VLC technology for indoor LTE planning

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Abstract: LTE indoor coverage, due to its importance, is becoming lately very important for cellular operator. In international literature there is a lot of research regarding VLC, especially indoor, to improve the expected throughput. To satisfy user expectations on operator's indoor high quality services and toprovide adequate capacity availability special issues have to be studied. Indoor users expect faster Internet with less interference and healthy environment.

1. Introduction

Optical communications have been used in various forms for thousands of years. Since ancient years through to Bell's Photophone introduced in 1880, people were using methods such as smoke signals or light signals in order to optically communicate over long distances. Finally, a long time later, after the invention of Light Amplification by Stimulated Emission of Radiation (LASER) sources and Light-Emitting Diodes (LED) in the 1960s, optical communications quickly revolutionized and spread around the world.

Today's optical communication technologies may be categorized into two groups: Fiber Optics and Free Space Optics (FSOs). The main difference between those two categories of optical communication technologies is the medium each of them is using in order to propagate their data. Fiber Optics is based on the optical fiber cable which it uses as a medium, while FSOs achieve their transmission over the air. They both use either LASERs or LEDs as their sources, usually at wavelengths such as Infrared (IR), Visible or Ultraviolet (UV). Both technologies have advantages and disadvantages. Fiber optics, for instance, can achieve much higher data rates than FSOs, while FSOs on the other hand are capable of achieving data transmission to places where either physical connection would be impossible to be deployed or absence of electromagnetic radiation is important or requested. Engineers around the world dealing with FSOs, fortunately tried to use LEDs at the visible spectrum as information sources anyway.

Since Physics provided us with the information that common incandescent light bulbs or even the more efficient fluorescent lamps would hardly be appropriate for that purpose, due to the poor, for data transmission, characteristics of the photons creating their illumination, the only way of using them as a source for FSOs was to force them to blink, in order to decode every instance of changing light condition as a bit of information. Apparently, these kind of regular light bulbs could not be turned on and off more than a few times per second and no longer than a few seconds before they burned out. Therefore, this method would have had huge disadvantages, mainly because of data rate limitation and furthermore because of the fact that a blinking light bulb would have been a bad solution for communication in the first place. Fortunately engineers focused on visible spectrum LEDs, whose light could be On-Off modulated and used as a data source. One of the main restrictions in On-Off modulation is the incapability of fast switching of solid state devices, like PN LED diodes, due to the rising time limitation. This limitation goes far inside the operating principles of LED and to be more precise back into quantum physics, where electrons experience a certain reaction time offset (inertia characteristics) in the presence of alternative voltages. Thus although LED could be switched on-off several thousand times per second this switching time is not enough to achieve thousands of Mbps bit rate. To overcome such problems engineers have proposed implementations of more than one communication channels at the same time. This solution could be implemented either on the optical domain or on the electrical driving circuit. On the optical domain the solution is using different colours, since one channel's wavelength would never interfere with the others'. On the electrical driving circuit this could be achieved by using spread spectrum techniques (Optical CDMA) or multi-carrier (OFDM). Nevertheless, the problem still was the limitation in high data rates or the rise of implementation budget, in contrast to the high rates IR sources which were already capable of achieving. Nowadays LED industry has made huge steps in developing more powerful and qualitative LED chips. Nowadays, white-coloured high-power LED modules, blue LED chips combined with a yellow phosphor, are being used for indoor and outdoor illumination. Their characteristics regarding power consumption and life time are by far better than those of commonly known incandescent light bulbs or even fluorescent lamps. The only disadvantage of such LED modules still lies in their price and general implementation costs, but this fact is believed to rapidly change in the next years, since the market already shows a tremendous interest in using them for various purposes (e.g. TVs and displays).

This was the breaking point where a new subcategory of FSOs was born, beside to the already existing IR technology: Visible Light Communication (VLC) or also well known as Wireless Light communications (Wi-Li). VLC is referring to data communication over a specific range of the Electromagnetic (EM) spectrum which is visible to humans. This range is measured to be approximately from 400nm to 700nm of wavelength, also known as "Visible Spectrum". The term VLC first appeared in 2003, when a small group of people at Keio University in Japan (Nakagawa Laboratory) started to experiment with LEDs and Photodiodes in order to achieve communication via visible light. The Nakagawa Lab then, together with some of Japan's biggest technology firms (NEC Corp., Panasonic and Toshiba), formed the so called Visible Light Communication Consortium (VLCC). VLCC later joined forces with the corresponding IR Consortium, the Infrared Data Association (IrDA). Since then, a lot of research activities regarding VLC have been carried out around the world, with the European Framework Programme (FP) 7 OMEGA project and work done at the University of Oxford, England, being the most notable among them. Furthermore, the IEEE Wireless Personal Area Network (WPAN) working group (802.15) is already working on the standardization of VLC.

What is the VLC ultimate goal? is the combination of illuminating an area and providing data communication at the same time via the same technology. Furthermore since VLC is referring to visible light, specific health-related issues have been arisen against around communication technologies which use Radio Frequency (RF), such as the broadly known and used IEEE 802.11x standards.

2. History of Visible Communications

One of the first implemented FSO systems was used by the French Military: *Chappe's Telegraph* system (semaphore) consisted of wooden structures mounted five meters high every 11 km, each featuring three movable arms to create 196 different signs with word and sentence meanings as well as telescopes to observe the signs from neighbouring stations in both directions. In one minute a single sign crossed a distance of 135 km. Lamps attached to the movable arms allowed night-time signalling.

The first experiment of VLC was exhibited by Graham Bell whose system was called Photophone. A brief description of its operation states that "Bell's Photophone made sound waves vibrate a beam of reflected sunlight". This may be nowadays understood as a simple kind of modulation. In a matter of fact, this experiment actually transmitted voice over the air long before the first radio transmission ever occurred!

During World War II both Axis and Allies used FSO technology for certain communication, such as the German *Lichtsprechgerät 80* and the American *Infrared Telephony* device. In 1955 Zenith introduced the first wireless TV remote control *Flash-Matic Tuning*, seen in Figure 1.4. This system used photoelectric cells in the four corners of the screen in order to control on/off, mute and channel selection. Although one year later ultrasound technology replaced the light system, infrared remote control is still common ever since. *RONJA* is a user controlled technology project of an optical point-to-point (or point-to-multipoint) data link first deployed in Prague, Czech Republic, in 2001. The link has a 1.4 km range and a stable 10 Mbps full-duplex data rate. You can mount RONJA on your house and connect your PC or any other networking device to it. All documents for a do-it-yourself project are available for free under the GNU license.

As a conclusion of this small reference to some particular points in the history of VLC and FSOs in general, one could say that this category of communication mediums has always been popular or at least considered in any way, and may be useful in many different applications in the future. Furthermore, by considering its advantages over other currently common wireless communication technologies, VLC seems to be here to stay.

3. Visible Light Communications – General Review

Wireless optical communication networks, when appropriately studied, developed and optimized, could provide a reliable, high security, interference insensitive, and especially for elders and health sensitive people **biologically friendly** indoor communication and monitoring network. This network would allow the creation and expansion of seamless computing applications, telemetry and medical sensor monitoring using large bandwidth high-frequency pulsed light instead of radio frequencies & microwaves. VLC technology uses modulated light, emitted and received, by Light Emitting Diodes (LEDs) for downlink and IR LEDs for uplink path. Both uplink and downlink could be provided sufficiently. IEEE has been working on standardization of VLC since 2009 in the context of Wireless Personal Area Networks (802.15) and recently provided a draft standard for Short-Range Wireless Optical Communication using Visible Light, including full MAC and physical (PHY) layer protocols.

3.1 VLC advantages – disadvantages

VLC is not however the unique existing technology for wireless optical communications. Other existing and well appreciated radio technologies are Zigbee, Bluetooth and WiFi. Although radio technologies are the most dominant nowadays due to their market penetration, especially for indoor applications solid state illumination technology with intensive Light Emitting Diodes (power LEDs) has been developed and found increasing market growth, because it **reduces significant power consumption** together with **expanding architectural capabilities**. It is profound that LED provides a good performance of cost vs. brightness against other illumination devices [1]. LED usage (actually the whole wireless optical solution) may help providing many services – indoor residence illumination, indoor & outdoor line of sight communications, area security functions, telemetry applications, remote medical monitoring. It is well known that WiFi technology is the most dominant and worldwide respected and accepted technology among all other radio technologies [2]. In most criteria VLC and WiFi are complementary on performance and in some aspects (power availability, Tx/Rx power, security and data density) VLC is even superior. WiFi could be superior on range and NLOS radio link environments. Indeed VLC suffers from shadowing and atmospheric absorption, thus restricting its high data rate applications to short distance communication links [1]. However by providing appropriate indoor illumination planning and number of LED lamp indoor design, range will always be sufficient small to provide enough signal strength on receiver and NLOS will never be the case. Moreover for sufficient ranges and after proper illumination design and multiple LED arrays in the building ceiling, data rate performance is comparable to all radio technologies since distance will be eliminated due to LED array reuse factor. To test the performance of VLC technology in several ranges a physical layer simple VLC prototype has been implemented, as part of undergraduate student thesis, in the telecom laboratories of the department of Telecommunication Systems and Networks of Technological Educational Institute of Messolonghi. This prototype was only a simple implementation, meaning that it was not protected against visible light interference and there was not implemented any preample electrical filter and channel equalizer to fight back ISI and multi-path channel fadings. Under several test measurements bit rates of 1 Mbps have been demonstrated [3]. Concluding about data rates and ranges, VLC under appropriate illumination design and LED array distance reuse, it provides superior performances over short range radio technology competitors, as ZigBee and Bluetooth, figure 1.

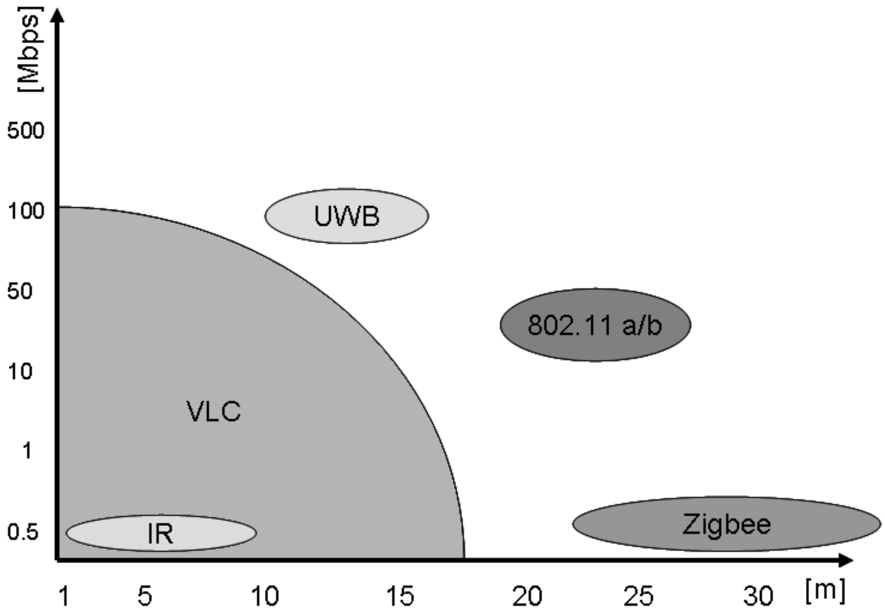

Fig. 1 Comparison among LTE and other existing optical wireless technologies.

The raising issue of interference of background light sources could be easily eliminated by using appropriate optical filters, a well known technique proposed in several applications, like OMEGA FP7 project [4]. Available bandwidth, interference and security is another issue that VLC is considered to be superior since it could provide both partial and full solutions to a number of wireless radio environment technological problems. Such solutions include the increasingly limited availability of conventional radio frequency (RF) bandwidths for electronic equipment, the possible communications interference with sensitive electrical equipment, the door-to-door data security [1].

The perceived negative health consequences of radio existing radio technologies [1], as indicated into figure 5, when exposed to raised radio frequency and microwave levels – specially for health sensitive human groups or buildings (schools, hospitals) - is a severe issue. From health perspective all such applications and solutions might relax indoor space from radio emissions of contemporary telecommunication systems (WiFi, WiMax, Bluetooth, UWB, etc.) which in certain cases are prohibitive (e.g. hospitals, airplanes, elderly areas, etc) or non-desirable (e.g. schools, university classrooms etc). Consequently, by replacing existing microwave and radio based wireless networks, a next generation green wireless communication network that will transform our everyday experiences and contribute to the idea of cyber green communication networks is obtained.

Moreover to all previously mentioned metrics, there is also one major advantage of optical VLC technology against any radio competitor. This advantage is the OFDM compatibility and superiority over VLC [5]. Indeed OFDM enables very high data rate transmission with low computational complexity at the receiver since it is robust to multi-path propagation. OFDM entirely eliminates the need for complex algorithms to cope with inter-symbol interference (ISI) which typically gets worse with higher data rates. However, a standard OFDM transmitter produces a complex-valued signal. Through a simple mathematical "trick", this signal can be converted to a real-valued signal whose amplitude greatly varies in time. As a consequence, the peak-to-average-ratio (PAR) is high. This causes concerns in RF communications because of the detrimental impact on system performance due to power amplifier non-linearities. For optical wireless communications this effect, however, can be turned into an advantage as the high PAR signal can be exploited for intensity modulation [6]. Given that the minimum illumination for reading purposes is 400 lx, and that this already translates into a SNR greater than 30 dB, OFDM combined with higher order modulation techniques such as M-level quadrature amplitude modulation (QAM) result in a powerful transmission technology for incoherent visible light sources. D-Light team, University of Edinburgh, has demonstrated real-time data transmission using off-the-shelf LEDs of 130 Mbps. Finally one last advantage of VLC against any other radio available technology competitor is the interference issue. Using VLC over OFDM results in high link-level data rates, making VLC over OFDM a very good candidate for indoor LTE implementation.

There is however one good question to be answered; what happens if multiple transmitters are deployed which together form an optical cellular network? On a recent publication [7] the Area Spectral Efficiency (ASE) of future interference limited wireless systems has been determined. The ASE is a measure for the maximum data rate per unit and per Hertz bandwidth. It assumes a wireless network that is composed of multiple randomly deployed access points where each access point uses the same transmission resource/bandwidth. Basically, if there are many access points, this means a high reuse of the same transmission resource and thus high data rate per unit area, but at a certain point this gain is outweighed by increased interference which results in a drop in ASE. On the other hand, if there are only a few access points, this means a low resource reuse and hence low data rate per unit area, but also low interference. Therefore, there is an optimum point for the ASE. This optimum ASE for an indoor environment is found to be 4 x 10-4 bits/second/Hz/m2.

Implementing cellular networks and presumably LTE over VLC technology has, among other aforementioned advantages, the benefit of security and privacy. Indeed using VLC technology there will be no interference for indoor applications among rooms as rooms are typically separated by walls and light does not propagate through walls; an option which does not hold in case of RF signals. If we assume a typical room of the size 4 m x 4 m = 16 m^2, and a VLC transmitter that is capable of delivering 130 Mbps with an off-the-shelf LED lamp of 20 MHz bandwidth, as demonstrated by the D-Light team, this would result in ASE of: 130 x 106 [bits/second] / (20 x 106 [Hz] x 16 m^2) = 0.41 bits/s/Hz/m^2

Comparing this result to the maximum 0.0004 bits/second/Hz/m^2 for state-of-the-art wireless systems, we can observe a **1025** times higher ASE. This essentially means that VLC technology has the potential to provide wireless Gbps indoor services (over fo course short ranges of 1-10 m) using standard off-the-shelf LEDs. This results in a massive RF spectrum relief which frees up RF resources for the provision of better services in areas were VLC technology is difficult to use such as in remote areas. Taking this idea further and exploiting particular LED light radiation characteristics from different light sources in a room coexistence scenario the expected ASE improvement could reach well beyond the factor of 2000 and more.

Concluding, VLC seems to be complementary and in some aspects superior to radio technologies. WiFi might be used for wide-area coverage within a building and zigbee for short range communications. However interference, unlimited bandwidth, health issues, OFDM and security support the VLC application and data rates could be in adequate level using many VLC LED arrays for short to medium range indoor communications. Following table 1 presents the major pros and cons of the VLC technology.

Table 1 Advantages and disadvantages of VLC technology

Advantages	Disadvantages
Harmless for the human body	Atmospheric absorption
Data transmission by sockets of existing light fixtures	Shadowing/Signal deterioration
Alleviation of problems associated with radio frequency (RF) communication systems	Beam dispersion
Far less energy consumption	Interference from background light sources
Increased security	
Compact integration on sensors through small dimensions	No communication if no “line of sight”
Huge number of channels available without interfering with other sources	Only discrete spectrum available as light source and sensor
Simple electronics as drive for the LEDs	Noise from interference of other sources has to be filtered
No influence to other sensitive equipment through radio waves	

3.2 VLC – Innovation and standards

Although VLC concept has its origin back to 1880 and Alexander Graham Bell [8] the first steps of a communication system using visible light while serving illumination requirements of indoor spaces were made in the end of last century [9]. Since then, several research groups have shown great interest in modeling, analyzing and developing prototypes in order to assess the feasibility and the performance of a VLC system. In this context, the work of Nakagawa laboratory of Keio University was pioneering and boosted the interest in VLC [10-14]. This work led to the establishment of the VLC Consortium (VLCC) Japan, in 2003, that provided the first standards (JEITA CP-1221 and CP-1222) for VLC systems in 2007.

The key component of VLC systems is an LED radiating visible light which is properly modulated for transmission information, while retaining its illumination capability. White light LEDs are the most promising ones from illumination and communication point of view. Most research work and experiments are based on phosphorescent white LED, which consists of a blue LED chip covered with a layer of yellow phosphor. These chips are of low cost and have simpler driving, but they present a low modulation bandwidth (2-3 MHz). Proper blue-filtering before the detector allows only blue component of white light, thus increases the bandwidth to the order of 20MHz [15,16] with a total of 100Mbps achievable bit rate using Discrete Multi-tone Transmission (DMT). Channel Equalization techniques have also been proposed [17,18] for further bandwidth enhancement. A good achievement of 500Mbps over a five meters distance has been announced in 2010 from Heinrich Hertz Institute and Siemens [19].

Since 2010 VLC has been standardised by IEEE in the context of Wireless Personal Area Networks (802.15) [20] for Short-Range Wireless Optical Communication using Visible Light, including full MAC and physical (PHY) layer protocols. IEEE specifies three physical layer modes; PHY I for outdoor usage, low data rate applications, On-Off Keying (OOK) with Manchester line coding and Variable Pulse Position Modulation (VPPM) with 4B6B line coding, data rates in the tens to hundreds of kbps, and RS outer coding; PHY II for indoor usage, moderate data rate applications, OOK with 8B10B line coding and VPPM with 4B6B line coding, data rates varying from 1.25 Mbps to 96Mbps and RS coding; PHY III for indoor high rate applications using color shift keying (CSK) with multiple light sources and detectors, supported data rates up to 96Mbps, using RS coding.

Important work has also been performed by the hOME Gigabit Access (OMEGA) project [4], funded by the European Union within FP7. The project ended by March 2011 with the development of a full VLC prototype for video broadcasting and a general Medium Access Control (MAC) protocol for home environments for Infrared (IR), VLC, Power Line Communications (PLC) and Radio Frequency (RF) physical layers interoperability.

4. LTE Implementation over VLC – Technical Review

Regarding the general concept of VLC, as already mentioned, a primary future vision of successful implementation and usage would be the combination of LED illumination along with data access. This is what makes VLC more promising in regards to its family FSOs: the fact that the medium itself may be used for additional purposes in parallel.

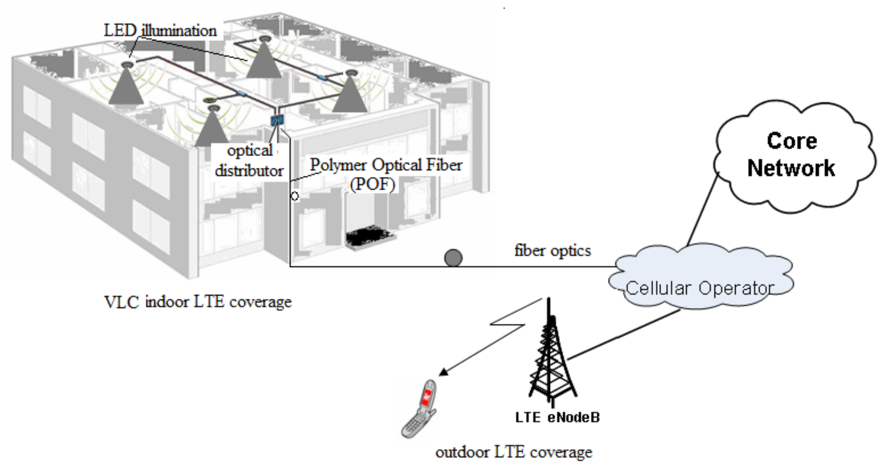

Fig. 2 VLC indoor LTE coverage implementation proposal.

Figure 2 presents the LTE indoor coverage over LTE technology proposal. VLC advantages and standards have been already presented previously. In such an implementation indoor planners could make use of several existing technologies. From outdoor cellular operator network to the indoor coverage glass single mode optical fibers should be used and appropriate capacity planning should be performed to provide appropriate bandwidth for optical Ethernet transmission. Inside buildings Polymer optical fibers could be used as a cheaper solution for the optical signal distribution. Optical distributors/splitters should be provided to distribute optical signal throughout building floors and rooms. Finally LEDs with appropriate driving circuit and optical to electrical converters should also be used as the indoor distribution and illumination system.

4.1 Glass Optical Fiber

LTE according to standards needs Ethernet links over fiber optics ideally. Optical fiber planning includes several stages. A wide variety of specifications shall be used at an early stage. Regarding the physical medium, system topology should be considered including cable location and/or cable routes. Existing cable protection should be carefully examined (none or building ducts or underground ducts). Cable specifications should follow standards (fibre, moisture ingression etc.) and number of fibers per cable shall be considered and defined. Regarding network issues, network applications and proposed topology shall be finalized together with transmission standards (SDH,SONET), available Ethernet bit rates, coding, multiplexing etc. Specifically for the fiber itself several parameters and characteristics have to be decided. First of all it has to be decided if multi-mode (MM) or single mode (SM) shall be used, the core size and fiber Numerical Apreture (NA), appropriate fiber attenuation for the link budget calculations. Also based on Ethernet supported bit rate, fiber dispersion, including all tolerances shall be considered. Mostly on metropolitan networks connectors and splitters are used quit. For this reason considerations on Connector types, connector losses and reflections, available tolerances, mechanical or fusion splices, loss and tolerances and termination enclosures and patch panel losses have to be calculated on link budget.

When planning is performed, always the worst case is considered, calculating also tolerances. As an example assume then worst case transmitter output power is -12 dBm and the worst case receiver input power needed is -30 dBm. Then Power budget = - 12 dBm - (- 30 dBm) = 18 dB of attenuation is possible over the link before failure (non availability) occurs. To find maximum available fiber attenuation we substitute from available 18 dB budget the expected loss due to connectors (connector attenuations 1 dB per connector) and splices (splice attenuation 1.5 dB per splicing) and we are left with total allowed fiber attenuation of 12.8 dB. However this is not always enough. Indeed we shall add also expected margins due to fiber ageing (the typical operating lifetime of a communications transmission system may be as high as 20 to 30 years), extra future splices, extra fiber length in future operator and maintenance repairing and extra upgrades in the bit rate or advances in multiplexing. Figure 3 presents an example of power budget calculation including all losses and expected margins.

In order to get a more sophisticated optical fiber planning, power penalties should be included in the analysis. Power penalty is indeed the initial calculated power increment in order to eliminate any undesired effects from expected system noise or system distortion. Most common penalties are calculated due to fiber dispersion effects and fiber attenuation. There are two dominant fiber dispersions, time dispersion and chromatic or material dispersion. Time dispersion is the dominant dispersion effect on multi-mode fibers; however when single mode fiber is involved time dispersion is almost eliminated and the only left is the material dispersion. Dispersion depends mostly on supported service bit rate and on fiber material response. Whenever dispersion is present BER is expected. Figure 4 presents the degradation of service due to dispersion. For a specific BER performance over the transmission link, there is a difference in expected required receiver power level (known also as receiver sensitivity). Indeed for BER = 10^{-9}, a typical Quality of Service (QoS) performance over optical links, when there is no dispersion expected the receiver sensitivity equals almost -35.5 dBm, while whenever dispersion is expected the receiver sensitivity is increased to -33.5 dBm requesting thus 2 dB higher initial transmitter power or dispersion penalty!!!

System: 70 km span, 0.8 km between splices

Transmitter o/p power (dBm)	0	
Number of Connectors	2	In most systems only two connectors are used, one at the transmitter and one the receiver terminal.
Connector loss per connector (dB)	0.5	
Total connector loss (dB)	1	
Fibre span (km)	70	
Fibre loss (dB/Km)	0.25	
Total fibre loss (dB)	17.5	
Splice interval (Km)	0.8	Fibre is normally only available in fixed lengths up to 2 km long, so fusion splices are required, to join lengths.
Number of splices	87	
Splice loss per splice (dB)	0.04	
Total splice loss (dB)	3.46	
Dispersion penalty estimate (dB)	1.5	In buildings fibre lengths will be much shorter
Receiver sensitivity (dBm)	-30	
Power margin (dB)	6.54	Answer

Fig. 3 Power budget calculation including margins and losses.

Specifically for optical link planning dispersion vs. receiver sensitivity curves might not be always provided. In such a case optical planners reading the technical sheet of the fiber they could make a rough estimation of the expected dispersion penalty. There is an approximation formula to provide such estimation:

$$\mathrm{D}_{chr} = C_c \cdot \mathrm{T}_{SB} \cdot L \tag{1}$$

Where D_{chr} is the chromatic dispersion, C_c is the specific fiber chromatic coefficient in [ps/nm . km], T_{SB} is the transmitter (mostly solid state laser diode) spectral bandwidth in [nm] and L is the overall fiber link length.

Losses are expected due to specific fiber material. There are specific optical windows that optical transmission shall take place where losses are minimum. As a simple example on losses figure 5 presents the optical windows. Keep in mind that such curves shall be always provided from optical fiber vendors. Most of single mode fibers on 1550 nm spectral band due to industrial standards follow ITU-T recommendation G.652 where attenuation is declared less than 0.25 dB/Km and chromatic dispersion coefficient is 18 ps/(nm.km). As an example consider a 100 km fiber link meeting G.652 standards with a oscillating cavity Laser Diode on 1550 nm and spectral bandwidth of less than 0.1 nm. Then expected chromatic dispersion would be 180 ps. Dispersion is very important to calculate because is inversely related to expected bit rate (BR) before intersymbol interference (ISI) occurs. A good approximation formula is BR = $1/4D_{chr}$ = 1.39 Gbps!! To approximate power dispersion penalty, following formula provides a good estimation:

$$\mathrm{P}_{pen}[dB] = -10\log_{10}\left(1 - \frac{\left(\pi\left(BR\right)\right)^2 D_{chr}^2}{2}\right) \qquad (1)$$

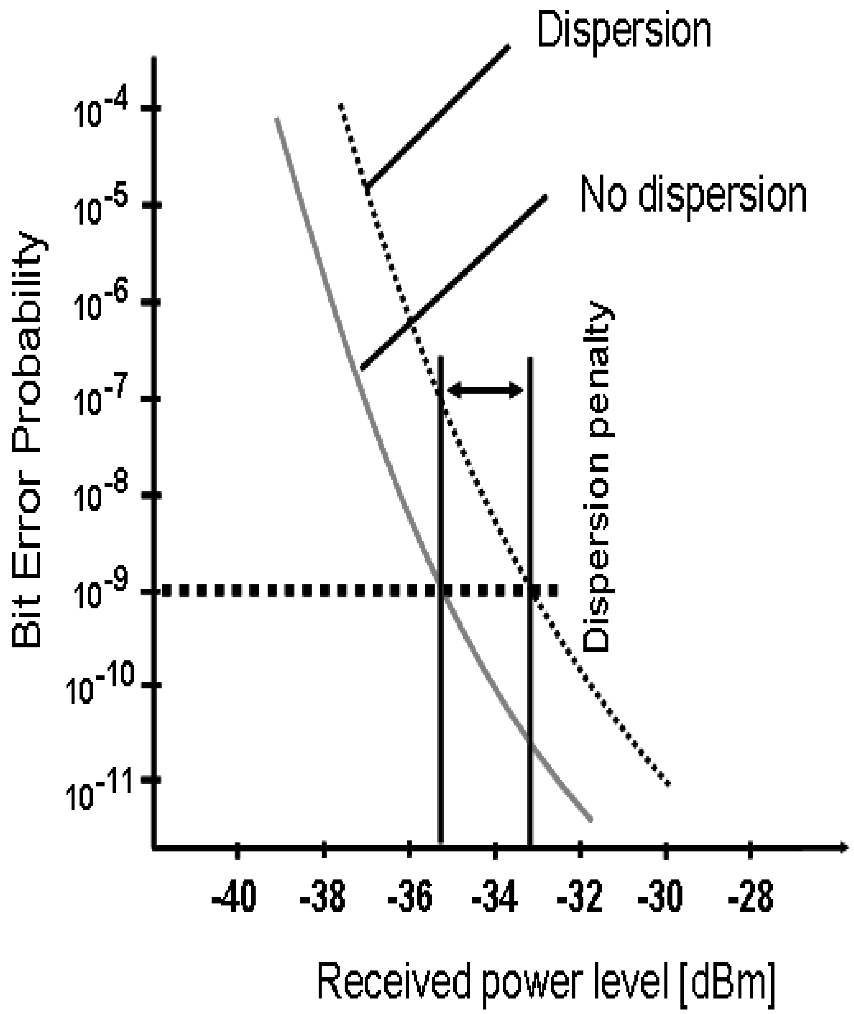

Fig. 4 Dispersion effect on expected quality of service BER metric and receiver sensitivity.

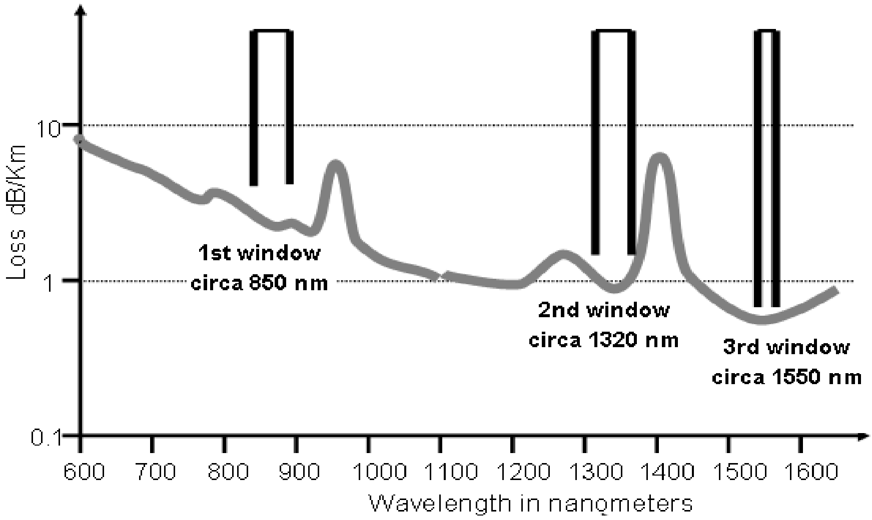

Fig. 5 Optical windows and fiber attenuation.

For Optical network, depending on available supported rates, different estimations could be made. Indeed for optical SDH (SONET) of supporting STM-1, STM-4, STM-16, STM-64, following curves provide a graphical representation of equation (1).

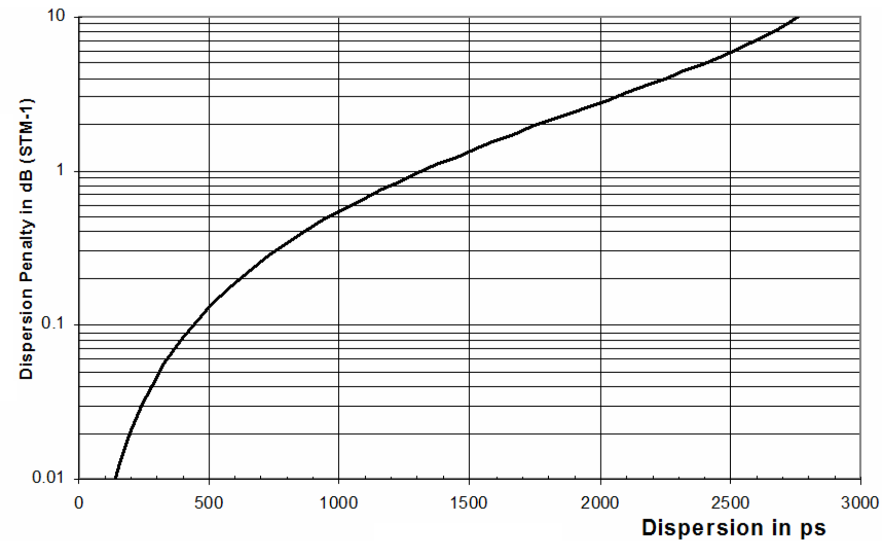

Fig. 6 STM-1 supported rate vs. optical dispersion penalty.

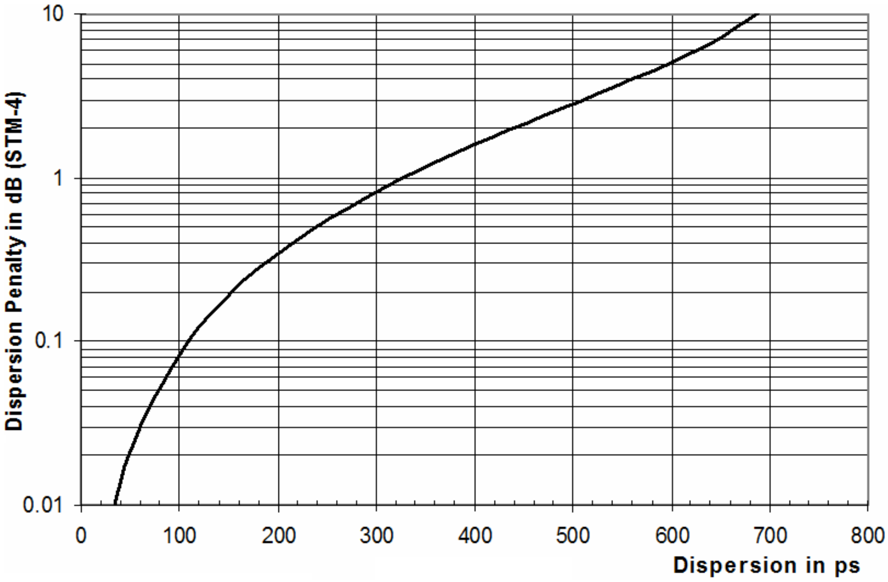

Fig. 7 STM-4 supported rate vs. optical dispersion penalty.

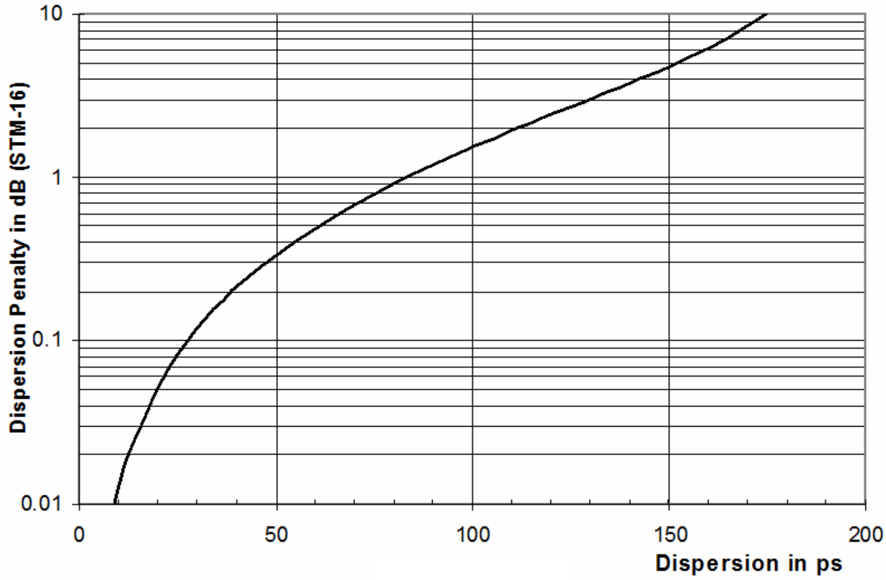

Fig. 8 STM-16 supported rate vs. optical dispersion penalty.

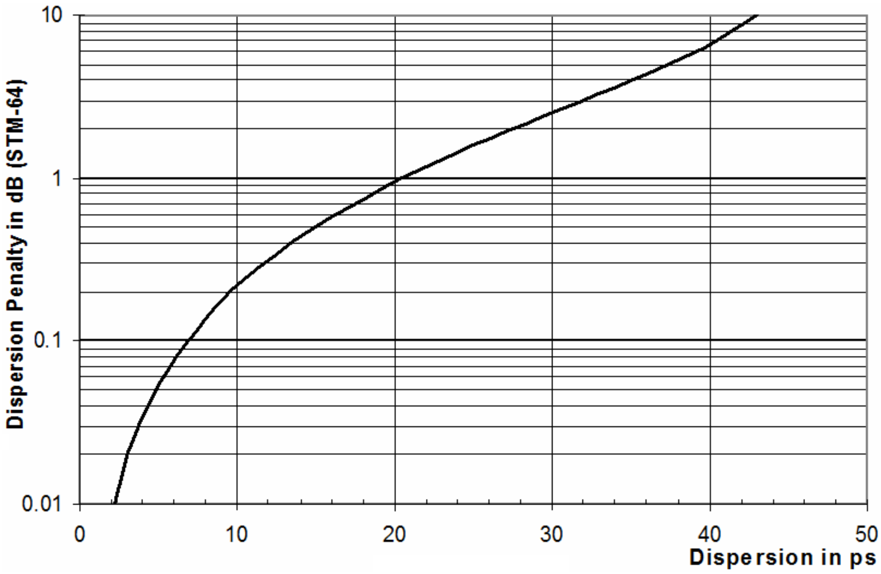

Fig. 9 STM-64 supported rate vs. optical dispersion penalty.

4.2 Optical Fiber Cabling

Indoor LTE radio planners over VLC, according to ISO standards, should provide appropriate cabling precautions. ISO/IEC 11801 specifies generic cabling for use within premises, which may comprise single or multiple buildings on a campus. It covers balanced cabling and optical fibre cabling. ISO/IEC 11801 is optimised for premises in which the maximum distance over which telecommunications services can be distributed is 2000 m. The principles of this International Standard may be applied to larger installations. Cabling defined by this standard supports a wide range of services, including voice, data, text, image and video. Safety (electrical safety and protection, fire, etc.) and Electromagnetic Compatibility (EMC) requirements are outside the scope of this International Standard, and are covered by other standards and by regulations. However, information given by this standard may be of assistance. ISO/IEC 11801 has taken into account requirements specified in application standards listed in Annex F.

According to ISO – 11801 there are defined and standardised three different fibers. OM1 fiber – 200/500 MHz.km OFL BW (in practice OM1 fibers are 62.5 µm fibers), OM2 fiber – 500/500 MHz.km OFL BW (in practice OM2 fibers are 50 µm fibers), OM3 fiber – Laser-optimized 50 mm fibers with 2000 MHz.km EMB at 850 µm. Figure 10 provides optical fiber cable attenuation according to ISO 11801.

Maximum cable attenuation dB/km				
	OM1, OM2 and OM3 Multimode		OS1 Single-mode	
Wavelength	850 nm	1300 nm	1310 nm	1550 nm
Attenuation	3.5	1.5	1.0	1.0

Fig. 10 Maximum cable attnuation vs different fibers.

Based on the supported service and network topology, ISO 11801 defines different fiber classes. Class OF-300 supports applications to a minimum of 300m distance, Class OF-500 supports applications to a minimum of 500m distance and Class OF-2000 supports applications to a minimum of 2000m distance. Figure 11 provides info about channel attenuation for different transmitter optical wavelength.

Channel Attenuation in dB				
Channel	Multimode		Single-mode	
	850nm	1300nm	1310nm	1550nm
OF-300	2.55	1.95	1.80	1.80
OF-500	3.25	2.25	2.00	2.00
OF-2000	8.50	4.50	3.50	3.50

Fig. 11 Fiber classes and channel attenuation.

4.3 VLC Indoor planning considerations.

VLC uses LEDs as data sources, thus the key to success is the ever growing LED industry and the market's turn towards them. LEDs have by far better characteristics than any other known light source in use today (except of course laser diodes which are extremely directional, thus inappropriate for indoor illumination); energy efficiency, life time and lumens output are some of them. It is estimated that in the next years, LEDs will globally overrun the existing light sources and will dominate the world of illumination. As soon as the price of LEDs reaches a more reasonable level for consumers to prefer them over common light sources, it will be motivating for companies to start developing and implementing VLC systems which allow the combination of light and data in any indoor facility. Even outdoor applications may be considered, as LEDs get more and more powerful. VLC could be a new milestone in local cloud access, just as 802.11x standards became a few years ago. VLC could provide adequate indoor solution for the *Last Mile* in a Metropolitan area. The term “Last Mile” refers to the final connection between an Internet Service Provider (ISP) and a customer. Initial planning goal is to achieve transmission of any signal over a wireless physical optical link by using visible light as a medium. The term Transceiver (TRx) may be a bit misleading since it refers to a module capable of both transmitting and receiving various signals while sharing most of the required circuitry. This particular design is rather a transmitter-receiver implementation, but could eventually be extended to a transceiver module by adding IR circuitry for the uplink at both the Transmitter (Tx) and the Receiver (Rx). VLC transmitter consists of three basic parts: the LED circuitry, the Bias-Tee network and the Trans-Conductance Amplifier (TCA) network, although the latter was not achieved to be included in the final design. On the other hand, the receiver’s basic components are the photodiode and the two-stage Trans-Impedance Amplifier (TIA) network. Figure 12 shows the basic schematic of an indoor VLC transceiver.

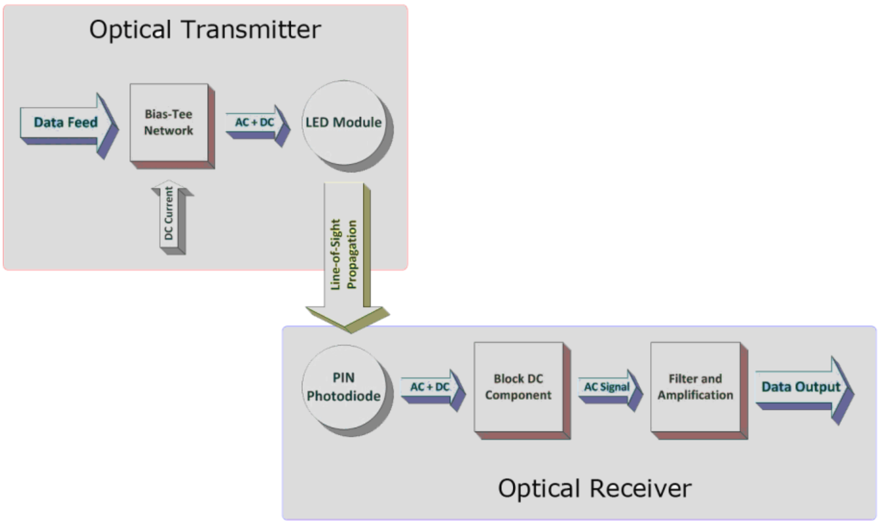

Fig. 12 VLC transceiver functional blocks.

In Technological Educational Institute of Messolonghi a transceiver circuit has been designed and tested under specific radio conditions. VLC transmitter diagram is presented on figure 13

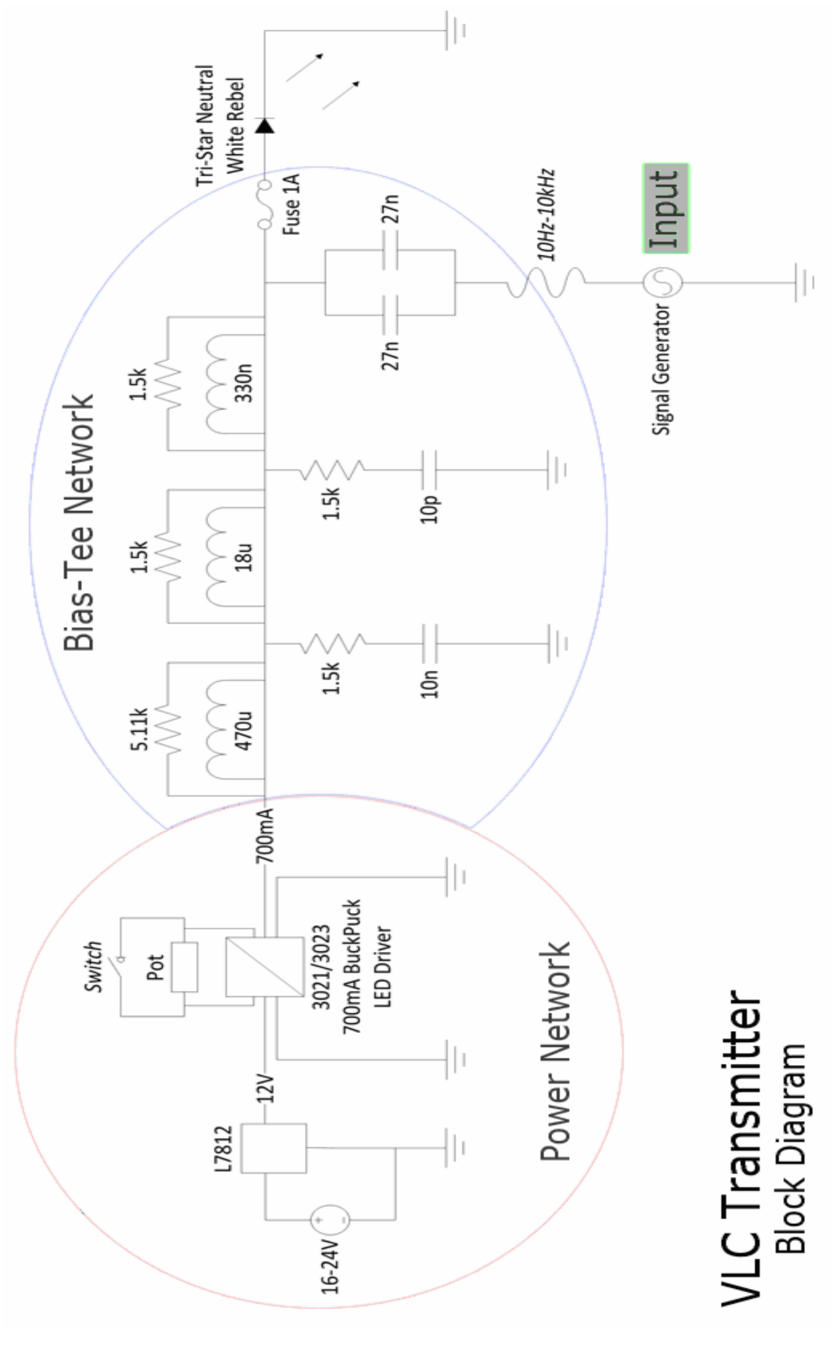

Fig. 13 VLC transmitter block diagram.

The power supply of the circuit had to be designed carefully, since properly regulated current is a requirement of high significance when working with LED chips. A Buck Puck driver was used in order to provide the LED module with constant DC current. In order to achieve both a stable consumption rate and convenient DC input values, a 12 V_{DC} voltage regulator was used to feed the LED driver (L7812), defining the input range from 16 V_{DC} to 24 V_{DC}. Since the forward voltage of each LED chip is 3V at 700mA, the tri-star module has a total forward voltage of 9V, a requirement which is met by providing the driver module with 12V. Regarding the transmitter's power consumption, it is easily calculated being 8.4W (12V * 0.7A = 8.4W). The power consumption was verified by measuring the current flow of the transmitter's power supply while operating. Compared to common light sources, the ratio of lumens output and power consumption of the LED module is incredibly higher. The Bias-Tee circuit used in the architecture was borrowed from Gary W. Johnson's "Wideband Bias Tee", which was designed for a wide input range of signals [20]. Although the prototype described in this document was tested with signals of much lower frequency, a broader approach was used in order to keep potential future goals of improvement in mind. Johnson's design had a minor detail which needed to be adjusted to the project's needs; it was designed for 250mA. An eventual saturation of the Bias-Tee's inductors would result in worse isolation, therefore high quality components were chosen, capable of handling up to 1A of DC current.

VLC Receiver prototype was mostly based on information obtained from the work done at the University of Oxford [4] particular European FP7 OMEGA project deliverables. The circuit is based on receiving the light with a photodiode and turning it into an electrical signal, which in turn needs to be filtered and amplified. Photodiode is considered the most valuable component of the receiver circuit, since the functionality entirely relies on its characteristics. A photodiode is a type of photodetector which converts light into either current or voltage. A common solar cell is a good example of a large area photodiode. Apart from solar cells, two other types of photodiodes are the most common ones in use today, Avalanche Photodiodes (APD) and PIN photodiodes. Main differences lie, among others, in sensitivity and wavelength. APDs have better sensitivity over PIN photodiodes; due to avalanche multiplication, they provide a built-in first stage amplification gain when applying a high reverse bias voltage. On the other hand, PIN photodiodes are wideband and capable of achieving much higher data rates. Their physical characteristics and differences are beyond the scope of this report. APDs had to be rejected because of wavelength limitation, since they do not respond to the visible window; thus, a silicon PIN photodiode was the most obvious choice. The main issue regarding photodiodes in FSOs is their lack of effective active area, since they are usually coupled to a medium, such as an optical fiber, in order to focus the light beam to the very core of the diode. This is mostly the reason why arrays of photodiodes are often used in similar applications.

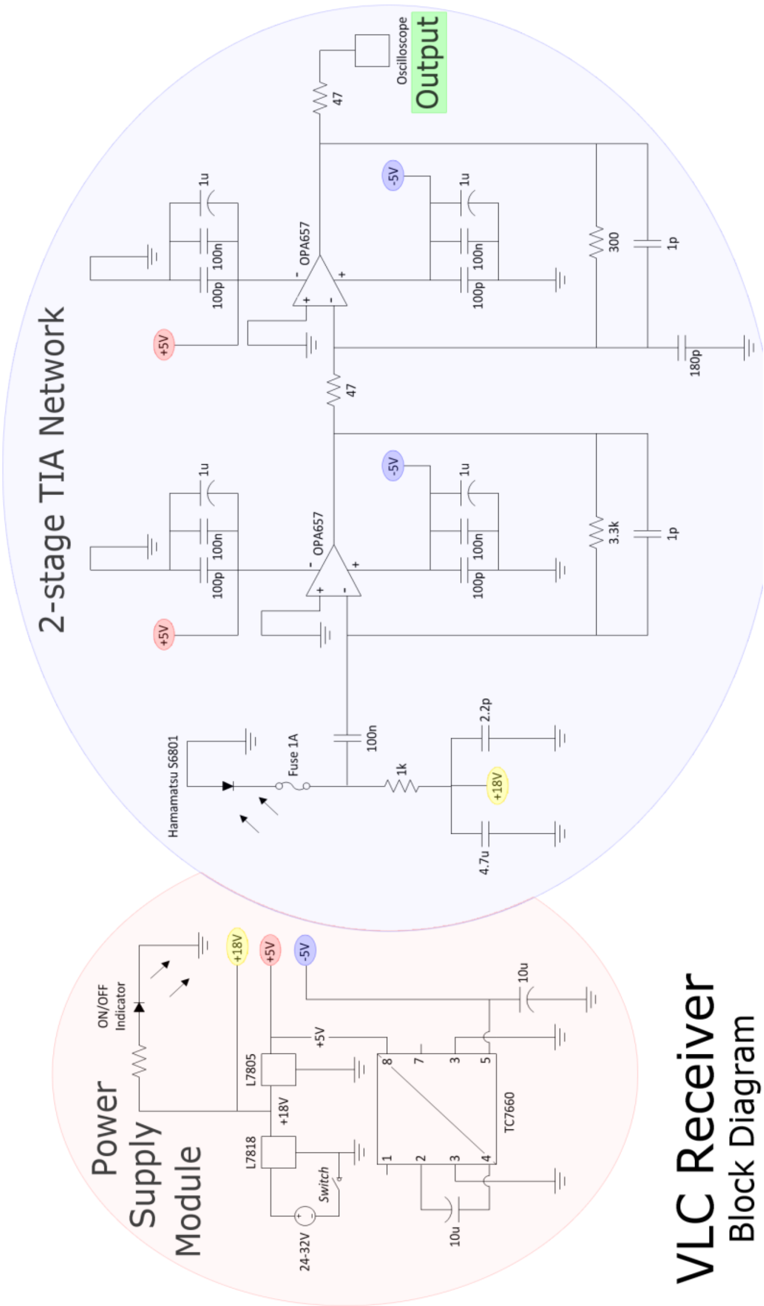

Fig. 14 VLC receiver block diagram.

A very specific photodiode came as a solution to this inconvenient detail; Hamamatsu is the only optics firm which was found to be producing and delivering photodiodes that are integrated into a concentrating lens, giving them optimal characteristics regarding directivity and active area. Specifically, the Hamamatsu Si PIN photodiode S6801/S6968 series come in a lens with a diameter of 14mm, creating 150mm^2 effective active area and 35° directivity, while their spectral response range perfectly covers visible light, making them the best choice for the prototype. The biggest benefit of using this specific component is the avoidance of a photodiode array and eventual additional components that might be required. Figure 14 provides the VLC receiver block diagram circuit. The receiver circuit provided by OMEGA was used in order to maintain the future target of extending this proof-of-concept prototype to a wideband application. A photodiode is usually reversely biased, in this case by 18 V_{DC}. The light captured by the photodiode is converted into electrical signals (current), which are at that point still AC/DC coupled. The DC component is eliminated by the 100nF capacitor, while the remaining AC signal flows into the first stage of the TIA network where it is turned back into a voltage signal. At the second stage of the TIA network the signal is electrically amplified and pushed to the output wire. An issue emerged regarding the power supply, with the OPA657 requiring a ± 5V input. A Microchip TC7660 voltage converter was used in order to produce the required negative voltage, as can be seen in Figure 3.2, but unfortunately it turned out that this component's operation is not as stable as one would like it to be. The first converter burnt just after a few times of powering the circuit. Having only one more left, it was decided to implement a back-up power supply module in case the initial circuit would proof totally inappropriate. The back-up power supply solution was achieved by connecting several 9V batteries in series and taking the first two's midpoint as the earth reference, creating in that way a ± 9V, while a third one provided 18V. The ± 9V source was then regulated down to +5V and -5V by using L7805 and L7905 voltage regulators respectively.

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