OptiPlex 9020 computer.

The USRP devices working by default from 50 MHz to 2.2 GHz frequency range which will be a bit high for the VLC testbed. To achieve low frequencies from DC to some 100 MHz the hardware of the USRP device need to be modified by changing RF daughter boars. The USRP RF daughterboards define systems frequency range, bandwidth and number of useful communication channels. In this testbed, four different daughterboards were used. Table 8 specifies the utilized daughterboards, frequency ranges and maximum bandwidths of them. [74]

Table 8. USRP RF daughterboards

	Frequency range	**Bandwidth**
LFTX	0 - 30 MHz	30 MHz
LFRX	0 - 30 MHz	30 MHz
BasicTX	1 - 250 MHz	100 MHz
BasicRX	1 - 250 MHz	100 MHz

Maximum theoretical bandwidth of the testbed is 30 MHz when using LFTX and LFRX daughterboards and 100 MHz when the BasicTX and the BasicRX daughterboards were utilized. The USRP N210 and NI-USRP-2920 devices host sampling rate is 25 MS/s with 16 bit samples and 50 MS/s with 8 bit samples limiting system bandwidth to the 12.5 MHz and a bit rate to the 12.5 Mbps in this type of use. In duplex mode, like when using bi-directional testbed, the maximum sampling rate will be limited to 25 MS/s which will allow the maximum bit rate of 12.5 Mbps for both up- and downlink. [48]

To achieve higher bit rates than 12.5 Mbps, which is limiting the results of this testbed, some SDR device with a higher sampling rate and faster interfaces should be utilized. For example an Ettus Research X300 device could allow communication even to 200 MS/s full duplex sampling rates through PCIe Express or dual 10 Gigabit Ethernet interfaces [78]. With the BasicTX and –RX card the data rate of 100 Mbps could be achieved. It will be also related to the calculation power of a host computer and its interfaces. With a single Gigabit Ethernet access, the sample rate cannot be improved from rate with the N210 or NI-USRP 9020 devices. The communication between a USRP device and a host computer demands a very high speed connection to work well.

3.3.2. Signal processing software

Connectivity from several software frameworks, presented in Figure 20, to the USRP devices are provided via UHD and NI-USRP hardware drivers. The drivers are installable to Linux, Mac OSX and Windows platforms which grant a universal connectivity to the devices. The UHD driver can be used with GNU Radio, MATLAB, Simulink and Python codec software and the NI-USRP with the LabVIEW software. The both driver are compatible and installable in the National instrument's and the Ettus Research's USRP devices. [77]

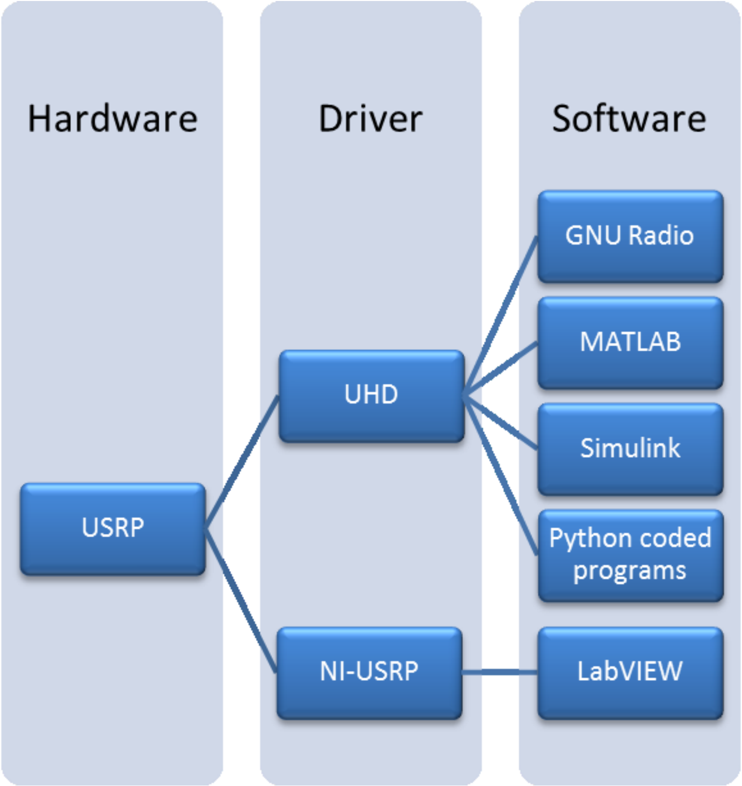


Figure 20. Software connectivity to the USRP devices.

During the implementation process, the GNU Radio and the Python code based software were mainly used in testing and measuring the functionality of the testbed. Use of MATLAB, Simulink and LabVIEW were left as options to be used in the future research. The open-source software GNU Radio was easy to adopt in the testbed and its communities are providing loads of support and examples for setting up different kind of communication systems. Python coded programs were also easy to use and it is providing even better results in testing purposes than GNU Radio. The GNU Radio has an adaptable graphical interface for producing software to use with the USRP devices. The graphical interface gives user an ability to use predefined communication blocks and by connecting them together enables a whole communication link.

Some Python coded programs were used in measuring purposes in the testbed and a program was used to handle TCP/IP connection between two USRPs and computers. Programs named benchmark_tx.py for the VLC transmitter and benchmark_rx.py for VLC receiver were used for measuring quality of the communication link. The programs were easily used in terminal windows of Ubuntu system. The use of the program only needs some parameters to add before running the program. The parameters which were mainly added and adjusted were the center frequency of transmitted signal, the bit rate, the amplitude and the used modulation as the other parameters were left to its default values. The results from received data were provided by benchmark_rx.py program to a terminal window. The results show how many data packets were received and how many of them were received without errors. There is a cyclic redundancy check (CRC) code included in data stream to show error induced in data packets. A Python program named tunnel.py was used to handle TCP/IP connection in bi-directional tests.

The USRP device and the software related to it have lots of possibilities to calculate and observe the shape and quality of a received signal. The three main tools for observing the signals were used inside the GNU Radio software platform: a Fast Fourier Transforming (FFT), a signal constellation plot and a signal scope. The FFT was the best tool for showing bandwidth and amplitude of the signal like shown in Figure 21. The constellation plot, an example shown in Figure 10, presented well the alignment of the constellation points. The signal scope was used for observing the received signal itself in time domain.

There were also some tools in the GNU Radio software for calculating the error rates of the communication. For example, a bit error rate (BER) and symbol error rate (SER) calculations can be used to present the quality of the communication. The GNU Radio containing good examples and model blocks for the error calculations, but the models cannot be used with separated computers like the one is handling the transmitting and the other receiving. The reason for that is the need for reference signal from transmitted data signal.

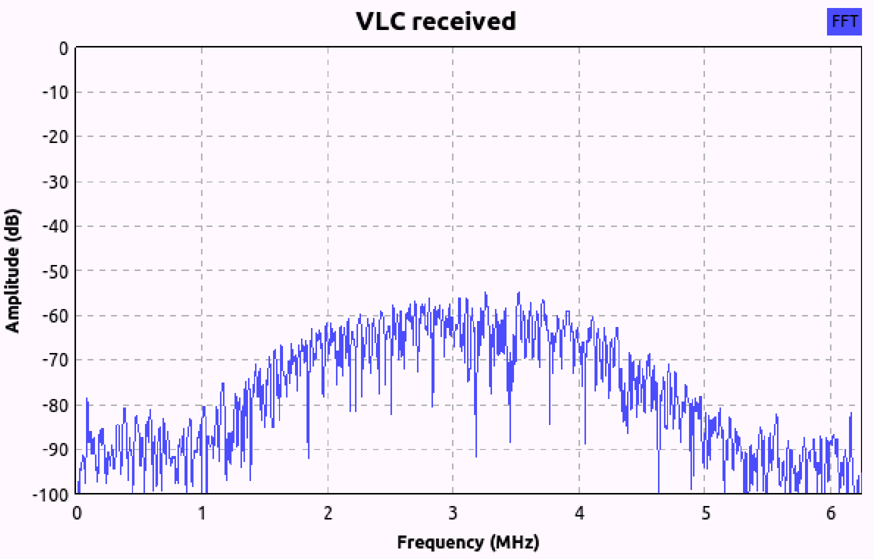


Figure 21. FFT from a received GMSK signal at 3.125MHz center frequency.

4. RESULTS

The result from this designing and implementation project is a versatile visible light communication testbed which provides a flexible platform to future work with the VLC and with the VLC combined to RF and IR communications. The results will be presented by separating them in two different parts. The first part will present VLC light channel measurements providing comparison measurements for the VLC testbed. The second part presents configurations and results from the five different types of implemented SDR testbeds. The first SDR testbed was made for measuring the packet error rate and quality of VLC link. The second testbed was designed for uni-directional video streaming. The third variation is providing a bi-directional Li-Fi internet connection through the VLC or IR channels. The fourth testbed go a bit further for connecting light infrastructure with power line communication (PLC) when providing the bi-direction Li-Fi access with integrated PCL connection. The fifth testbed provides an idea about a platform to research the hybrid channel networks. Figure 22 depicts the basic structure of the testbed.

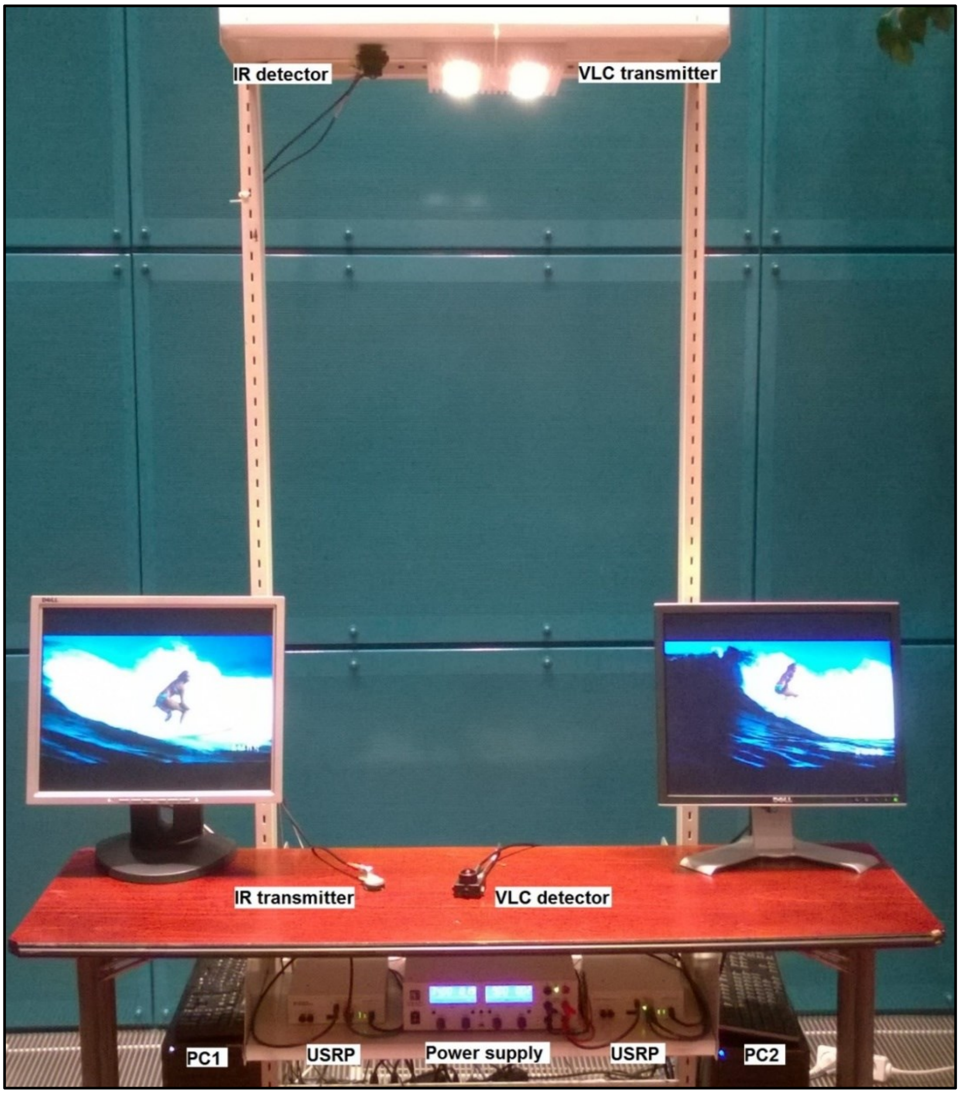


Figure 22. The implemented visible light communication testbed.

4.1. VLC measurements

Basic measurements were done for deepening the understanding of the VLC and the light propagation channel by transmitting modulated information signals from a Rohde&Schwarz SMIQ06B signal generator through the Bias-T to a LED and receiving the intensity changes with the PDA36A photo detector connected to an Agilent E4446A PSA Series spectrum analyzer and Agilent 89600 VSA 16.0 software. The analysis bandwidth for the measurements was limited to 8 MHz by the spectrum analyzer.

EVM results as a function of distance for Osram Star LED is presented in Figure 23. From this result, it can be seen that QAM is outperforming the other modulation candidates. The GMSK, BPSK, QPSK and 8-PSK also provided good EVM results in VLC use. It provided feasibility to implement modulation methods to the VLC testbed. The results cannot be compared to results from VLC testbed, because the system uses different amplification levels, pulse shaping and detection filters. For example the GMSK uses Gaussian filter and the other uses root-raised-cosine filter for pulse shaping and detection. However, further investigation is still needed to verify the suitability of other modulation techniques in different conditions and with different types of post processing such as equalization and filtering.

Comparative measurements, shown in Appendix 1, were done with VLC testbed. The results showed the GMSK performed as the best and the QAM had lack of its performance. The results proved the need for future measurement work with VLC.

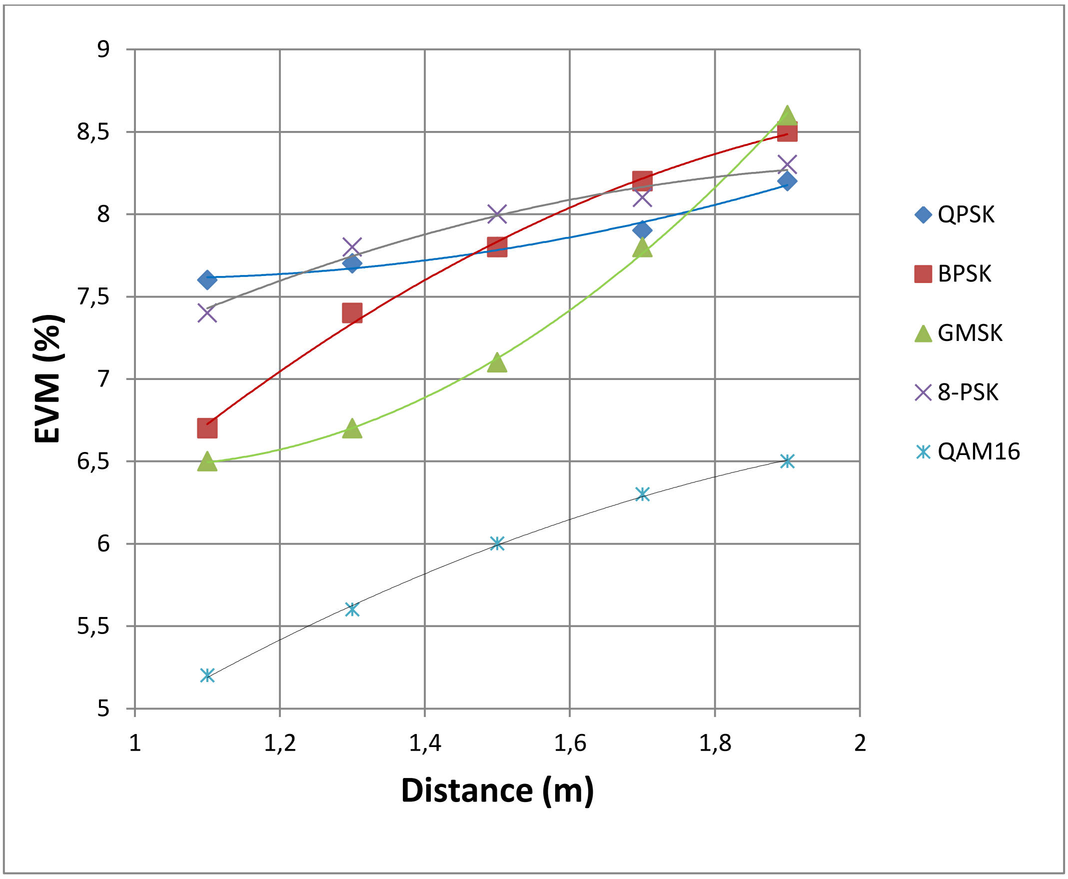


Figure 23. EVM measurements for QPSK, BPSK, GMSK 8-PSK at 2 MHz frequency and 2 MSymbol/s rate with an Osram Star LED spot.

4.2. Software defined VLC testbeds

Five VLC testbed variations were implemented for measuring and demonstrating purposes using the designed VLC testbed structure on the software defined USRP devices. All five SDR testbeds variations can be used and modified easily for future needs. Measurements and implementations will be easy to make in the testbed when obeying the limitations explained in Table 9. The implementation process was quite fast after the basic knowledge for the USRP devices and software were studied. If the knowledge has learned from earlier experienced for example from RF implementation with the same equipment the transition to the VLC will be very fast. The use and implementations will be cost efficient because the testbed based on software defined radio devices.

Table 9. Limitations of the testbed

Parameter	**Value**	**Limiting component**
LED voltage	48 V	Capacitor in the Bias-T circuit
LED current	1.05 A	Inductor in the Bias-T circuit
Data bitrate (GMSK)	12.5 Mbps	Maximum USRP sample rate is 25 MS/s
Horizontal distance	0 – (7m)	Light power and optics (achieved)
Vertical offset	0 – (20 mm)	Optics of the light detection (achieved)

The most limiting feature in the testbed is the maximum sample rate of the USRP device. The sample rate limited the measured data rates to the 12.5 Mbps in the GMSK modulation. With a modulation technique carrying higher amount of bits per symbol, the data rate could be increased. The current and voltage limits could be adjusted by changing components inside the Bias-T circuit, but it is not be preferred solution to increase the power levels as it will increase health risks.

Another main goal of this VLC project was to provide ability for video streaming through the VLC channel. The video stream will be an illustrative example for demonstrating visible light communication by allowing the observer to block the light and see how it affects the communication. A video demonstration has been arranged several times during the project creating a lot of interest. The demonstration has also been running two days in a University of Oulu “Abipäivät” –event.

4.2.1. Packet error rate testbed

Measuring a bit or packet error rate is a good method for calculating quality of the communication link. It will also show the limits of the system and gives indications for finding solutions to further develop the system. Because the VLC testbed has so many parameters and components to change, we have to get a way to measure the effect of the parameter and component alterations. Result of the error rates are recorded using different link distances, bit rates, light intensities and LED light sources. The measurements were first made using the VLC testbed and then compared it to results of the light link replaced with a cable connection. In this way, the light link error rates were isolated and the overall systems weaknesses did not affect to the measurements.

The packet error rate testbed was built up using the same structure as the other testbeds using the USRP devices and appropriate software. The Python example program benchmark_tx.py was used to send data packets from transmitter side and the benchmark_rx.py to receive the packet and show the results of the communication. The results showed how many data packet were successfully received and how many of them were received with errors. There are two ways for errors reporting in the software. First report counts successfully received access codes and headers and the second report indicates whether the CRC32 of the payload was correct. The results were collected from the program by counting the value of how many transmitted packet were received correctly. [49]

Codes and parameters for using the benchmark software are presented in this work for allowing an easy access to the testbed for future users. An example command to be executed to running the benchmark software is:

```
#open the folder containing the benchmark_tx.py file
cd /usr/share/gnuradio/examples/digital/narrowband
#execute the program
./benchmark_tx.py -addr=192.168.10.4 -m gmsk -f 6.25M -r 6.25M --tx-amplitude=1 –M 100 -v
```

For running the receiver part of the packet error rate testbed, the commands below, can be used.

```
#open folder containing the benchmark_rx.py file
cd /usr/share/gnuradio/examples/digital/narrowband
#run the program with a command
./benchmark_rx.py -addr=192.168.10.2 -m gmsk -f 6.25M -r 6.25M -v
```

The main parameter, which were used during the measurements sessions are shown in Table 10. In the table, the main parameters and its value ranges are shown in the first four columns. The fifth column is providing some extra arguments without its values.

Table 10. Benchmark_tx.py and benchmark_rx.py command line arguments

-m modulation	**-f center frequency**	**-r bitrate**	**--tx-amplitude gain min-max**	**extra arguments:**
BPSK	≥ 1M	0,390625M	≥ 0	-M amount of data
GFSK	≤ 250M	0,78125M	≤ 1	-S size of data packet
GMSK		1,5625M		-v verbose
QPSK		3,125M		-addr USRP address
PSK		6,25M		-p number of constellation points
QAM		12,5M		--rx-gain receiver gain

Some measurement results and usable software parameters are provided in Appendix 1 to prove the functionality of the testbed.

4.2.2. Video stream testbed

A main goal of this VLC project was to demonstrate video streaming through the VLC channel. The video stream will be an illustrative example for demonstrating visible light communication by allowing the observer to block the light and see how it resulting to the communication.

The bandwidth and quality of the VLC broadcast link should be good enough for high-definition (HD) video stream which means the streaming bit rate is about 2 Mbps for 720p HD video and around 6 Mbps for higher quality 1080p HD video. The data rates also depend on used video codecs and which type of audio stream is included in it. A distance between transmitter and receiver should be about 2 meters and offset is not too directed to easy installation and use.

A structure of the software inside the video stream testbed is shown in Figure 24. To get continuous streaming to work, the video was first streamed to the local host of the PC with using an UDP stream. The stream was inputted in the Gnu Radio, the signal processed and the stream sent to the UHD driver. The UHD driver streamed the generated samples through Gigabit Ethernet to the USRP devices and the VLC transmitter.

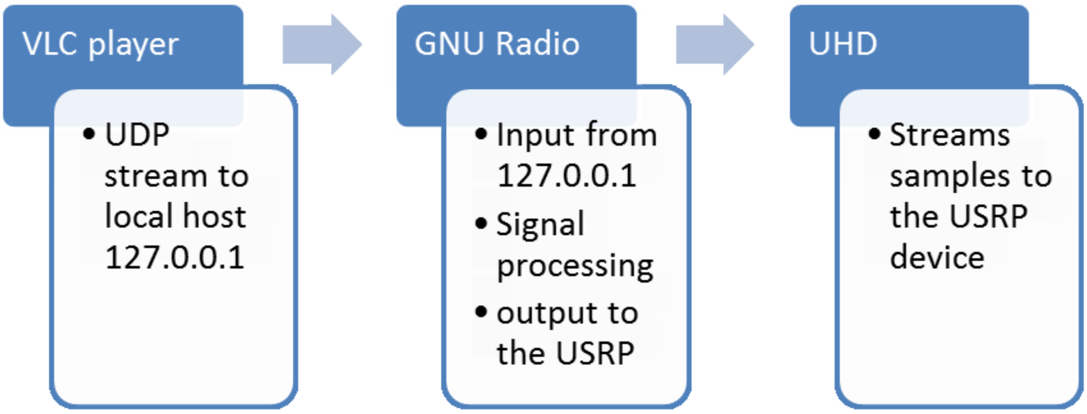
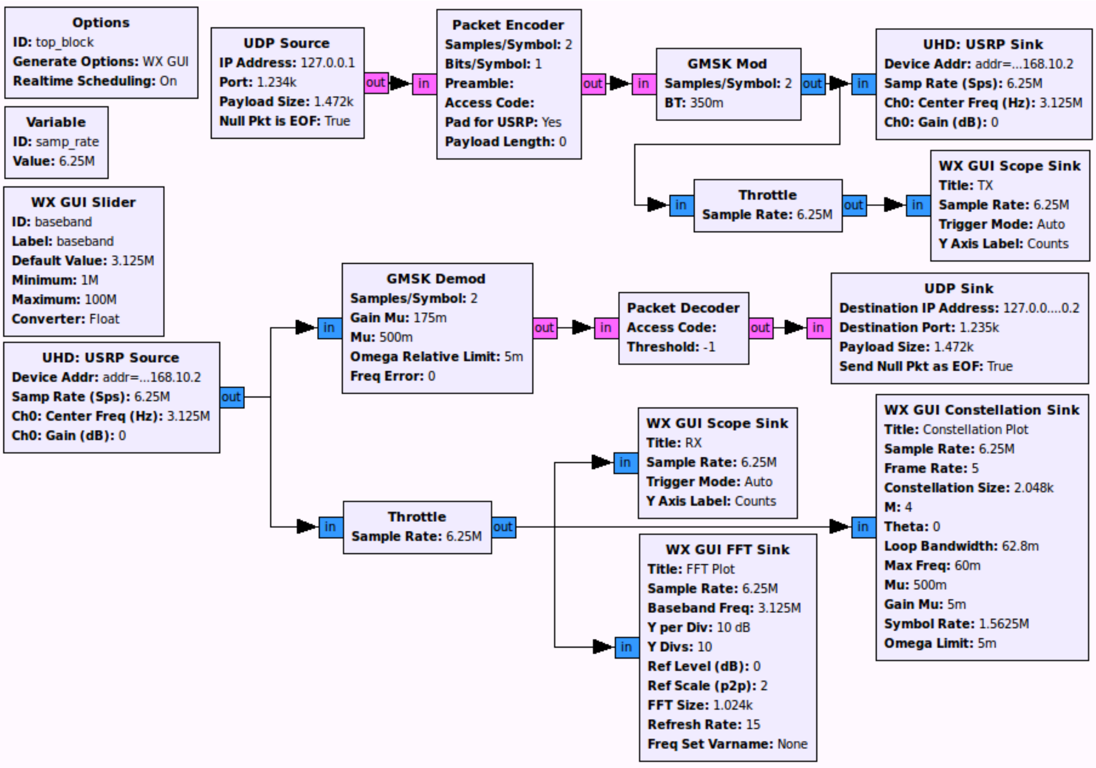


Figure 24. Software for video streaming.

The Figure 25 demonstrates a GNU Radio block diagram used to handle video streaming from the VLC player to the USRP device. Both transmitter and receiver ends are shown in the same figure because the videos can be streamed to the both directions at the same time. The video stream transmitter block diagram contains four blocks on the upper right corner of the Figure 25, while the “Throttle” and the “WX GUI Scope Sink” were only connected to analyze the transmitted signal and to show the condition of the UDP streaming. The first block named “UDP Source” was set to provide an input of the UDP stream packets from the local host. The “Packet Encoder” was set to wrap the data received from “UDP Source” to a packet and put a header, an access code and a preamble to it. As the data packets were coded, the signal was modulated in the “GMSK Mod” block. After the modulation block, the signal was transmitted to the UHD driver with using a “UHD: USRP Sink” block.

The video stream testbed receiver structure of the GNU Radio block diagram was defined in Figure 25. The detected and received information signal was input from the USRP and the UHD to the block diagram in the “UHD: USRP Sink” block. Then the signal was demodulated in “GMSK Demod” and decoded in “Packet Decoder”. The demodulated signal was then send to UDP local host via “UDP Sink”. If no errors occur, the video can be viewed from the local host address.


Options
ID: top_block
Generate Options: WX GUI
Realtime Scheduling: On

Variable
ID: samp_rate
Value: 6.25M

WX GUI Slider
ID: baseband
Label: baseband
Default Value: 3.125M
Minimum: 1M
Maximum: 100M
Converter: Float

UHD: USRP Source
Device Addr: addr=...168.10.2
Samp Rate (Sps): 6.25M
Ch0: Center Freq (Hz): 3.125M
Ch0: Gain (dB): 0

UDP Source
IP Address: 127.0.0.1
Port: 1.234k
Payload Size: 1.472k
Null Pkt is EOF: True

Packet Encoder
Samples/Symbol: 2
Bits/Symbol: 1
Preamble:
Access Code:
Pad for USRP: Yes
Payload Length: 0

GMSK Mod
Samples/Symbol: 2
BT: 350m

UHD: USRP Sink
Device Addr: addr=...168.10.2
Samp Rate (Sps): 6.25M
Ch0: Center Freq (Hz): 3.125M
Ch0: Gain (dB): 0

Throttle
Sample Rate: 6.25M

WX GUI Scope Sink
Title: TX
Sample Rate: 6.25M
Trigger Mode: Auto
Y Axis Label: Counts

GMSK Demod
Samples/Symbol: 2
Gain Mu: 175m
Mu: 500m
Omega Relative Limit: 5m
Freq Error: 0

Packet Decoder
Access Code:
Threshold: -1

UDP Sink
Destination IP Address: 127.0.0....0.2
Destination Port: 1.235k
Payload Size: 1.472k
Send Null Pkt as EOF: True

Throttle
Sample Rate: 6.25M

WX GUI Scope Sink
Title: RX
Sample Rate: 6.25M
Trigger Mode: Auto
Y Axis Label: Counts

WX GUI FFT Sink
Title: FFT Plot
Sample Rate: 6.25M
Baseband Freq: 3.125M
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 1.024k
Refresh Rate: 15
Freq Set Varname: None

WX GUI Constellation Sink
Title: Constellation Plot
Sample Rate: 6.25M
Frame Rate: 5
Constellation Size: 2.048k
M: 4
Theta: 0
Loop Bandwidth: 62.8m
Max Freq: 60m
Mu: 500m
Gain Mu: 5m
Symbol Rate: 1.5625M
Omega Limit: 5m

Figure 25. GNU Radio block diagram of the UDP stream structure.

There are two parameters which should be adjusted in the streaming block diagram of the GNU Radio. The most important value of the GNU Radio is a sample rate. The value defines a maximum available sampling rate of the block diagram and limiting the bit rate to the half of the sample rate. The sample rate should be twice as high as the highest information rate. This meaning the maximum video bit rate of the stream should be lower than half of the sample rate. Changing the value will highly affects to the load of the PC. The other parameter to need to be changed is a center frequency of the USRP device. The frequency should be as high as the bandwidth of the information signal is fitted in the communication band. All other parameter should be left to their default values in this setup.

Evaluating and testing video codecs is quite challenging because there is a huge variety of encoder and decoder software and video codec types available. Another challenge is that all the available codecs use a variable bit rate coding (VBR), but the GNU Radio software sends data in using a constant bit rate. A better choice for the codec type would be a constant bit rate (CBR) codec, but there was none available when writing this. VideoLAN organization streaming features lists helps evaluation process [79]. An exclusionary selection style was used to find the best video stream codec for the testbed. The first rough selection was made for finding a container type for packaging video, audio and subtitles in a file. Container types transport stream (TS) and Raw allows streaming for UDP which were used in this testbed. Second selection was the video and audio codecs included in the container. The selected combinations of the available containers and the formats are shown in a Table 11.

All four video and three audio formats were tested in the VLC testbed. The best combination for streaming was obtained when using the H.264 video and AAC audio formats.

Table 11. Video stream container and codec combinations [79]

Container type		**TS**	**Raw**
Video format	MPEG-1 video	Yes	Yes
Video format	MPEG-2 video	Yes	Yes
Video format	MPEG-4 video	Yes	Yes
Video format	H.264/MPEG-4 AVC	Yes	No
Audio format	MPEG Layer 1/2/3 audio	Yes	Yes
Audio format	AC3 (i.e. A52)	Yes	Yes
Audio format	MPEG-4 audio (i.e. AAC)	Yes	No

4.2.3. Bi-directional Li-Fi testbed

A bi-directional light fidelity (Li-Fi) testbed provides TCP-IP internet connections through a host PC to a client PC using the bi-directional VLC link and dedicated software. The VLC link handles the physical OSI layer of the communications and the software the other layers of the OSI model. The testbed structure is shown in Figure 26. This was made for demonstrating a wireless internet connection from a commercial LED light bulb.

To ensuring an easy use of the Li-Fi testbed, all software commands needed for running the Li-Fi testbed were written in a single file. It only needs to double click a file in the host and the client PC to get the Li-Fi connection running. There is some explanation inside the code to explain the purpose of the commands. The command are divided into client and host portions and presented below.

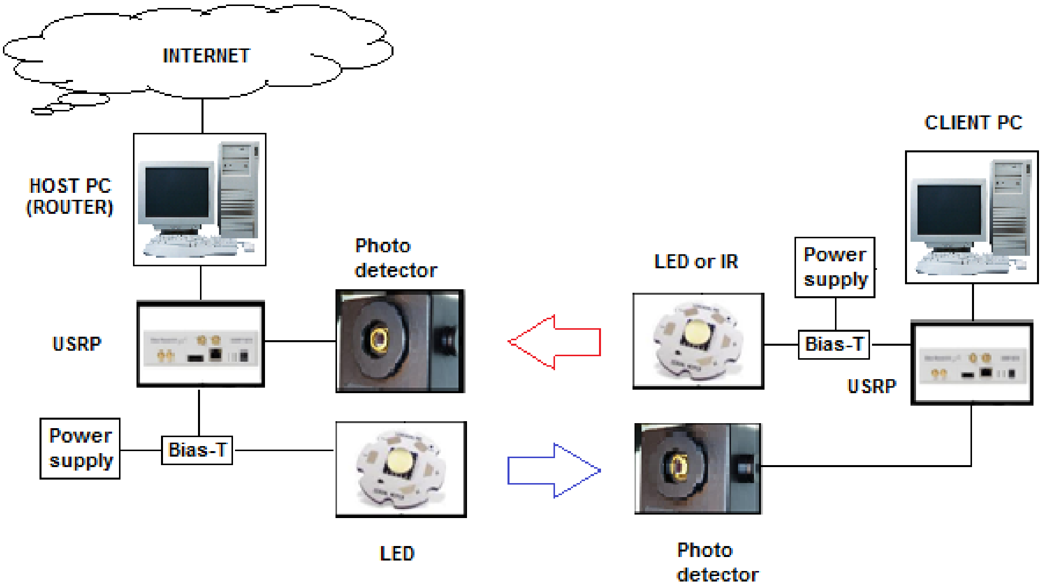


Figure 26. Li-Fi testbed.

1. Terminal commands to run Li-Fi testbed on the host PC

```
#!/bin/sh
#open new terminal and put it wait for ip configuration command
sudo echo "starting vlc demo... "xterm -e sleep 5 && sudo ifconfig gr0
192.168.200.2 &&
#set IP forwarding and run tunnel.py
sudo sh -c "echo 1 > /proc/sys/net/ipv4/ip_forward" & sudo
/usr/share/gnuradio/examples/digital/narrowband/tunnel.py -f 3.125M -r 3.125M -
v --tx-amplitude=1
```

2. Terminal commands to run Li-Fi testbed on the client PC

```
#!/bin/bash
#replace resolv.conf from preconfigured file to set the DNS addresses
sudo cp /etc/resolv.conf.vlc.backup /etc/resolv.conf
#open second terminal and leave it wait to the IP configuration
xterm -e sleep 6 && sudo ifconfig gr0 192.168.200.1 && sudo ip route add default
via 192.168.200.2 dev gr0 & echo "Settings for vlc client ..." && sleep 1
#run the tunnel.py
sh -c "sudo /usr/share/gnuradio/examples/digital/narrowband/tunnel.py -f 3.125M
-r 3.125M -v --tx-amplitude=1"
```

The IP address configurations in the testbed are shown in Table 12 to clarify the network configurations. The PC and the USRPs have static IP addresses but the TUN/TAP driver addresses are set after the tunnel.py program is launched.

Table 12. IP configurations of the testbed

Address	**Host PC**	**Client PC**
PC	192.168.10.6	192.168.10.5
USRP	192.168.10.2	192.168.10.4
TUN/TAP driver	192.168.200.1	192.168.200.2
External IP to the internet	x.x.x.x	No direct internet connection

4.2.4. Power line communication testbed

A power line communication (PLC) is a cost efficient way to implement VLC to the infrastructure of buildings, offices or houses. The PLC uses electrical wires for transmitting information providing power to electrical equipment at the same time. There is no need for additional Ethernet cabling which provides cost efficient and fast implementation for VLC system. A simple implementation consists on a power line connection to internet and a light bulb customized for VLC purposes. The VLC light bulb could be made by adding a single communication circuit to a common light bulb.

In this testbed, the PLC was tested with using commercial PLC adapters which were added to connect computer and the USRP device through power lines. The idea of the structure for PLC connected VLC or Li-Fi transmitter is shown in Figure 27.

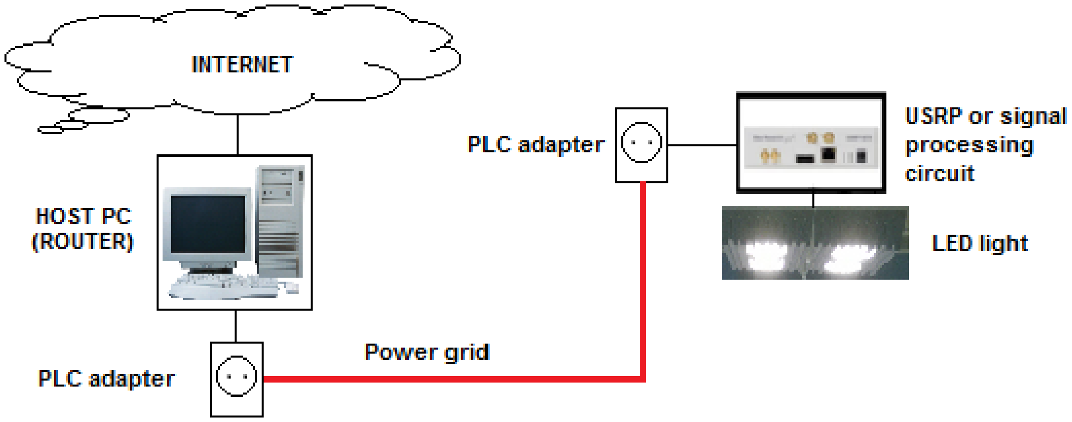


Figure 27. Power line communication connected to the VLC transmitter.

The PLC was implemented as a part of previously demonstrated testbeds. Only drawback was the achieved data rates which were limited by a connection speed of the PLC adapters. The connection speed between the PLC adapters was 600 Mbps which was not enough to connect a PC to an USRP when using faster data rates. The maximum error free VLC data rate achieved in using the PLC was about 2 Mbps. The data rates above that were causing underruns to the USRP which means the host PC cannot provide new samples through network as fast as the USRP sends them out. This clearly shows the suboptimal implementation but presents a proof of concept.

4.2.5. Hybrid channel testbed

The USRP devices provide a good platform to combine different communication schemes together and an ability to use them parallel. The idea of this testbed is to provide a platform to research directive high bandwidth VLC or IR communication together with wider coverage providing RF technique. The combination of optical and radio frequency communication will enhance the wireless communication by providing a high bit rate VLC in a determined area while the RF is providing the mobility. Also, variation between up- and downlinks could be used separately by selecting the best channel to the communication. An example of combining WLAN and VLC was proposed in [80].

The hybrid channel testbed combines VLC, IR and RF media for providing wider bandwidth and flexibility to choose the best available media for the communications. There is enormous bandwidth available for communications if combined the VLC, IR and RF media to the data transmission [14]. The technology can be used in parallel or selecting the most robust available media to the communication.

To provide undisturbed use of the media, the system must be capable to do handover between the communication schemes automatically. One idea to handle the handovers in the VLC is proposed in [81]. The designed receiver was selecting the best channel from seven color separated light channels. The switching can be done in the user space of the operating system or in the kernel level.

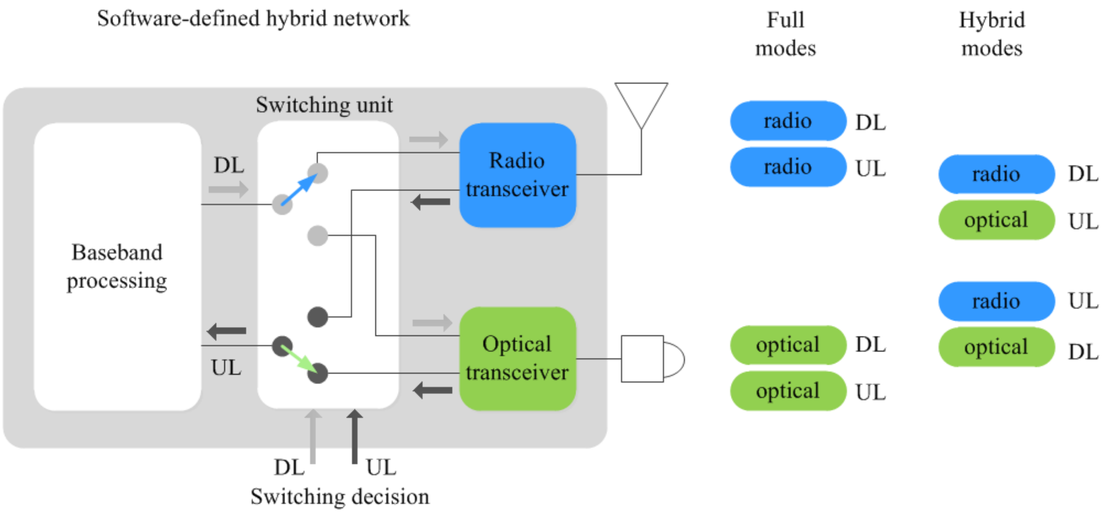


Figure 28. A software-defined hybrid network model.

5. DISCUSSION AND CONCLUSIONS

The purpose of this thesis was to provide a first practical implementation of the visible light communication at the University of Oulu. The idea was to design and implement a bi-directional VLC testbed for providing a platform to test and research the subject in the future. The testbed was designed to use software defined radio devices which allowed an easy and fast implementation and enormous abilities to change the parameters of the communication links. The SDR devices allowed also the ability to use open-source software, allowing thus cost efficient implementation. The selected implementation platform was a good choice but required large amounts of working hours to get all the software to installed and learn to use them right. After the work with the software, the future use of it will be very simple. This thesis will hopefully help and clarify future work with the testbed.

Electrical implementations of the testbed were quite clear and the basic idea of the using a Bias-T was easily founded in the literature. In the beginning of the project, some time was used for finding some specific VLC circuit diagrams or commercial offered testbeds. The limitation of them was so dominant that it would make the future work harder. After some initial tests, performance and limitations of different receiver components were analyzed and characterized and it was find out that needed voltage and power levels were sufficient to use several types of LED lighting. The first VLC implementation was made by using analog sound cards, a LED torch and a cheap photo diode.

To conclude the results, a bi-directional communication at 12.5 Mbps bit rate was successfully achieved in the testbed limited by a sample rate of the system. The result was encouraging considering the similar kind of testbeds reported in the literature. Distances of the achieved communication were between 0.5 to 7 meters depending on the used optics and utilized data rates. The solutions of optical problems were explained in this work and new ideas for better receiver optics were provided. A TCP-IP communication to the internet was also established with using light and infrared communication links. The internet connection was also established using a power line communication to provide data and electricity to the lighting through the same cable. The results from the work were obtained by using a GMSK modulation. GFSK, QPSK, 8-PSK, 16-QAM and OFDM modulation schemes were also implemented in the testbed and some initial performance results were obtained but more accurate measurements and use of them will be left as a future work.

The road from starting point to the final testbed was very long and proceeded in small steps. The project was successfully completed and the obtained results were better than anticipated at the beginning of the project. The testbed was also described and the results were presented in an article of the VLC in a newspaper Kaleva [12]. Also, a paper from results of this work has been published in the "1st International Conference on 5G for Ubiquitous Connectivity" [13]. The video stream demonstration has also been presented several times for interested people during the project.

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7. APPENDICES

Appendix 1 Packet error rate test bed measurements

Bit rate (Mbps)	Transmitted packets	Received packets	Packet error rate (PER)	Settings:
1,5625	178747	178747	0	Modulation: GMSK Tx-amplitude: 1 Voltage: 32 V Blue filter: on Packet size: 1500 bits Sensor: APD Distance: 1.15m Software: benchmark Light: Philips Ledino [56]
	56558	56558	0	
	10052	10052	0	
3,125	76664	76664	0	
	24562	24562	0	
	10225	10225	0	
6,25	400347	400347	0	
	47993	47993	0	
	10170	10170	0	
12,5	126054	126047	5,5532E-05	
	26353	26351	7,5893E-05	
	200340	200326	6,9881E-05	

1,5625	27117	27117	0	Modulation: GMSK Tx-amplitude: 1 Voltage: 31 V Blue filter: off
	29460	29460	0	
	10005	10005	0	
3,125	20562	20562	0	
	20260	20260	0	
	10015	10015	0	
6,25	27556	27556	0	
	108233	108233	0	
	10254	10254	0	
12,5	251155	0	1	

1,5625	4972	4972	0	Modulation: 8-PSK Tx-amplitude: 0.55 Voltage: 32 V Blue filter: on
3,125	3566	3566	0	
6,25	100261	100261	0	
	59420	59420	0	
	12512	12512	0	
12,5	114422	0	1	

1,5625	10067	10067	0	Modulation: 8-PSK Tx-amplitude: 0.55 Voltage: 31 V Blue filter: off
3,125	21641	21641	0	
	26423	26423	0	
	23464	23464	0	
6,25	12550	0	1	
12,5	12332	0	1	

1,5625	7655	7655	0	Modulation: GFSK Tx-amplitude: 0.9 Voltage: 32 V Blue filter: on
3,125	1933	1933	0	
6,25	64443	64443	0	
12,5	57472	57457	0,000261	
	18691	18683	0,00042801	
	10210	10205	0,00048972	

1,5625	4341	4341	0	Modulation: GFSK Tx-amplitude: 0.9 Voltage: 31 V Blue filter: off
3,125	16433	16433	0	
6,25	39841	39841	0	
	46416	46416	0	
12,5	12251	0	1	

1,5625	1230	1230	0	Modulation: 16-QAM Tx-amplitude: 0.4 Voltage: 32 V Blue filter: on
3,125	4545	4545	0	
6,25	21197	21197	0	
	35501	35501	0	
12,5	12001	0	1	

1,5625	4566	4566	0	Modulation: 16-QAM Tx-amplitude: 0.4 Voltage: 31 V Blue filter: off
3,125	1234	1234	0	
6,25	26875	26826	0,00182326	
	13333	13325	0,00060002	
	3311	3308	0,00090607	
12,5	3223	0	1	