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State of the Art - optical wireless

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Abstract

This deliverable provides an overview of the state of the art of optical wireless (OW) communications. It includes an overview, application scenarios, and specific requirements for OW. Two different types of system are considered specifically: VLC – Visible Light Communication and IRC – Infra Red Communication. The state of the art presented in this document provides a foundation for the specification of the OMEGA optical wireless system, which will be specified in Task 4.1.

Keyword list

Optical Wireless, OW, VLC, Visible Light Communication, IR, Infra Red, IRC, Infra Red Communication, Free Space optic, FSO,

Executive Summary

The OMEGA project will use infra red and visible light to provide optical wireless communications, as part of the overall physical infrastructure. In order to correctly specify these systems a survey of the state of the art has been undertaken and the results are presented here.

Two distinct types of system are surveyed. Infra-red Optical Wireless (OW) communications is an established area of study, and the work in OMEGA aims to create Gbit/s class systems that use near IR wavelengths for communications. Visible Light Communications (VLC) is a new area, and uses white light provided by solid-state sources that are normally used for general illumination.

The aim of the document is to survey the current state of the art in both these areas, including the research and industrial activity, results achieved so far, as well as a review of the components and subsystems and the challenges faced in achieving high data rates.

The deliverable is divided into several sections. Chapter 1 introduces the topic, and chapter 2 presents requirements for OW systems, including typical environments and quality of service aims. The remaining chapters present the technical aspects of the system, including the choice of wavelength, components and subsystems. In addition requirements for the Medium Access Control (MAC) layer and techniques to achieve this are also presented.

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List of Acronyms

Acronym	Meaning
ACK	Acknowledged mode
CC	Convolutional Codes
CD	Committee Draft
CENELEC	European Committee for Electrotechnical Standardization
CEPT	Conference of European Post and Telecommunication administrations
CSMA	Carrier Sense Multiple Access
DIF	Diffusion
EC	European Commission
ECC	Electrical Communication Committee
EMC	Electro Magnetic Compatibility
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
FEC	Forward Error Correction
FP7	Framework Programme 7
HAN	Home Access Network
HD TV	High Definition Television
HF	High Frequency
HWO	Hybrid Wireless Optics
ICT	Information & Communication Technologies
ID	Internal Deliverable
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IPTV	Internet Protocol Television
IST	Information Society Technologies
ITE	Information Technology Equipment
ITU	International Telecommunication Union
ITU-T	ITU - Telecommunication standardisation sector
IR	Infra Red
IRC	Infra Red Communication
LDPC	Low Density Parity Check codes
LOS	Line Of Sight

MAC	Medium Access Control layer
MIMO	Multiple-Input Multiple-Output
MPDU	MAC Protocol Data Unit
MSDU	MAC Service Data Unit
NC	Not Communicated
OFDM	Orthogonal Frequency Division Multiplexing
OMEGA	Home Gigabit Access
OQAM	Offset QAM
PAM	Pulse Amplitude Modulation
PHY	Physical layer
PON	Passive Optical Network
QAM	Quadrature amplitude modulation
QoS	Quality of Service
RS-CC	Reed Solomon
SAP	Service Access Point
SC	Sub Committee
SME	Small and Medium Enterprises
SOHO	Small Office – Home Office
TC	Technical Committee
TCM	Trellis Coded Modulation
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
ToC	Table of Contents
ToR	Terms of Reference
TR	Technical Report
UDP	User Datagram Protocol
UWB	Ultra Wide Band
VHF	Very High Frequency
VLC	Visible Light Communication
VoIP	Voice over IP
WLAN	Wireless Local Area Networks
WLOS	Wide Line Of Sight
WP	Work Package
WWRF	Wireless World Research Forum
xDSL	Digital Subscriber Line

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1 Introduction

The OMEGA project aims to use optical wireless communications to provide a Gbit/s communications network using infra-red wavelengths, and 100Mbit/s communications using Visible Light Communications (VLC). These are perhaps the most demanding specifications for these types of system set so far.
Point to Point communications in outdoor environments is well established, with a number of commercial ventures providing systems for Gbit/s over ranges of several hundred meters, as well as communications between satellites. However, indoor wireless systems are more challenging, with a requirement to provide coverage, as well as data rate. The wide field of view required for robust indoor coverage makes these systems considerably more challenging than their outdoor counterparts. In addition this must be achieved whilst meeting the most stringent eye safety requirements.
There are a small number of indoor applications that use optical wireless communications. Infra red remote controls, and devices that communicate according to the Infra-Red Data Association (IRDA) are in widespread use and these are the largest area of application. Finally there have been a number of high-speed point to point link demonstrations, and products. A high-data rate example is the Luciole link by JVC. This provides a 1.5Gbit/s link for uncompressed High Definition TV, and uses a line of sight link with a tracking capability.

Although there are a number of point to point link demonstrations, a successful OMEGA project will represent a substantial improvement in the state of the art as it will demonstrate an optical wireless network, rather than simple point to point connections. This document outlines some of the requirements for optical wireless within the project, and the technologies and techniques available to meet them.

2 System requirements

2.1 Data rate requirements

Figure 1 shows the increase in requirements for data transmission, and those available using representative communications standards (based on the 802.11 WiFi standards). It can be seen that demand continues to grow, with a requirement for Gbit/s wireless communications, a demand that OMEGA aims to meet. For more than a decade, the data rate evolution for WLANs – Wireless Local Area Network has increased rapidly and does not seem to have obtained its asymptote. The success of equipment based on the IEEE 802.11(WiFi) specification shows the demand for this type of connection.

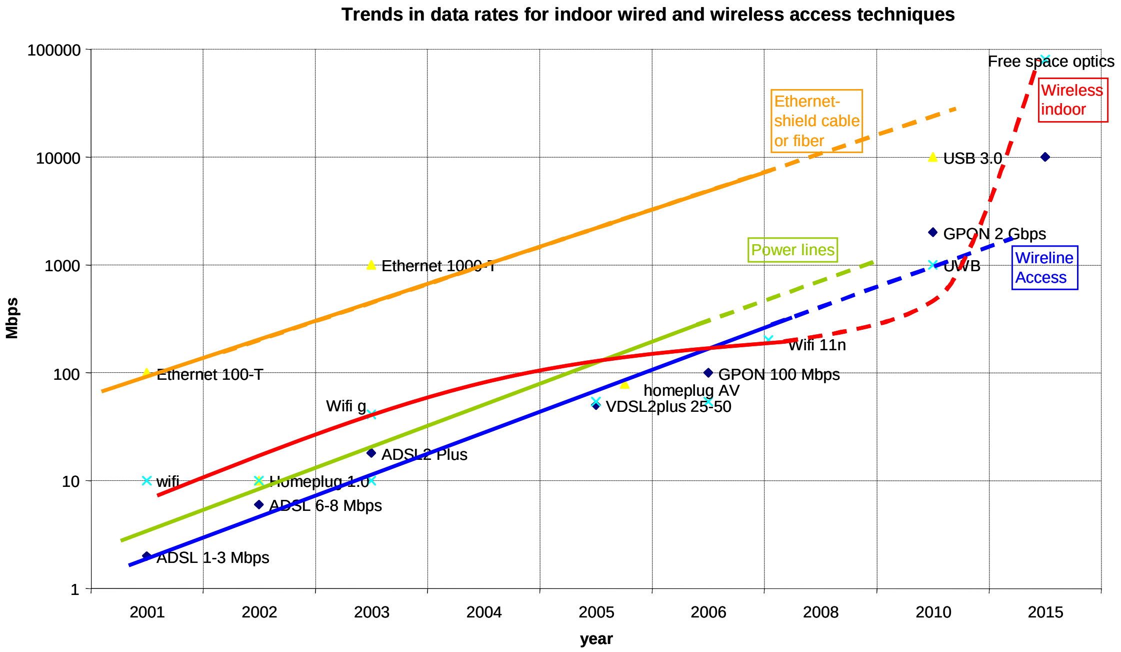


Figure 1 : Evolution in data rates (source : Orange White Paper)

2.2 Typical indoor environments

A survey of the size and number of rooms in typical dwellings across Europe, using data from ad-hoc surveys, or larger national data sets. A presentation of the results for each country is now set out in the Omega project public document: D1.1 Final Usage Scenarios report.

2.3 Key parameters of for determining quality of service (QoS)

Any optical wireless system must be able to provide communications with an acceptable Quality of Service (QoS), and several of the parameters that determine this are described now in the Omega project public document.: D1.2 Requirements, Architecture & Topology Report.

3 Optical wireless systems: introduction and physical layer

The OMEGA HWO systems will use (i) High-speed Line of Sight (LOS) links to provide Gbit/s class transmission capability and (ii) Visible Light Communications to provide information broadcasting at 100Mbits/s. This chapter reviews the available components, wavelength of operation and impairments relevant to this work. A number of the key components and parameters for optical wireless systems are described in the following section.

3.1 Introduction to IR communications

Any optical wireless (OW) system consists of a transmitter, which emits modulated optical radiation corresponding to the input data. Light then propagates through the channel and an optical receiver detects the modulated radiation and recovers the original data.

IR based optical wireless systems use a number of different topologies, and the performance available is dependent on the propagation and type of system used. The basic system types fall into diffuse or line of sight systems. Figure 2 shows a diffuse system. A source illuminates a wide field of view and radiation is scattered by the internal surfaces of the space, much as light from lamps. This creates a large number of paths from source to receiver, which makes the system robust to one of them being blocked. However, the path losses are high and multipaths create inter-symbol interference (ISI). In RF systems it is possible to overcome ISI using multi-carrier techniques and signal processing, but the very high link loss of diffuse channels makes it unlikely that data rates of 1Gbit/s can be achieved in the near future.

The first optical wireless data communication system proposed by the authors Gfeller and Bapst [GFE 79] was a diffuse infra-red system operating at about 950nm and 1Mbit/s, and the fastest 'pure' diffuse system reported is a 50Mbit/s system reported by Marsh and Kahn[MAR96]. Quasi-diffuse systems illuminate the walls and ceiling with controlled illumination, and use a receiver that only accepts radiation from a limited range of angles. This aims to combine the robustness of the diffuse system with high data rates. Figure 3 shows the geometry of such systems. Such a geometry was first proposed in [YUN 92], where multiple sources that illuminate the ceiling are used in combination with are used in conjunction with an array of narrow field of view receivers that 'see' one spot which is not dispersive as all the path lengths from transmitter to receiver are close to the same distance. This paper introduced the concept of the imaging receiver to achieve this function. There are many later examples using this principle (see for instance [DJA00]).

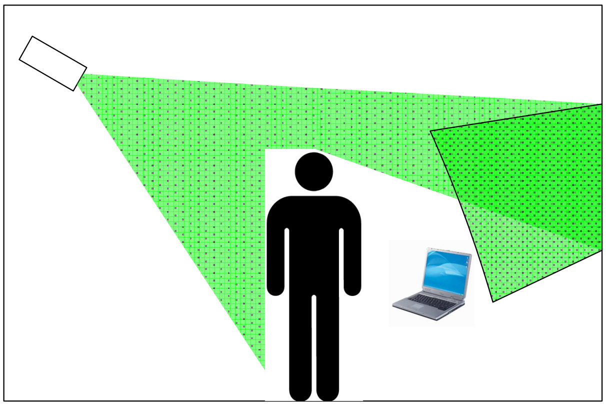


Figure 2: Diffuse Link

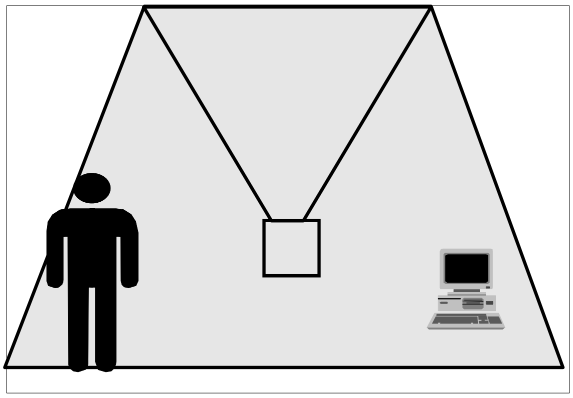


Figure 3: Quasi -diffuse link

Line of sight systems do not suffer impairments from the channel other than geometric loss, and there is no ISI. The geometric loss and transmitter and receiver field of view determine the link budget and available data rate, and in general the narrower the field of view the higher data rate is achievable. Figure 4 and Figure 5 show the geometry for Wide LOS (WLOS) and Narrow LOS (NLOS) systems.

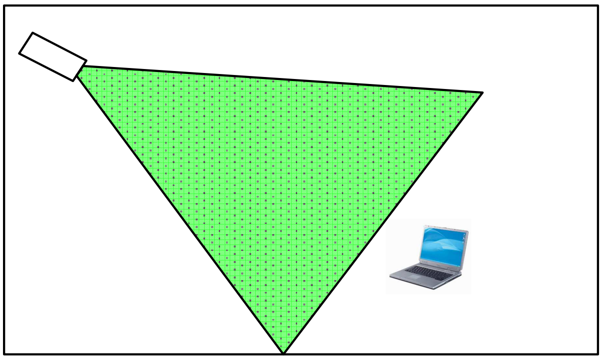


Figure 4: Wide Line of Sight (WLOS) Link

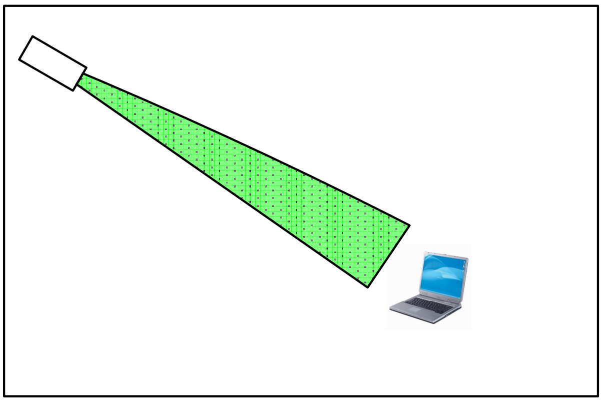


Figure 5: Narrow Line Of Sight (NLOS) Link

However, such narrow links do not provide coverage, and cellular systems use a number of LOS links to provide coverage and high data rates. Figure 6 shows an LOS cellular geometry. Several approaches have been taken to implementing the multiple element transmitters and receivers. In [PAR 01] and [WIS 97, OBR 03b] an imaging approach is taken. An array of sources is imaged to a range of angles, providing a cellular coverage pattern within the desired coverage area. The receiver uses a detector array, where radiation from different angles is imaged to particular elements of a detector arrays. This approach allows the multiple channels required to be implemented using monolithic, albeit custom, components and is illustrated in Figure 7. The alternative approach is to build an angle diversity system that uses individual sources and detectors that are arranged to point at different angles to provide the necessary coverage. Such angle diversity receivers are described in [CAR 00] and shown in Figure 8. Both these systems suffer from blocking, and appropriate geometries must be used in order to minimise this, including multiple base stations addressing individual terminals.

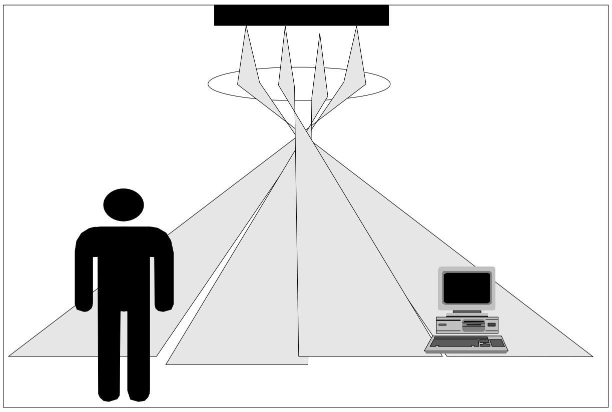


Figure 6: Cellular geometry

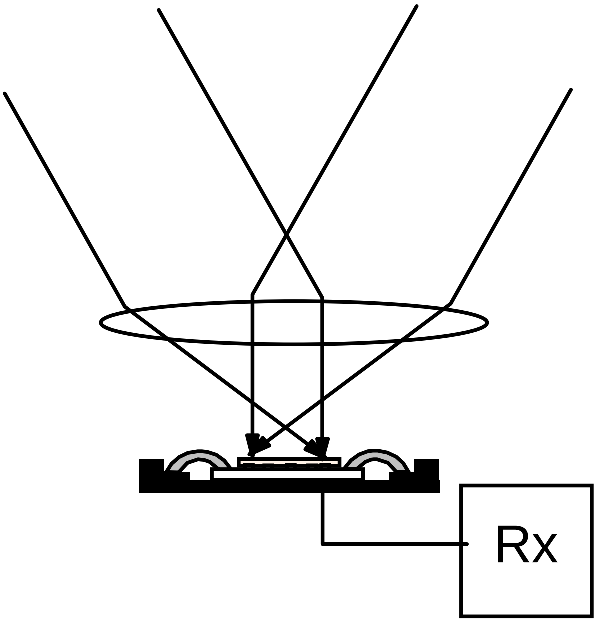


Figure 7: Imaging receiver

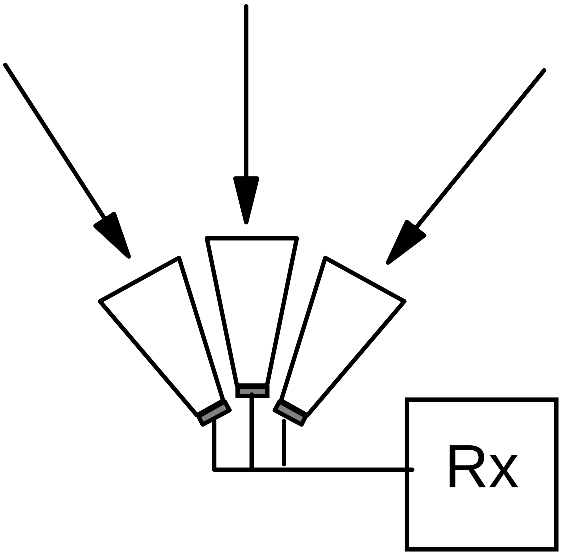


Figure 8: Angle diversity receiver

In the context of OMEGA diffuse propagation is not feasible for the high data-rates required for the IR system, and channel modelling reported for the VLC system also indicates that the effect of diffuse propagation in this context is small.

3.2 Introduction to Visible light communications

Visible Light Communications (VLC) uses modern solid-state lighting to broadcast information. Most approaches use high-power white LEDs (although there are some efforts with fluorescent light [TAL]). These sources can be modulated at high-speed (compared with other lighting sources) and are predicted to become widespread in general lighting applications.

The pioneering work of the Japanese VLC consortium [VLC] has led to widespread interest within the research community, leading to the formation of an IEEE study group for VLC standardization [HAR 08]. The particular appeal of VLC lies in the fact that the same sources can be simultaneously used for both lighting and data transmission.

VLC can provide information broadcasting within (semi)public areas (offices, airports, trains, railway stations, conventions…), or high-speed downloads to mobile devices (PDA, phone,…), and other appliances. The use of LEDs for traffic signals and automotive lamps also offers the potential for VLC in the area of intelligent traffic systems.

Research efforts of the group from Keio University in general assume a VLC system consisting of RGB LED lamps positioned suitably on the room ceiling, to create lighting levels that meet typical office illumination standards (as illustrated in Figure 9). Within the scope of their work, they have investigated the propagation effects in the VLC channel that lead to degradation of the system performance, such as multipath dispersion [TAN 01,FAN 02,KOM 04a,KOM 04b] or shadowing [KOM 04c]. Consequently, various approaches, such as application of different modulation formats (RZ-OOK and OFDM with BPSK in [TAN 01], PPM in [FAN 02]), transmitter and/or receiver with narrow FOV in combination of tracking (in [KOM 04a,KOM 04b]) were suggested to mitigate these effects. However, the predicted transmission rates reported in these papers (e.g. 400 Mbit/s with OFDM in [TAN 01], or even 1Gbit/s in [KOM 04b]) lead to believe that the modulation bandwidth of the signal is an order of magnitude of 100 MHz, which seems to be very questionable for a system with white LEDs without equalization. In [KOM 04c] it was argued that with several LED lamps distributed on the ceiling, shadowing is not a problem for high speeds (~800Mbit/s).

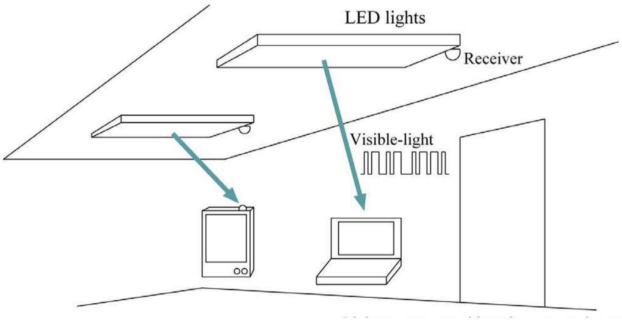


Figure 9: VLC system utilizing white LEDs in an indoor environment [KOM 04].

Improvement of system performance in environments with ISI by the use of equalizers was investigated in [KOM 05]. Simulated NRZ-OOK signals (at 100Mbit/s-1Gbit/s) were used to evaluate the potential of an adaptive equalizer with a Least Mean Squares (LMS) algorithm. The simulation results showed that both FIR (linear) and Zero Forcing –Decision Feedback Equalizers (ZF-DFE) are effective for rates of up to about 400Mbit/s, whereas ZF-DFE was found to be more suitable at higher rates.

An OFDM-based system for VLC was also investigated at the University of Bremen. In [AFG 06], a data rate of 8 kbit/s (without pilots or synchronization overhead) was demonstrated over a distance ~1 m, when a RGB LED was intensity modulated by an electrical OFDM signal, where each electrical sub-carrier was QPSK-modulated. They also showed the influence of different noise sources (sunlight, fluorescent light) on the BER, compared with a low noise case such as a dark room. In [ELG 07], a similar system was considered, and this used pilot sub-carriers to correct frequency synchronisation errors, training sequences for channel estimation and time synchronisation routines. Forward error correction (FEC) coding was used. It was shown that for COFDM (coded OFDM) with QPSK modulation and a single LED (this time however a blue chip with phosphor), a BER of 2e-5 was achieved for a distance of 90cm between transmitter and receiver. Nevertheless, higher order modulation formats still resulted in a worse BER even for significantly shorter distances (60 cm). (It was not feasible to use 64-QAM with respect to the electrical subcarriers).

Another demonstration of a VLC link using a white LED as broadcast emitter was reported in [LOP 06], where a data rate of 500 kbit/s was achieved using a pulse position modulation (PPM) scheme. Work reported in [GRU 07a,GRU 07b] also considered the widely available white LEDs consisting of a blue LED chip and phosphor layer. It has been shown in [GRU 07a] that the impact of the long response time of the phosphorus component on the LED modulation bandwidth can be mitigated by detection only of the blue peak of the emission spectrum of the white LED. The resulting modulation bandwidth is then approximately 15-20 MHz, i.e., an order of magnitude larger than when no filtering is made (see Figure 10). Similar to work in [TAN 01,FAN 02,KOM 04a], and [KOM 04b], the potential for high speed broadcast using OFDM-signals (which intensity modulate LEDs) as well as M-PAM modulation were evaluated. Simulations performed in [GRU 07a] have shown that the achievable rates are comparable for both techniques and are in the range of several hundreds Mbits/s (over the distances of 1.6-4 m), due to the very strong LOS in the channel (when using typical illumination levels). The proof of concept is reported [GRU 07b], where 40 Mbit/s was achieved with NRZ-OOK, and 100 Mbit/s with OFDM. In this case the power of the high subcarriers was adjusted to pre-compensate for the non-ideal characteristic of LED modulation bandwidth up to 20 MHz.

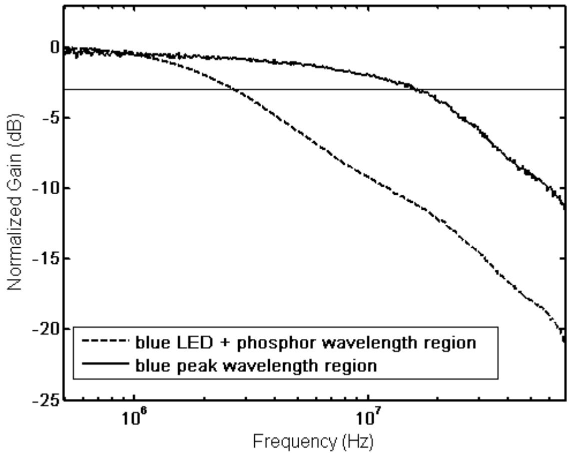


Figure 10: Modulation bandwidth of a phosphorescent white-light LED without (dashed) and with (solid) filtering, [GRU 07a].

Simulations aimed at the optimization of the LED distribution on the ceiling were reported in [DEQ 07].
As each of the LED lamps needs a power supply, power line communications (PLC) is an attractive method of delivering data to the VLC transmitters. Figure 11 shows a schematic of such a system. In [KOM 03] and [KOM 06], an integrated system of VLC and PLC was analyzed. Transmission rates of 1Mbit/s using SC-BPSK modulation where experimentally shown in [KOM 03]. In [KOM 06], PLC in combination with narrowband OFDM (reaching up to 200 kbit/s) was suggested and simulated. Future PLC standards aim to support the high data rates that will be required to match those required for VLC, and an aim of OMEGA is to improve available rates for PLC.

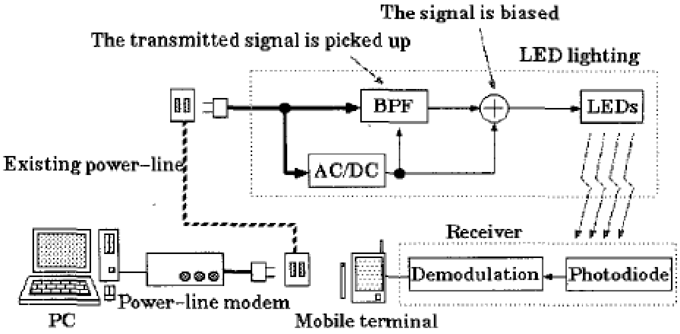


Figure 11: Combination of PLC and VLC system [KOM 03].

In [MIY 06], spatial multiplexing to increase the available data rate was proposed. The aim is to achieve 1 Gbit/s between a transmitter consisting of two-dimensional LED panel (24x24 chips with bandwidth of about 10MHz), sending different data streams in parallel, and a two-dimensional receiver composed of lens and image sensor. Figure 12 shows a schematic of the system. In order to combat the interference between the channels, a special algorithm for LED allocation was developed.

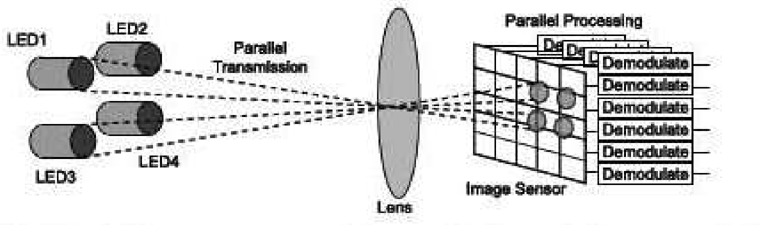


Figure 12: The concept of parallel optical wireless communication (MIMO) [MIY 06].

A challenge for VLC is to allow variable levels of illumination, but maintain a communications channel. Two mechanisms for brightness control were proposed in [SUG 07] – pulse width modulation (PWM) and adjustment of modulation depth, both in combination with PPM for information transmission. Nevertheless, lower Tx powers undoubtedly lead to lower transmission rates or distances.

Even though majority of proposed VLC systems are based on white LEDs (as is the case in OMEGA), there have also been efforts towards modulation of fluorescent light, nevertheless for special applications, requiring very low speeds. For example, [LIU 06] and [LIU 07] proposed a system which uses a combination of RFID, Bluetooth and VLC connections to provide a guidance system for visually impaired. Some experiments were performed with user speeds between 0.5 – 3 m/s and data rates between 1200 – 9600 bit/s.

Widespread use of LEDs in traffic applications and growing interest in Intelligent Transportation System (ITS) presents an opportunity for VLC. Figure 13 shows a typical application. Different light sources have been investigated (LED traffic lights) [AKA 01], [BIN 06], [IWA 07], [ARA 07], [HAR 07], and [PAN 99], as well as LED road illumination [KIT 03]). In [IWA 07], however, communication between vehicles using brake lights is also proposed. Theoretical analyses from Keio University [AKA 01], [BIN 06] and [KIT 03] examined the effect of different modulation schemes (OOK, SC-BPSK and 2-PPM) on system performance. Different experiments were also performed to evaluate the feasibility of VLC based ITS. In [PAN 99], transmission up to 20m with 441 LEDs is achieved. In [IWA 07] and [ARA 07], parallel transmission was implemented by modulating each of LEDs on traffic lights individually. Both systems had data rates of about 100kbit/s and distances up to 70 m were reached in [ARA 07]. The target of [HAR 07] was long-distance and high-speed. In this system, an audio signal was encoded with pulse width modulation. A distance of 100m and a speed of few Mbit/s were reported.

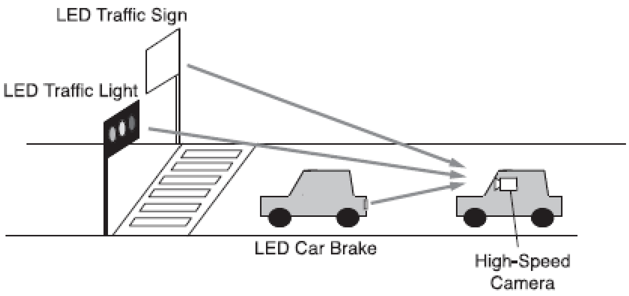


Figure 13: Road-to-vehicle communication using LED traffic light and high speed camera [ARA 07].

The next section details typical link budget constraints and modelling techniques for the LOS channel, and for completeness reviews the work on the diffuse channel-although this has limited importance for the work described here.

3.3 Link budget and link modelling

In this section we provide a brief state of the art on the channel modelling for optical wireless systems. The indoor optical wireless channel is essentially modelled as a baseband channel. At the receiver, the detected electric current is given by [JMK97];

$$i(t) = Rh(t) \otimes P(t) + n(t)$$

where R is the detector responsivity, $h(t)$ denotes the channel's impulse response, $P(t)$ is the optical power at the transmitter while $n(t)$ is the noise current at the receiver and $\otimes$ denotes convolution. The optical power at the transmitter is determined by the modulation type used (see section 4.3).

3.3.1 Propagation Types

The impulse response $h(t)$ is determined by the propagation and room type as well as the transmitter and receiver positions. It comprises of a line-of-sight component which is a Dirac (delta) function and a diffusive component arising from reflections at the walls of the room [JRB93]. Figure 14, shows the basic transmitter-receiver arrangement.

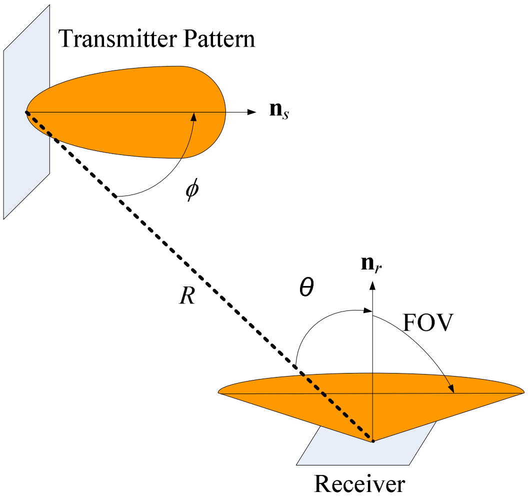


Figure 14: Example of a receiver-transmitter arrangement

Depending on the propagation type, the channel impulse response may have different attributes. There are several propagation types that can be considered for indoor optical wireless systems:

Narrow Line of Sight (NLOS): This is the simplest and the most well known configuration used in optical wireless point-to-point communication systems. In this case, the emitter and the receiver are aligned, manually or automatically to establish a direct LOS link. Multiple transmitter/multiple receiver systems could provide an alternative towards achieving good room coverage and lower blocking probability.

Wide Line of Sight (WLOS): This configuration is characterised by emitters with a large angle or divergence offering wider coverage, and receivers having a larger Field Of View (FOV) than the NLOS case. This wide coverage offers additional tolerance in the alignment between the emitter and the receiver, at the expense of a larger geometric power loss, which may degrade the performance of the link.

Diffuse: In this configuration there is either no line of sight path, or power is distributed evenly between LOS and NLOS paths. The receiver collects the power originating from reflections on various surfaces on the room.

3.3.2 Line of Sight Component

The LOS component $h_{\mathrm{LOS}}(t)$ of the impulse response can be calculated in a straightforward manner. We define the effective detector area $A_{eff}(\theta)=\mathrm{A}T_s(\theta)g(\theta)\cos\theta$ for $0\leq\theta\leq\mathrm{FOV}$ and $A_{eff}(\theta)=0$ otherwise where $T_s(\theta)$ is the signal transmission of the filter, $g(\theta)$ is the concentrator gain and A is detector area. If the transmitter transmits a radiant intensity of $P_tR_0(\phi)$ then the DC channel gain is [JMK97]:

$$H_{LOS}(0)=\frac{A}{R^2}R_0(\phi)T_s(\theta)g(\theta)\cos\theta$$

where $H_{\mathrm{LOS}}(f)$ is the Fourier transform of $h_{\mathrm{LOS}}(t)$. Usually $R_0(\phi)$ is assumed to obey a Lambertian law [GFE79], $R_0(\phi)=[(m+1)\cos^m\phi]/2\pi$ where m can be related to the transmitter semi-angle at half power. An idealized concentrator achieves a gain given by $g(\theta)=n^2/\sin(\mathrm{FOV})$ if $0\leq\theta\leq\mathrm{FOV}$ and $g(\theta)=0$ otherwise [XN87] where n is the internal refractive index of the concentrator.

3.3.3 Diffusive component

The diffusive component $h_{DIFF}(t)$ of $h(t)$ is somewhat harder to calculate as one needs to take into account the various surfaces in the room. When a light ray impinges on a surface, part of it is reflected and hence the surface acts as a virtual transmitter. Most surfaces present irregularities and thus they reflect the incident rays of light in all directions, independently of the incident ray's orientation. The radiation pattern of this virtual transmitter is usually described by a Lambertian law with $m=1$,

$$R(\theta) = \rho P_i \frac{1}{\pi} \cos(\theta)$$

where ρ is the surface reflection coefficient, P_i is the incident optical power and θ observation angle. A more general model was adopted by Phong in which the radiation pattern is

$$R(\theta, \theta_0) = \rho P_i \left[\frac{r_d}{\pi} \cos(\theta) + \frac{m+1}{2\pi} (1 - r_d) \cos^m (\theta - \theta_i) \right]$$

with r_d is the percentage of incident signal that is diffusely reflected, m the directivity of the specular component of the reflection and θ_i is the angle of incidence. This model allows the treatment of reflections on smooth surfaces with a high specular component, considering them as the sum of one specular component and a diffuse one (Lambertian term).

To calculate the impulse response $h(t)$ of the channel taking into account the diffusive component, one must resort to numerical simulations in order to account for light reaching the receiver from multiple reflections on the various surfaces of the room. In 1993, Barry et al [JRB93] came up with a recursive model for simulating multiple reflections. In 1997, Perez-Jimenez et al presented a statistical model for estimating the impulse response [RPJ97], while Lopez-Hernadez et al proposed the DUSTIN algorithm [FJLH97]. In 1998, the Monte Carlo scheme involving random ray generation was proposed for the simulation of the multipath indoor optical wireless environment [RPJ98a], [RPJ98b]. Carruthers et al proposed a new iterative site-based model to estimatethe impulse response [JBC02].

A recent comparison [AS03] of these techniques shows that the Monte Carlo schemes outperform the DUSTIN algrorithm with respect to the computational time and rates fairly well in terms of memory requirements with respect to the rest of the methods. Monte Carlo schemes may handle up to 40 ray bounces providing improved accuracy. In such schemes the simulation is performed in three stages: a) Generation of rays, b) Characterization of the walls and c) Calculation of the response of the photodiode. Rays are generated randomly at the emitter site depending on the emitter radiation profile. The impact point of each ray is then calculated. The impact point may either lie on the receiver plane or in one of the walls of the room. If the impact point lies on a wall then this point is considered as a secondary light source and a new ray is generated as before. If the impact point lies on the receiver then the incident power is recorded on a vector at the appropriate position which is calculated by estimating the total delay of the optical path from the transmitter to the receiver. In the *modified Monte Carlo scheme* [RPJ98b], a line of sight contribution between the source (wall or emitter) and the receiver is calculated every time the ray bounces on a wall (Figure 15) and this can speed up the computations considerably.

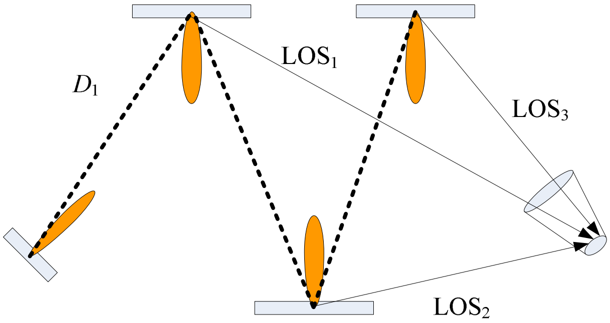


Figure 15: Modified Monte Carlo scheme

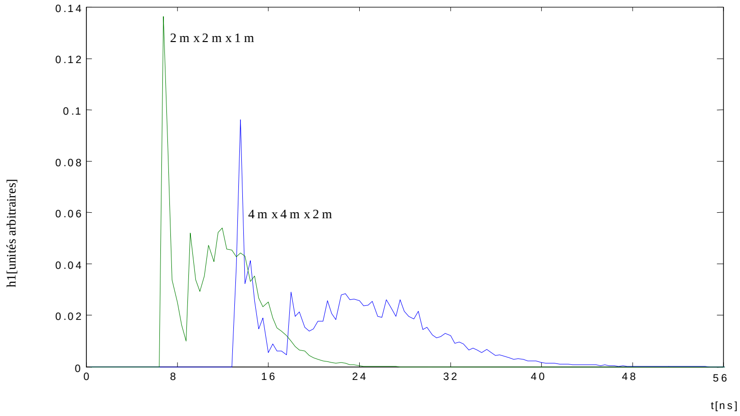


Figure 16: Typical indoor optical wireless channel impulse responses.

A model proposed by Alqudah in 2003 [YAA03], may also lead to large computational time saving when the impulse response needs to be estimated for various receiver positions in the room. In Figure 16, typical examples of optical wireless channel impulse responses are given. One clearly observes a sharp peak occurring early on the time axis, corresponding to the line-of-sight component $h_{LOS}(t)$ and a broader part corresponding to $h_{DIFF}(t)$. In systems with a larger FOV at the receiver (WLOS systems for example), the impulse response $h_{DIFF}(t)$ may constitute a considerable part of $h(t)$ since rays bouncing on the room walls reach the receiver from many different directions. Reducing the FOV, reduces $h_{DIFF}(t)$ and in systems with narrow FOV, $h_{DIFF}(t)$ can be ignored and the channel may be assumed flat within a large frequency range.

3.3.4 Intersymbol Interference

Intersymbol interference (ISI) may arise from the diffusive part of the channel's impulse response. Assuming for example a simple On/Off keying modulation, the transmitted power can be written as:

$$P(t)=\sum_m b_m p(t-mT_b)$$

where b_m is the m^{th} encoded bit and $p(t)$ is ideally a square pulse contained inside [0 T_b] and T_b is the bit duration. In this case, the decision variable at the receiver is

$$D(t_s)=R\sum_m b_m p(t_s-mT_b)\otimes h(t_s)\otimes h_r(t_s)+n(t_s)\otimes h_r(t_s)=R\sum_m b_m c_m+n(t_s)\otimes h_r(t_s)$$

where the coefficients c_m are given by $p(t_s\text{-}mT_b)\otimes h(t_s)\otimes h_r(t_s)$ and $h_r(t)$ is the receiver filter. If the diffusive part of $h(t)$ is negligible then $h(t)$ is proportional to a dirac function and c_m=0 for $|m|>0$, implying zero ISI. If this is not the case, ISI appears and depending on the bit rate and the duration of the diffusive part of $h(t)$, ISI can impose restrictions on the performance of the link.

3.3.5 Noise Statistics

The noise at the receiver $n(t)$ is due to various sources: thermal receiver noise [GE96], ambient light noise [ABC96] and interference from fluorescent lighting [RN96]. Many infrared systems operate in the presence of steady, high intensity background radiation, and this background-induced shot noise is typically much stronger than the signal shot noise. Neglecting the signal shot noise, the ambient-induced shot noise can be considered additive Gaussian Noise. The thermal noise may also be considered Gaussian and additive. In contrast, fluorescent lighting induces an interference signal which is nearly deterministic. Lamps driven at the power-line frequency induce interference harmonics up to ~50KHz [AJCM95]. Electronic ballasts use transistors which modulate the power at higher frequencies and introduce interference harmonics up to ~1MHz [AJCM95]. It is useful to separate the interference signal contribution, writing the receiver noise as

$$n(t)=n_g(t)+n_i(t)$$

where $n_g(t)$ is the Gaussian noise component and $n_i(t)$ is the interference induced component. The noise term $n_g(t)$ is completely characterized by its spectral density. Considering a transimpedance preamplifier with a bipolar junction transistor in the first stage and a photodiode capacitance C_{det}, the thermal noise one-sided power spectral density is [JBC00]:

$$S_t(f)=\frac{4kT}{R_f}+2qI_b+4kT(2\pi f)^2\times\left[C_{\text{det}}^2R_{base}+\left(C_{\text{det}}+C_\pi\right)^2\left(\frac{1}{2g_m}+\frac{1}{R_cg_m^2}\right)\right]$$

where R_{f} is the feedback resistor, I_{b} is the front-end transistor base current, g_{m} is the transistor transconductance and C_π is the base-collector capacitance. The temperature, T, is in Kelvin, q is the charge of an electron and k denotes Boltzmann's constant. The spectral density of the ambient light noise component is [JMK97]:

$$S_a(f) = 2qI_{ambient} = 2qRP_{ambient}$$

where I_{ambient} is the current of the ambient light noise, $P_{ambient}$ is the irradiance of the ambient light noise at the photodetector, and $q = 1.6 \times 10^{-19}\,\text{Cb}$ is the electron charge. The value of $P_{ambient}$ can be calculated numerically based on measurements of the spectral emittances of the walls of the room and a Lambertian model for the radiation pattern of the room lamps. The Gaussian total noise power σ_g^2 of the noise $N=n_g(t_s)\otimes h_r(t_s)$ can be computed, integrating the total filtered spectral density:

$$\sigma_g^2 = \int_0^{+\infty} df\, |H_r(f)|^2\, S_g(f)$$

where $S_g(f)=S_a(f)+S_t(f)$ and $H_r(f)$ is the receiver filter response. The Signal to Noise ratio, SNR is

$$\text{SNR} = \frac{c_0}{\sigma_g}$$

The above formulas correspond to unequalized system. If an equalizing scheme is used (e.g. Distributed Feedback Equalizer) is used, the SNR can also be calculated analytically [QY06].

3.3.6 System Performance Evaluation

Probably the most useful system performance figure-of-merit is the bit error probability at the receiver P_e, also referred to as the Bit Error Rate (BER). For the unequalized system, it is relatively straightforward to derive a formula for P_e. Assuming On/Off Keying [GE96],

$$P_e = \frac{1}{2}Q\left(\frac{c_0 - V}{\sigma_g}\right) + \frac{1}{2}Q\left(\frac{c_0 + V}{\sigma_g}\right)$$

where V depend on the neighboring bits and the filtered interference signal,

$$V = R\sum_{m\neq 0} b_m c_m + n_i(t_s)\otimes h_r(t_s)$$

Note that the formula of P_e given above actually refers to the error probability obtained conditioned on the value of V. To obtain the average P_e one must average over all possible values of V and hence all possible combinations of the neighboring bits and interference signal instances need to be considered. In addition, although the formula holds for On/Off keying it is possible to derive similar formulas for the BER for various other modulation formats such as multi-level Pulse Amplitude Modulation (PAM) or Pulse Position Modulation (PPM) [MDA95].

3.4 Infra-red optical wireless components

The following sections describe the transmitter and receiver components that are used for infra-red optical wireless, together with some of the constraints on their performance.

3.4.1 Transmitter

The transmitter consists of a source of radiation that can be modulated, drive electronics, and optical systems to render the source eye safe and shape the radiation into the desired pattern. Each of these components is described in the following sections.

3.4.1.1 Sources and drive electronics

The main element of the transmitter is the optical source. LEDs are typically too slow for high-speed operation, although Resonant Cavity LEDS (RCLEDs) were operated at up to 300Mbit/s in the optical wireless system described in [OBR 05]. For the gigabit class data-rates considered in OMEGA semiconductor lasers are required as a source.

There are several options to provide the power required. Edge emitting lasers are commonly used, and are available in a wide range of wavelengths and power levels. These have the advantage of low resistance, but the beam profile is usually highly asymmetric, requiring further beamshaping to achieve a circular emission. Vertical Cavity Surface Emitting Lasers (VCSELs) have circular beam profiles and optical design is therefore more straightforward. However, the power levels available are usually limited to 10s of mW [ROI 08].

An important consideration is the ability to modulate these sources at high data-rates. A wide range of commercial laser driver ICs is available [MAX 05], for telecommunications and consumer applications (such as Blue-Ray disc laser drivers), but providing sufficient current to drive lasers emitting more than 100mW is likely to be challenging. In addition lasers operating at these power levels are usually not specified at the operating wavelengths required.

Alternative approaches

An alternative approach that is appropriate at 1500 nm is to use a telecommunications laser in combination with an Erbium Doped Fibre Amplifier. This can provide transmission powers >1W, and has been used in long-range outdoor point to point links [GOE 05]. An indoor fibre based distribution system was demonstrated in [SHI 05] and this used amplified light from a WDM source that was routed in free-space. Arrays of sources can increase the transmitted power, and also provide a tracking transmitter. In this case each source addresses a small range of angles, providing a large overall field of view and high bandwidth. This was the approach used in [OBR 05].

3.4.1.2 Transmitter optics

The transmitter optical system directs light from the source to the desired coverage area, and diffuses the source if required. For LOS systems a narrow beam is required, and high Numerical Aperture (NA) optics can be used to collimate the beam. For arrays of sources a collimated lens also provides a means to direct individual beams to particular directions in the coverage space, and this was used in the system described in [OBR 05].

In some cases a diffuser is required to increase the angular extent of the source, thus rendering it eyesafe. This can be achieved using a ground glass plate, or more sophisticated engineered diffuser elements, including holographic [EAR 96] and reflective [BEN 02] examples. This latter device has been incorporated in a commercial optical link [JVC 03].

3.4.2 Receiver

A typical OW receiver consists of an optical system to collect and concentrate incoming radiation, an optical filter to reject ambient illumination, and a photodetector to convert radiation to photocurrent. Further amplification, filtering and data recovery are then required

Optical systems

The receiver optical system collects light from a defined field of view and concentrates it onto the photodetector. The optical gain (that is the ratio of the collection area to the detector area) is constrained by the constant radiance theorem.

This states that

$$A_{coll}\sin^2(FOV)\le A_{\det},$$

where A_{coll} is the collection area, $A_{\det}$ is the photodetector area, and FOV is the field of view (half angle). For a diffuse system, where light is received from all directions the detector area sets how much power can be collected, and an optical system will not change this (except by an amount n^2) where n is the refractive index of the system.

Both imaging and nonimaging optics [WEL 78] can be used to collect and focus radiation onto single element detectors and these can have performance that approaches the thermodynamic limit [WEL 78]. However, for wide field of view high bandwidth designs, the usage of a single photodiode-concentrator combination is unlikely to meet the system requirements, since a quite small photodiode area $A_{\det}$ (and hence capacitance) has to be used to obtain high bandwidth. For a wide FOV, this leads to a small A_{coll}, so that multiple detectors are required. These can be combined using angle or imaging diversity. Angle diversity allows multipaths to be resolved and collection areas for each receiver element to be increased [CAR 00]. Imaging receivers [OBR 05] and [KAH 98] can also carry out this function. These use a large-area pixellated detector array and an optical imaging system. Light from narrow range of directions is collected by a single pixel, and together the array of pixels offers a large overall field of view. It also allows multipaths from different directions to be resolved as they are imaged to different pixels on the array. The array also allows the large detection area to be segmented, reducing the capacitance on each of the receiver front ends. Both of these topologies can to some extent resolve multipaths, and this may offer some means to reduce the effect of shadowing, by selecting an alternative non shadowed path. It is also possible to use a combiner/equaliser to maximise the received signal and BER [CAR 00].

3.4.2.1 Optical filtering

Ambient light is the most important source of interference and it may greatly deteriorate link performance [BOU 96]. Constant ambient illumination will generate a DC photocurrent, but the DC current itself will normally be blocked by the AC coupling of the receiver [PHA 98]. However, as a result of the quantum nature of light, this current is always accompanied by shot noise. Compared to the residual noise sources within the preamplifier (such as the thermal noise of the load resistance), the background light induced shot noise often dominates. Since its power spectral density depends linearly on the power of the received background light, optical filters need to be used to allow sensitive receivers to be built. Artificial illumination, particularly modern high frequency fluorescent illumination induces electrical harmonics in the received signal, with components up to 1 MHz [NAR 96] and this can greatly affect the link performance. Various studies of this have been undertaken, including [MOR 96] and [OFA 96].

Optical filtering is used to reject out of band ambient radiation. Various different filter types have been demonstrated; a longpass filter in combination with a silicon detector provides a natural narrowing of the bandwidth and absorption filters can be used to reject solar and illumination [STR 97]. Whereas coloured glass filters exhibit a slowly transition from the stop band to the passband, absorption filters made of direct semiconductors like GaAs provide a much sharper transition [WOL 02]. Bandpass interference filters can be used, although care has to be taken to allow sufficient bandwidth to allow for passband shifting with the varying angle of incidence. It is also possible to filter by incorporating appropriate layers into the photodetector [OBR 00]. Holographic receiver front-ends also allow ambient light noise to be rejected [JIV 01].

Electrical highpass filtering can be used to reduce the effect of the illumination harmonics, but possibly at the cost of inducing baseline wander. Work on the optimal placement of the filter cut-offs for particular modulation schemes is reported in [SAM 98].

3.4.2.2 Detectors

The detector and preamplifier together are the main determining factor in the overall system performance. Both PIN structures and APDs have been used in single detector systems, whilst array receivers have tended to use PIN devices.

Silicon PIN and APD devices are suitable for operation at wavelengths up to 1000nm. Figure 17 shows the wavelength dependent responsivity R_λ of an ideal silicon-PIN photodiode, were it was assumed that all impinging photons generate electron-hole pairs which contribute to the photo current. For a given optical power, it becomes clear that the diode current linearly increases with λ unless λ exceeds the cut-off wavelength (about 1100 nm), i.e., unless the band gap of silicon exceeds the photon energy. In other words: the efficiency of the opto-electrical conversion increases with λ, as long as λ does not exceed the semiconductor specific cut-off wavelength.

The bandwidth of a receiver is a function of the capacitance limited risetime of the detector/preamplifier combination and any transit time limitations the detector may have. The optimum devices balance transit time and capacitance limited response. High-speed epitaxial PIN diodes (that are not transit-time limited) with capacitances of approximately 5pF/mm^2 are available, although modelling shows that custom devices should perform better.

At 1300nm and 1500nm InGaAs devices are typically used, and commercially available devices have capacitances of 60pF/ mm^2. Work in [OBR03] demonstrated custom devices with 23pF/ mm^2 but these are not optimal and had poor leakage currents. This means that for a similar capacitance and hence bandwidth devices have a smaller area than their silicon counterparts. This effect is balanced by their higher responsivity, the overall relative response being dependent on the devices used.

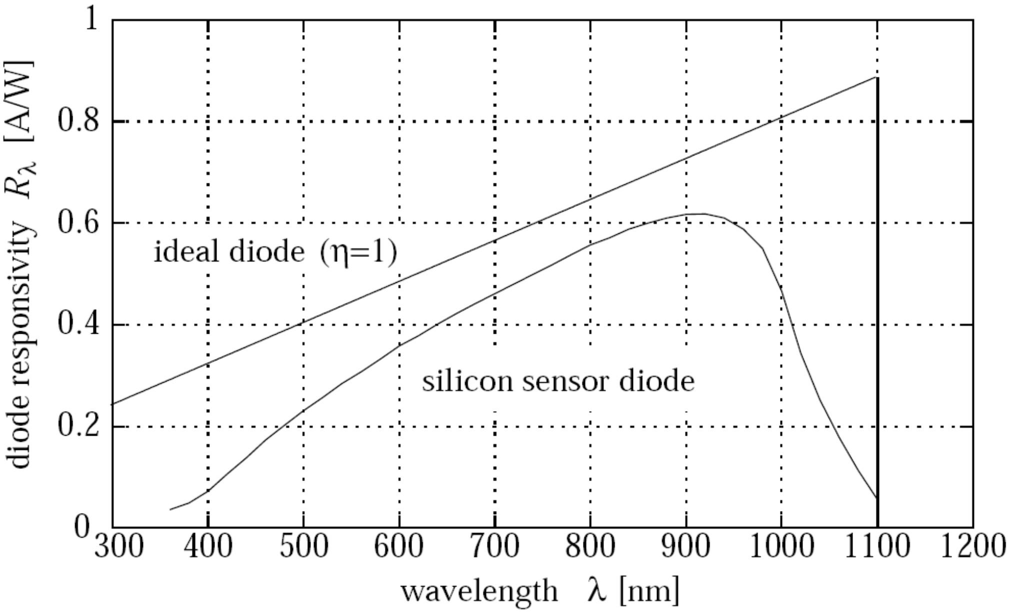


Figure 17: Photo diode responsivity R_λ as a function of the wavelength. An ideal silicon PIN-diode is compared to the silicon-sensor diode SSO-PD20-6.

3.4.2.3 Preamplifiers

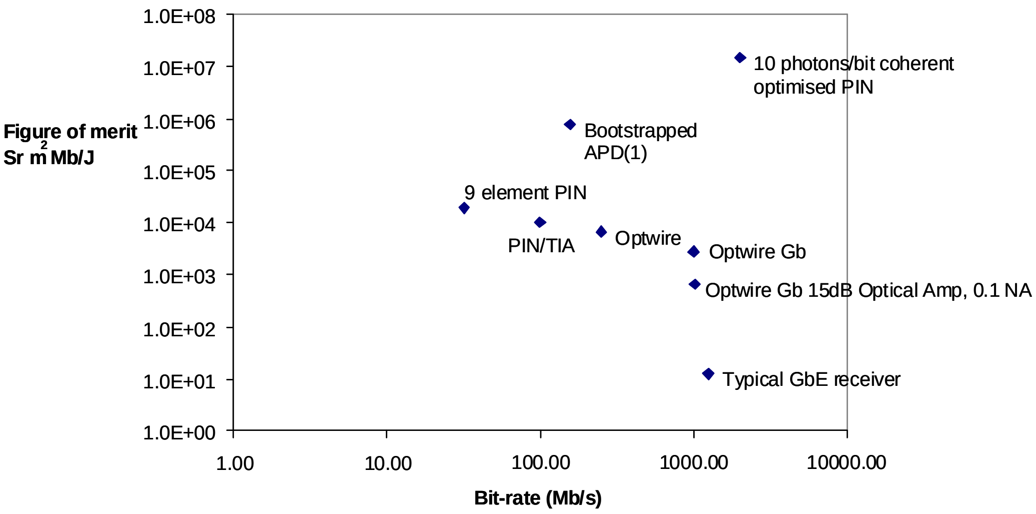
Various approaches to mitigating the effect of input capacitance on bandwidth have been taken. Beside the widely used transimpedance designs [VAN 84], bootstrapping [MCA 94], equalization [MAR 96] and capacitance tolerant front-ends [OBR 05], [LAL 01] and [HOL 01] have all been investigated.

3.4.2.4 Receiver figure of merit

From the previous sections it can be seen that sensitivity does not completely describe a receiver, as a sensitive receiver with a very small photodetector can receiver substantially less power than another design and therefore be less useful. In [OBR 05a] a figure of merit that allows an initial comparison of designs is introduced. This takes into account the sensitivity S_e, bit-rate of operation R_b, field of view Ω, detector area *A* to create *FOM* where;

$$FOM = \frac{\Omega A R_b}{S_e}$$

Figure 18 shows a plot of this value for reported designs, simulations and calculations. Of particular note is how poor a typical Gigabit Ethernet receiver, that is optimised for fibre optics systems.



[1] M. J. McCullagh and D. R. Wisely, "155Mb/s Optical Wireless Link Using a Bootstrapped Silicon APD Receiver," Electronics Letters, vol. 30, pp. 430-432, 1994.

All other data calculations or measurements of Oxford group receivers

Figure 18: Figure of Merit for various reported and simulated receiver designs.

3.4.3 Tracking links

Tracking allows a link with a narrow beam to cover a wide field of view, and to provide alignment of transmitter and receiver, which improves the link margin. Mechanical tracking, MEMs based approaches and Risley prisms have all been used for this purpose. [SAN 06].

3.4.4 Advanced techniques: MIMO

For systems where the channel or optical sources available may limit the bandwidth the use of arrays of sources and detectors may be attractive. Normally sources would need careful alignment to provide a parallel optical interconnect, but Multi-Input Multi-Output techniques can be used to relax the tolerances on alignment [OBR 06a]. In this case the channel matrix is measured during a training phase, and this can be used to recover the transmitted data from that measured at the receiver array. This work is in its early stages and it is not possible to ascertain whether such methods have advantages over the alternatives.

3.5 Visible Light Communications components

3.5.1 Transmitter

3.5.1.1 Sources and drive electronics

In principle, the radiation from any (visible) light emitter could be modulated, either by external modulator or by internal means. Since most practical light sources are partially incoherent and since, e.g., air turbulence degrades the coherence of the transmitted light, transmission is almost exclusively relied on intensity modulation and direct detection [KAH 95]. In order to avoid light-intensity flicker that can be perceived by the (human) eye one needs to resort to light sources that offer a modulation bandwidth of at least 100 Hz [WAL 08], a requirement excluding light sources like standard incandescent and halogen light bulbs from VLC applications. While fluorescent lighting has been used for VLC [TAL] it is expected that white LEDs will displace the former as the prime lighting device. Since they will not be used for the OMEGA VLC prototype we are consequently excluding them from this review.

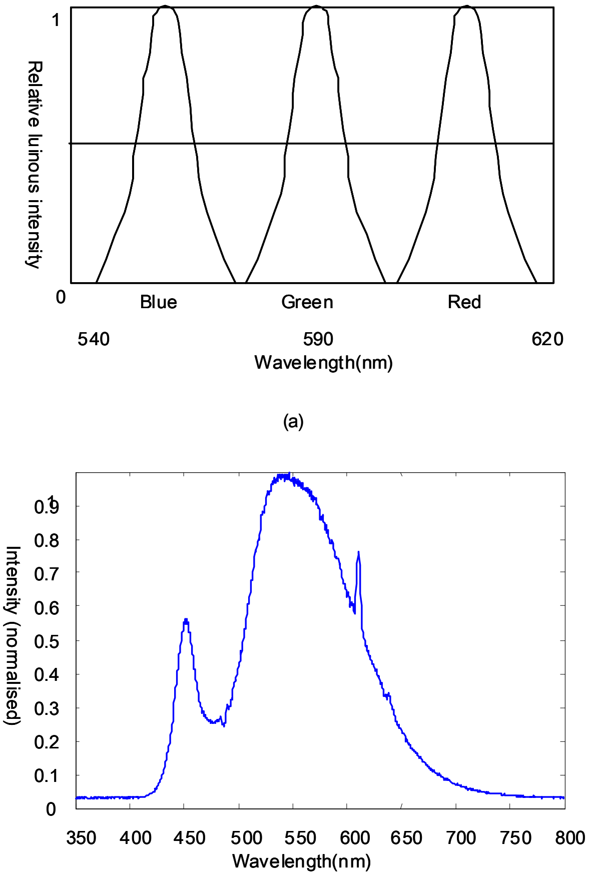
Typically LEDs have been used for signalling and display applications, while LED-based illumination devices recently entered the market. Moreover, LEDs have also enjoyed wide-spread application in optical communications, e.g. as infra-red LEDs in IrDA, or, more recently, as red LEDs in fibre-based communications [LEE 08]. Therefore two main application scenarios: simultaneous signalling/illumination and data transmission as well as sole data transmission have to be considered. Also, from a technology point of view, white light LEDs have not been widely applied in VLC and there remain some unanswered questions about these devices and their VLC potential.

In the following we provide a brief overview of ‘coloured’ LEDs in the field of VLC and a more extensive overview of the state of the art concerning white LEDs.

LED’s used for non-illumination applications, e.g., for displays, are usually limited to 20 MHz and lower [KIM 06], while LEDs developed for pure high-speed communications applications offer much higher bandwidths. For example, red resonant-cavity LEDs enable data transmission of several hundred Mbit/s. If even higher data rates are required one has to resort to diode lasers [FIR] or spatial multiplexing [WON 08b]. By use of the latter transmission speeds of 1 Gbit/s have been demonstrated.

For a thorough discussion of LED-based white-light generation schemes we refer the reader to the excellent overview provided by Schuster [SCH 06b]. Generally, there are two distinct avenues for generating white-light from LEDs. One is to combine three LED chips that emit elementary colours (mostly red, green, and blue). A typical spectrum of such devices is shown in Figure 19(a). These triplet devices are commonly referred to as RGB LEDs and typically consist of a single 3-chip package including combining optics. One application of growing importance for such devices are multi-colour LED displays. With such devices three distinct communication channels can be provided, one for each LED chip [PAR 07], however, one has to ensure that the colour balance of the emitted light is not altered due to VLC transmission.

The other avenue is to use a single, mostly blue LED and to generate the other, red-shifted spectral components needed for white light by exciting a phosphor with the blue light. The LED is either coated or sometimes even embedded in a phosphor layer. A typical spectrum for a Luxeon star (Philips, [LUM 06]) is shown in Figure 19(b). The LED emits approximately at 440 nm (visible as a small peak) and the cerium-doped yttrium aluminium garnet phosphor, which is covering the blue LED chip, absorbs a major portion of the blue emission and converts it into red-shifted phosphorescence.



(a)

(b)

Figure 19: Spectra from white LEDs (a) Schematic spectrum of a of an RGB triplet device; (b) Measured spectrum of a single-chip LED (Luxeon star) [OBR 08].

The power of the light emitted by an LED can readily be modulated by altering the driving current applied to the device. For small-package LEDs typical DC driving currents amount to 10s of mA and for lighting white LEDs the driving currents can exceed 1 A [OST 06]. The modulation range of the LED is typically smaller than two times the DC driving current. In practice the data is modulated onto the AC component of the driving current and is then added onto the DC bias current by aid of, e.g., a bias tee (see Figure 20). Notice, that LEDs only accept unipolar driving currents and that thus the absolute driving current (DC + AC) has to be larger than zero.

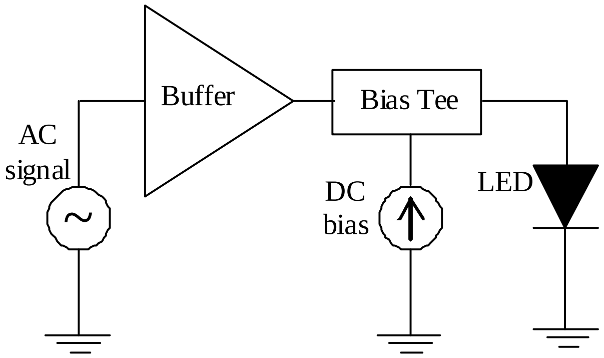


Figure 20: Typical driver circuit for modulating the optical output from a (white) LED [OBR 08].

The driving currents of several hundred milliamps at several volts for high-luminance white LEDs, e.g. Luxeon Star and OSTAR, are supplied by commercial driver ICs and units [OST 06, NAT 06, FAI 06]. These devices typically create electrical noise in the kHz and MHz region. For illumination this is not considered as long as the EMC thresholds for lamps are not exceeded [EN 94,IEC 94]. However, since the data signal is conveyed by the AC component of the driving circuit the excess electrical noise from the DC source will decrease the signal-to-noise ratio of the transmitted data signal, which is of particular concern when increasing the data rate beyond the bandwidth limit by use of multi-level modulation [GRU 07b]. Therefore, in such circumstances additional low-pass filtering of the DC output has to be performed before mixing it with the VLC signal.

Without a phosphor present the modulation bandwidth of the LED is in essence limited by both the radiative lifetime of the excited carrier-hole pairs and be the parasitic capacity of the LED [SCH 06b]. The latter can become the dominating limitation for large-area LEDs, e.g. the LUXEON star [LUM 06]. For LEDs emitting white light typical modulation bandwidths, i.e. the 3-dB bandwidth of the emitted power, lie between some MHz and 10s of MHz [KIM 06]. For phosphorescent white LEDs the light emitted by the blue LED has been reported to be ~ 20 MHz for small-chip LEDs [GRU 07a] and ~ 12 MHz for a Luxeon Star [OBR 08]. However, the radiative lifetime of the phosphors typically used for white LEDs are (much) longer than that of the blue LED [MIY 03], a phenomenon limiting the achievable bandwidth to 2 and 3 MHz, respectively, in the above cases when the entire spectrum is detected. Figure 21 shows the significant dependence of modulation bandwidth on the detected spectrum for a Luxeon Star.

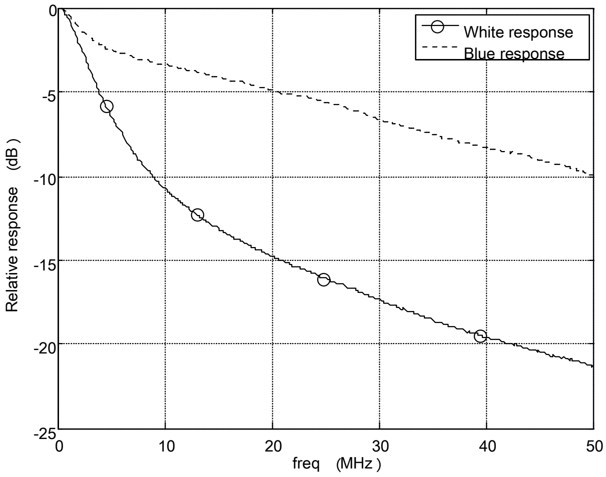


Figure 21: Measured small-signal modulation bandwidth of a Luxeon Star [LUM 06], showing unfiltered (the whole visible spectrum is detected) and filtered (only the blue portion of the spectrum is detected) responses. The responses are normalised to their respective peak values [OBR 08].

One could argue that when modulating the emitted white light in excess of the phosphor modulation bandwidth, the slow phosphor component could simply be suppressed by high-pass filtering of the received light. However, since the phosphorescent light comes with shot noise that exhibits frequencies up to the THz region, the phosphor component would compromise the achievable signal-to-noise ratio. Another downside of the phosphorescent light is that its radiative lifetime and thus the modulation bandwidth vary with wavelength, which makes frequency filtering of the received light power more difficult. For the above reason it is advisable to spectrally filter the received light before passing it on to the photo detector. This approach was used to generate the measurement data in Figure 21 and Grubor et al. exploited this approach for the free-space transmission of OOK data streams at 40 Mbit/s [GRU 07b]. A potential disadvantage of this approach is the reduction of the received light power, e.g., through a mismatch of the spectral transmission of the filter and the emission spectrum of the blue LED.

In addition to the aforementioned challenges one has to face the wide spread deployment of illuminance diming devices for LED lighting. The most common approach to white-LED dimming is pulse-width-modulation, which by definition alters the AC component of the emitted light power. Typical modulation repetition frequencies amount to 10s of kHz [NAT 06, FAI 06] and one needs to devise transmission and modulation schemes that ensure the coexistence of PWM diming and VLC data transmission. A low-data-rate PHY-layer scheme for PWM coexistence has already been proposed and standardised in Japan [LOP 06] while there has not been any discussion of MAC-layer approaches nor approaches for high-data-rate transmission.

VLC Transmission optics

The role of the transmission optics in single-purpose optical wireless data links is to

- Maximise the optical power at the receiver, viz. the link budget
- Minimise multipath dispersion caused by reflections at surfaces

The above goals have been translated into optics design rules and have been discussed in detail elsewhere in the literature [OBR 06b] (see also section 3.2.1).

While there exist many degrees of freedom for the optimisation of single-purpose optical wireless links the situation is quite different from dual-purpose links, i.e. signalling/illumination in combination with data transmission. Here, data transmission is subordinate to the signalling/illumination task. In other words not only the communication channel but also the transmitter optics is pre-defined by the super-ordinate task.

While this pre-determination of the transmission optics seems to imply severe limitations to VLC data transmission quite the opposite is true, which can be attributed to

- The high energy efficiency required from contemporary lighting, resulting in optimised lighting levels at target surfaces (e.g., writing desks) and the comparably high energy densities needed for human vision.
- The fact that most illumination is of the direct type, i.e. the light travels directly from the lamp to the target area without any intermediate (diffuse) reflection.

Consider, for instance, the dual use of office lighting for illumination and data transmission. The luminous flux in such settings is regulated in standards and the achievable power levels and thus signal-to-noise ratios at the receiver are thus predetermined by standards. Both Komine et al. provided detailed modelling of such a setting and concluded that signal-to-noise ratios in excess of 50 dB are readily available for illuminance levels above 100 lx [KOM 04a].

Furthermore, due to the direct type of illumination, Grubor et al. showed that the propagation of the light in an office setting is dominated by strong LOS connections between lamps and receiver and that the 3-dB bandwidth of the free-space channel is thus much larger than that of white LEDs considered for this scenario (100 MHz compared to 20 MHz, [GRU 07a]).

Both attributes combined result thus in links

- That are virtually unaffected by the free-space channel, and
- That offer a link budget comparable to LOS connections.

The fortunate combination of both attributes has been shown to enable spectrally efficient data transmission beyond 100 Mbit/s by the use of multi-level modulation [GRU 07b].

3.6 Modulation and coding

3.6.1 Modulation

Whereas coherent detectors may be considered as a attractive solution for highly directed optical free space links such as those between satellites, coherent optical detection is considered to be not feasible for wireless indoor communications in the immediate and intermediate future [OBR 08b]. Although non-coherent detection can also rely on differential detection (the received signal has to be superimposed by a delayed version in the optical domain, [WIN 06]), wireless indoor communication requires direct detection (DD) and thus “intensity modulation” (IM). Here the instantaneous optical power is varied depending on the digital information to be transmitted. This may include the usage of multiple optical wavelengths, as long as all wavelengths are processed individually by means of an optical bandpass-filter and a photodiode, comparable to envelope detection of FSK as used in RF-communications.

3.6.2 On-Off Keying- OOK

Depending on the binary information to be transmitted, an optical pulse is generated or not. This pulse is usually a rectangular pulse. Compared to other pulse shapes with more than 2 “amplitude” levels, such rectangular pulses simplify both the transmitter and the receiver design notably. Furthermore, for rectangular pulses, the laser or LED-driver can be a truly digital amplifier, which consumes much less power than a linear, “analog” amplifier.

OOK can rely either on the NRZ- (non return to zero) or on the RZ (return to zero) format. The RZ-format ensures that the transmitted signal returns to the zero power-level even if 2 or more adjacent “1” Bits are transmitted. Compared to the NRZ-format, where the pulse width (FWHM-width) is equal to the bit interval, the RZ format has several advantages. By using the RZ-format, a transition from the 1-level to the 0-level is introduced with any “1” bit, which is favorable from the clock recovery point of view. Furthermore, as long as the receiver noise is dominated by white noise, every reduction of the pulse width by a factor 2 promises a 1.5 dB gain with respect to the optical power [WOL 05]. Since the pulse duration (both for a transmitted as well as for a received pulse) of RZ-OOK is smaller when compared to NRZ-OOK, the RZ-format is also more resistant to multipath induced ISI [WIN 06]. One drawback of the RZ-format is that the optimum detector threshold is not at zero (supposing that the DC-component of the signal is eliminated by means of a highpass filter).

Although RZ-OOK ensures more pulse transitions than NRZ-OOK, long sequences of “0” bits still contain no timing information and may lead to a “transient baseline wander”. For that reason, OOK has always to be combined with a line coding scheme. This line coding scheme introduces a certain degree of redundancy to ensure a balanced number of “1” and “0” bits at the input of the OOK-modulator within a certain time window.

It should be noted that any kind of Pulse-Position Modulation can be treated as coded OOK, too. Example: if 4-PPM is considered as coded OOK, the corresponding code-words are “1000”, “0100”, “0010” and “0001”. The relative redundancy is 50%.

3.6.3 Pulse Position Modulation (PPM)

This type of modulation is considered as an attractive technique for LOS optical communication systems employing IM/DD, because it offers increased power efficiency. PPM schemes are used in various optical communication systems and are also adopted in the IEEE802.11 as well as the IrDA standards for the physical layer.
PPM can be distinguished into five major types:

L-PPM: In this case, each of the *L* different PPM-symbols contains a single pulse with a duration equal or shorter than the symbol duration $\log_2(L)T_b$ divided by *L*. All *L* symbols are orthogonal, since the *L* pulse positions do not overlap. For *L*>4, L-PPM is more power efficient than uncoded NRZ-OOK. 2-PPM, which is also referred to as “manchester coding”, requires 1.5 dB more optical power than NRZ-OOK if hard-detected [BAR 94]. L-PPM is generally less bandwidth efficient than NRZ-OOK, which limits the usability for highspeed infrared or VLC-systems.
Multipulse-PPM (MPPM): each of the *L* different PPM-symbols contains more than one pulses (for a single pulse, MPPM would be identical to L-PPM). Hence, 2 different PPM-symbols are not necessarily orthogonal. For a given bandwidth (or chip-rate), MPPM may provide a higher power efficiency than L-PPM [PAR 96]. However, this power advantage will be only obtained for quite long PPM-symbols (many pulse positions), which complicates the decoding. Furthermore, the detection may also suffer from a transient base line wander.

- Overlapping-PPM (OPPM): like MPPM, but all pulses within one symbol have adjacent positions which limits the number of PPM-symbols compared to M-PPM.
- Differential PPM (DPPM): in this case, the PPM-symbols have different lengths. DPPM is obtained from L-PPM by deleting all “0” chips following the “1” chip. This increases the bandwidth efficiency and simplifies the symbol synchronization, since a pulse is always transmitted at the end of a symbol [SHI 99]. These advantages are bought by a non-constant short time average (the number of “0” chips and “1” chips within a certain time interval is not constant), which is a serious problem if hard detection be means of a fixed decision threshold should be applied. Furthermore, as a result of the varying symbol lengths, MPPM needs buffering.
- Digital Pulse-Interval modulation (DPIM): very similar to DPPM. Unlike to DPPM, the beginning of a symbol is always indicated by a pulse.

–

It should be noted that although PPM has good power efficiency it has poor spectral efficiency, which impacts on the required receiver bandwidth at high required data rates such as those required for OMEGA. In addition receiver complexity is increased, and most available high data rate clock recovery and data processing components require simpler modulation schemes (such as OOK) for correct operation.

3.6.4 OFDM

Orthogonal Frequency Division Multiplex (OFDM) is a bandwidth efficient multicarrier transmission technique, which provides excellent performance in dispersive fading channels. It is applied in many RF-systems such as DAB, DRM, DVB-T or WiMAX. In OFDM the baseband signal, which consists of a number of individually modulated subcarriers, is generated digitally by means of an IFFT. The inverse operation, an FFT, takes place at the receiver as a major part of the demodulation process.

Since optical transmission implies intensity modulation and direct detection, several important differences compared to RF have to be considered. Whereas in RF the real and the imaginary part of the (complex) OFDM-baseband signal modulate two orthogonal RF-carriers (i.e., the inphase and the quadrature carrier), this is impossible, if intensity modulation is applied. In this case, the baseband signal to be transformed into the band-pass range needs to be real valued and positive.

A real valued baseband signal can be easily obtained by extending the one-sided spectrum of the corresponding complex signal by its complex conjugated version, that is, the frequency vector (as the argument of the IFFT) has to be extended by its complex conjugated version resulting in twice as many IFFT points. (Note: the subcarrier with the frequency f=0 needs to have a real valued weight in the frequency domain.) This doubles the sampling rate in the time domain.

The real valued baseband signal has to be equipped by a DC offset before it can intensity modulate the optical carrier, since negative amplitudes would clearly result in clipping/non-linear distortions. This limits the useful number *N* of electrical subcarriers, since the required DC-offset, which wastes power, increases with *N*. Similar to RF, approaches which limit the peak power [ALS 08] and with it the required DC-offset are required.

Furthermore it should be noted that the RF-channel exhibits strong frequency selective fading (demanding for FEC to be combined for OFDM), but the optical channel does not. It rather has a low pass characteristic (possibly caused by the optoelectronic components) with a more or less frequency flat pass-band. This difference has been investigated in, numerous publications, especially with respect to VLC, [HAR 03] and [XIO 06] are a few examples. It is believed that the adaption of OFDM to intensity modulation and direct detection can provide substantial gains [ELT 08a] and [ELT 08b].

3.6.5 Other modulation formats

OFDM is an implementation efficient multiple-subcarrier modulation (MSM) scheme. Due to the small frequency separation of the subcarriers it is also bandwidth efficient, roughly twice as efficient than the same modulation scheme applied to a single electrical subcarrier. The performance of MSM based optical transmission in general was discussed in many publications, such as in [CAR 96] and [KAH 02]. The latter one is of particular interest, since the channel capacity for IM/DD was evaluated.

The major problem with MSM is the required DC-offset which wastes power. Therefore other bandwidth efficient schemes like pulse-amplitude modulation (unipolar amplitude-shift keying) or single-subcarrier transmission based on QAM or M-PSK have also gained attention, cf. [BAR 94], [GRU 07b]. It should be noted that single carrier transmission with frequency domain equalization is a intensively discussed technique with respect to wireless RF-communications, since it greatly relaxes the linearity requirements [FAL 02].

Although multipath fading does not exist in wireless optics, spread spectrum modulation (direct sequence spread spectrum) has also gained some interest for wireless optical transmission. For instance, [FAR 08] investigated the applicability of binary Barker codes for diffuse optical systems. The modulations scheme was denoted as “sequence inverse keying” (SIK): depending on the binary data, either the unipolar Barker code is transmitted as it is, or its (logical) inverted version is transmitted, which clearly results in orthogonal transmission (very similar to 2-PPM). For Additive White Gaussian Noise (AWGN) (and without ISI), this modulation scheme promises the same power efficiency as NRZ-OOK, if the chips are soft detected. For hard-detection, it would already consume 1.5 dB more optical power than NRZ-OOK. The Barker code was motivated as the best known binary code with respect to the autocorrelation properties. However, one even more simple “code” having still better autocorrelation properties was ignored: the RZ-format (example: a “code” word for a spreading factor of 5 would be “10000”). Although it was argued that RZ-OOK is not as interesting since it requires a high peak power, it ignores the fact that RZ-OOK also reduces the average optical power compared to NRZ-OOK, and therefore compared to SIK, too. Even for AWGN, RZ-OOK will outperform hard detected SIK by a factor $\sqrt{2N}$ with respect to the average optical power, if N is the spreading factor. If a dispersive channel is considered, the gain is more increased. Hence, the relevance of direct-sequence spread spectrum based on “dense” bipolar codes is very questionable, if these codes should only provide advantages in dispersive (band-limed) channels.

3.6.6 Coding

Coding can be basically classified in to line coding (also referred to as modulation coding) and into Forward Error Correction (FEC). Line coding (in conjunction with the modulation scheme) converts the signal into a waveform which is suitable for the specific channel. If NRZ-OOK is considered as an example, some bit sequences have to be discarded for usage, since these sequences do not allow bit clock recovery or introduce a baseline wandering at the AC-coupled receiver. To discard all these sequences at the encoder output, the line coder has to introduce redundancy. Well known line codes are the ternary AMI-code used in fibre optics or the binary 8B10B IBM code with a relative redundancy of 2/10, that is 20%. It should be noted that any form of PPM can be also considered as coded OOK. For instance, 4-PPM, has a relative redundancy of 50% and ensures, that not more than two adjacent “1” and not more than 6 adjacent “0” are transmitted. This enables a reliable clock recovery and leads to quite small transient baseline wander, if the signal is highpass filtered to reject ambient light interference. An other well known runlength limited code is the HHH(1.13) IrDA-code. The main intention of FEC in conjunction with wireless optical transmission is to reduce the average required optical power. The average optical power is an important parameter from the eye-safety and battery power consumption point of view. It should be noted that various codes exist which both provide the properties of line and of FEC codes. Examples are all kinds of PPM as well as some runlength limited codes like the HHH(1.13) code. At very high data rates in the Gbit/s range, FEC codes with a large code rate (small redundancy) like the Reed-Solomon code RS(255,239) used in fibre optics with about 7% redundancy are of particular interest.

3.6.7 Discussion

Within OMEGA the multicarrier approach is being pursued for VLC, but in the case of high-speed IR simpler baseband modulation is being considered due to the challenges in implementing such a high speed OFDM scheme. Any investigation of the potential of the system will be undertaken as part of the roadmap activity. Coding will likely be part of any OFDM scheme, and the potential will be investigated for the IR system. Any analysis will take into account the increase in bandwidth required, and hence the potential drop in received power due to decreased detector area, compared with the improved power efficiency.

3.7 Operating Wavelength

The wavelength (λ) at which transmission takes place is an important parameter of any wireless optical system, since it determines both technical and economical properties. The choice of wavelength is a function of technical parameters, such as eye safety, link budget, availability of high-speed sources, and the opportunity to build WDM systems, as well as the relative cost of each type of source. The following sections give a brief overview of the candidate bands, eye safety and interference aspects.

3.7.1 Candidate wavelengths

Wireless optical transmission is currently feasible at wavelengths between about 400 nm and 2000 nm. As a result of biological effects, transmission based on ultraviolet radiation with $\lambda<400$ nm is surely out of the scope. Operation beyond about 2000 nm requires that the detector-devices be cooled to reduce the thermal generation of carriers resulting from the low bandgap. Hence, such wavelengths are also outside the useful range. Figure 22 shows the candidate wavelength bands for indoor optical wireless transmission. At wavelengths greater than 2000 nm the poor sources and detectors make it unattractive for this application, so the longest wavelength considered is in the telecommunications 'window' at 1500 nm, where components are readily available.

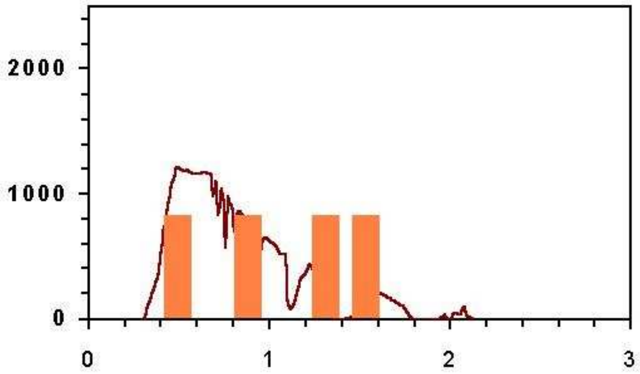


Figure 22: Spectral bands 1 to 4 (x-axis: wave length in µm, y-axis: irradiance of skylight in W/m^2/µm)

Similar to fibre optics, it is possible to define several optical bands:

1. A band between 400 and about 750 nm, which is the visible spectral range. It is used for VLC (Visible Light Communication), which combines illumination and communication.
2. A band between about 750 and 950 nm (near infrared), where Silicon based photodiodes can be used.
3. A band at about 1300 nm.
4. A band at about 1550 nm.

The bands at 1300 nm and at 1550 nm correspond to the second and the third optical window known from fibre optics. Since these two windows are only a result of characteristics of the fibre, it is also possible to consider only 3 different bands, where the third band corresponds to all the wavelengths outside detection range of Silicon.

Each of the bands has associated advantages and disadvantages. From the technical point of view, the wavelength determines

- the physical properties of the channel between the transmitter and receiver
- the physical properties of the individual optical and optoelectronic components (especially of the photodiodes)

- the maximum transmit powers, which are permitted from the laser safety point of view.

Thus, important technical parameters like data rate, transmission range and energy consumption depend strongly on the wavelength range chosen. However, the operation wavelength determines also economic aspects such as the manufacturing costs or aspects which are important from the user's point of view, such as the compactness of the devices. Table 1 gives an overview of the basic characteristics associated with the four bands discussed above. The table below presents an initial comparison of these candidate bands. It can be seen from the table that there is no ‘clear winner’ in terms of wavelength, and a major part of our initial work is to undertake a more detailed comparison. It should also be noted that this is mitigated by availability of components within the timescale of the project, and that the availability of custom components may yield a different choice of wavelength in the future. This will form part of the planned roadmap activities within the project.

Characteristics	**550 nm**	**850 nm**	**1300nm**	**1550 nm**
Cost of components	**	***	*	*
Link margin (for point sources)	*	**	***	***
Eye and skin safety	**	**	**	**
Ambient light components sensitivity to ambient light	*	**	***	***
WDM usage	*	*	*	*
Available components	**	***	**	**
Possibility of integration with fibre networks (for example FTTx)	*	*	**	**

***: advantageous; **: average; *: disadvantageous

Table 1: Comparative study of wave length

3.7.2 Noise and interference in optical wireless

Optical wireless channels are susceptible to noise and interference caused by unwanted light from sunlight, or artificial lighting sources. These have been extensively studied and are characterised below. Especially at very high data rates, the noise generated in the preamp has also to be considered. It should be noted that the noise power of the so called “ f^2 -noise" increases with the third power of the signal bandwidth. In other word: increasing the data rate by a factor 10 increases the power of the f^2 -noise by a factor 1000.

Artificial light and daylight cause a DC photocurrent that is normally blocked by the AC coupling of the receiver circuitry. However, these currents induce **s**hot noise which degrades receiver sensitivity. This is of particular importance in APD receivers where the amplified shot noise component limits the available avalanche gain and hence the improvements in receiver sensitivity available.

- Artificial light is driven either directly from mains AC voltages in the case of incandescent lamps, or via ballasts in the case of fluorescent sources. Mains voltage induces a 100Hz (120Hz in the US) variation in received photocurrent in incandescent lamps, with significant components at harmonics of this due to non-linearities. Fluorescent light ballasts can create significant components at up to several hundred KHz, depending on their type, as detailed below
    - The incandescent lamp or the low frequency fluorescent tube, with a principle component at 100 Hz, then harmonics at 200 and 300 Hz.
    - The high frequency fluorescent tube, with a main component at 44.2 kHz then a harmonic at 88.4 kHz.
    - The high frequency compact fluorescent lamp, with a main component at 33 kHz then harmonics at 66 kHz and other lower harmonics at 99, 132 and 198 kHz.

These components are not blocked by simple AC coupling, so filtering must be used to reduce them. Figure 23 shows the relative magnitude of the DC level of the interference from each source. This shows that sunlight provides the highest level of interference, although this can be blocked by an AC coupled receiver.

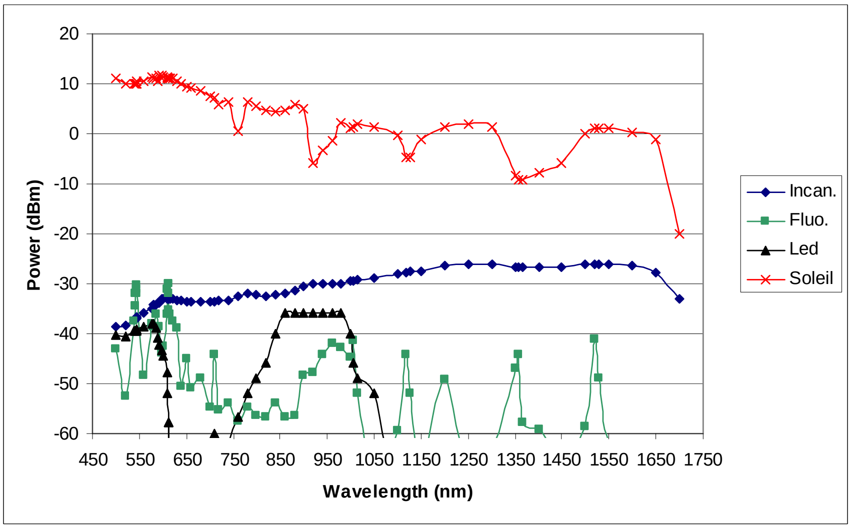


Figure 23: Power spectrum of four principal sources of light

3.7.3 Optical radiation safety requirements

Biological tissue can be damaged by optical radiation due to thermal, photochemical and nonlinear effects. [EUR 07].

With respect to the eye, sources emitting infra-red radiation with λ> 1400 nm represent a corneal hazard. Sources emitting in the visible or near infra-red wavelength range (400 nm to 1400 nm) mainly cause a retinal hazard as the radiation will be less absorbed due to the cornea or the lens. The skin can tolerate much more exposure than the eye, where visible light may cause pigment darkening, photosensitive reactions and skin burn. Skin burn is also the dominating pathological effect for infra-red radiation.

Laser safety is covered by the international standard IEC 60825-1, and this is relevant to the choice of wavelength for the IR system within OMEGA. LEDs are now regulated within a separate standard, but their use in communications may still fall within the laser standards. The authors Horak and Neuhaus have recently argued that the application related laser standards

- IEC 60825-2 (laser equipment safety — Part 2: safety for optical fibre telecommunication systems) and
- IEC 60825-12 (laser equipment safety — Part 12: safety for open space optical communication systems used for data transmission)

still cover LEDs, if these devices are used for data communications: Thus, it may occur that for one and the same IR-LED both, the laser or/and the lamp requirements have to be applied, depending on whether it is used for communication purposes or not [HOR 07].

The classification of laser sources is based on a *maximum permissible exposure* (MPE) matrix, which was determined experimentally depending on the exposure time and the wavelength. The MPE is the "level of laser radiation to which, under normal circumstances, persons may be exposed without suffering adverse effects …. MPE values are set below known hazard levels and are based on the best available information from experimental studies." [EUR 07].

The *accessible emission limits* of the various laser classes are derived from the MPE-values. Each class corresponds to a different level of hazard and (consequently) to specific safety requirements like labels and protective housings. A laser product is assigned to a particular laser class, if it does not permit human access to laser radiation in excess of the *accessible emission limits* (AELs) tabulated for that class. As the MPEs, the AELs depend on the wavelength and on the exposure time.

Class 1 laser products are safe under all reasonably foreseeable conditions, and the IR and LED based systems must meet this requirement. The AEL allowed depends on the source dimensions, and the wavelength of the source, and Figure 24 shows the permitted radiant intensity of class 1 sources for different apparent source diameters *D*. *D*=0 corresponds to a point source. If the spatial coherency of the source is destroyed by means of a diffuser, much higher radiant intensities are possible (for wavelengths from 400 nm to 1400 nm), since the size of the retinal image is increased which leads to a decreased irradiance.

Explanations of these calculations can be found in the OMEGA internal document on wavelength choice.

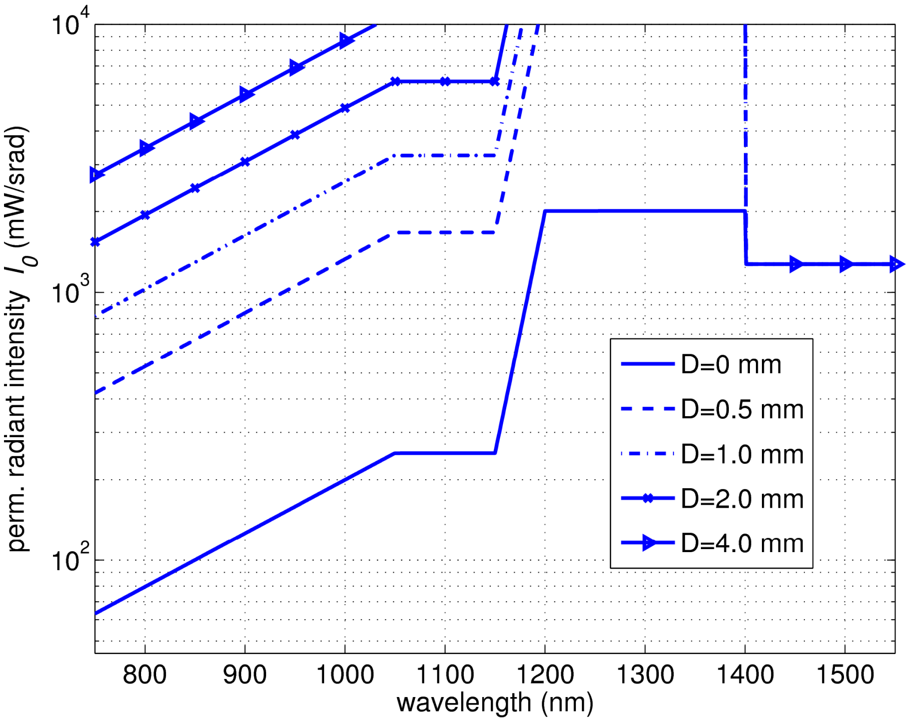


Figure 24: **Permitted on-axis radiant intensity for extended sources.**

The key points are that for wavelengths >1400nm the radiant intensity is fixed, and cannot be increased by increasing the size of the source *D*, If it is possible to 'close' a particular link budget in this region with the available radiant intensity then a simple point source emitter can be used, making link optical design straightforward. However, if there is not sufficient radiant intensity then it cannot be increased. In this case improvements in receiver performance are required.

At wavelengths <1400nm the radiant intensity available can be increased by using a diffuser to extend the size of the source *D*, which offers an additional degree of freedom in improving link budget design. This may be particularly useful as data rates increase in the future- as there are additional degrees of freedom at both transmitter and receiver, whereas link budget improvements are only available at the receiver in the case of wavelengths>1400nm.

3.8 Energy consumption

It is generally difficult to compare the energy consumption of different systems. The total consists of the energy to transmit the data, as well as that consumed in the modulation and demodulation and associated signal processing. The table below shows an approximate comparison, based on available data, of the consumption of different standards. These indicate that optical communications can be competitive with other standards, largely due to the simpler signal processing that is typically involved. Such figures should be treated with caution however.

Standard	Power consumption(W)	Bit rate(Mbit/s)	Normalised energy consumption(J/Mb)
IEEE802.11(g) [DLI 05]	1.25	54	2.31E-02
Ultra-WideBand(UWB) [DLI 05]	0.75	114	6.58E-03
Optical link[M39 05]	0.3	150	2.00E-03

Table 2: Energy comparison

3.9 State of the art systems and representative link budgets

In the following sections the link budgets for several commercial and proposed systems are detailed, in order that the typical requirements for particular data rates and capabilities can be seen.

3.9.1 IrDA systems

Data for the IrDA Smartbeam system from BELKIN is shown. This provides a bidirectional link that operates in accordance with the USB 1.1 standard.

3.9.1.1 Data

The Base Station (BS) parameters:

- *Power* P_t (dBm) : 4 (2.5 mW)
- Emission angle *HP (°) :* 45
- Sensitivity *Se (dBm) :* - 30
- Effective area A_{eff} (mm2) : 100
- Field Of View *FOV (°) :* 45
- Wavelength (nm) : 880
- Data rate (Mbit/s) : 2

The Module (MOD) parameters:

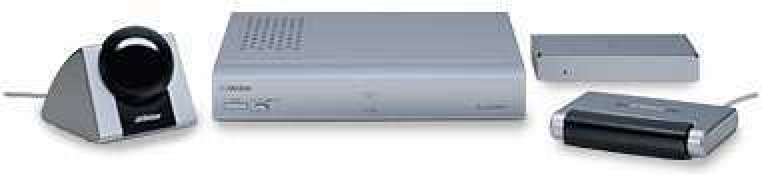
- *Power* P_t (dBm) : 4 (2.5 mW)
- Emission angle *HP (°) :* 45
- Sensitivity *Se (dBm) :* - 30
- Effective area A_{eff} (mm2) : 100
- Field Of View *FOV (°) :* 45
- Wavelength (nm) : 880
- Data rate (Mbit/s) : 2

This link is designed to operate over a distance of 1m

3.9.2 JVC Luciole

The Luciole link is a point to point tracking link that is used to transmit High Definition (HD) video signals from a source to a large screen TV. The data rate is 1.5Gbit/s and it is available over a range of 5m

ptical HD transmission system, Ref LW-HDW1UC, name : Luciole



3.9.2.1 Data

The product parameters:

- *Power* P_t (dBm) : 6 (4 mW)
- Emission angle *HP (°) :* 1.5
- Sensitivity *Se (dBm) :* - 35
- Effective area A_{eff} (mm2) : 10
- Field Of View *FOV (°) :* 5
- Wavelength (nm) : 855
- Data rate (Mbit/s) : 1 500

3.9.3 JVC VIPSLAN

JVC produced LAN units that transmit 100Mbit/s Ethernet data, named the VIPSLAN-100. This operates over a range of several metres and has a wide field of view base station and narrow field of view tracking receiver.

3.9.3.1 Data

The Base Station (BS) parameters:

- *Power* P_t (dBm) : 30 (1 W)
- Emission angle *HP (°) :* 60
- Sensitivity *Se (dBm) :* - 34
- Effective area A_{eff} (mm2) : 10
- Field Of View *FOV (°) :* 60
- Wavelength (nm) : 870
- Data rate (Mbit/s) : 100

The Module (MOD) parameters:

- *Power* P_t (dBm) : 5 (3.2 mW)
- Emission angle *HP (°) :* 3 + tracking
- Sensitivity *Se (dBm) :* - 34
- Effective area A_{eff} (mm2) : 10
- Field Of View *FOV (°) :* 3 + tracking
- Wavelength (nm) : 870
- Data rate (Mbit/s) : 100

3.9.4 Prototype Techim@ge

A French regional research project is aiming to fabricate a system with the following parameters. This will operate at long wavelength over a range of up to 7m.

3.9.4.1 Data

The Base Station (BS) parameters:

- *Power* P_t (dBm) : 30 (1 W)
- Emission angle *HP (°) :* 45
- Sensitivity *Se (dBm) :* - 34
- Effective area A_{eff} (mm2) : 40
- Field Of View *FOV (°) :* 45
- Wavelength (nm) :
    - Emission : 1550
    - Reception : 1560
- Data rate (Mbit/s) : 1000

The Module (MOD) parameters:

- *Power* P_t (dBm) : 25 (0.3 W)
- Emission angle *HP (°) :* 15
- Sensitivity *Se (dBm) :* - 34
- Effective area A_{eff} (mm2) : 40
- Field Of View *FOV (°) :* 15
- Wavelength (nm) :
    - Emission : 1560
    - Reception : 1550
- Data rate (Mbit/s) : 1000

3.9.5 Discussion

It can be seen that data rates of Gbit/s and above are available, particularly in the Luciole product from JVC. However, this is a point to point link, rather than a network, and it uses narrow beams that are mechanically tracked to align transmitter and receiver. The Giga-IR work represents very short distance links and these are not comparable to the work in OMEGA where links operating in rooms are required.

The techimage prototype also aims to create modules that operate at 1Gbit/s, with similar link specifications as Omega. It represents ‘planned’ state of the art, and has similar targets to OMEGA at least at a link level. In summary, Gbit/s links represent the state of the art in high-speed indoor optical wireless, but there are no Gbit/s networks, and this represents the advance a successful OMEGA project will bring.

4 Optical wireless systems: Medium Access Control (MAC) considerations

A key challenge for the OMEGA project is the development of an appropriate MAC layer, either by adaptation of existing work, or taking a new approach. This section presents a survey of existing techniques that have been used in optical wireless.

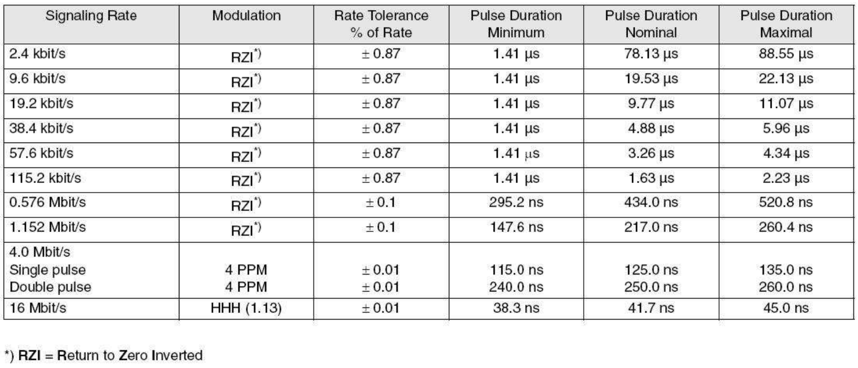
4.1 Existing Point-to-point protocols

4.1.1 IrDA protocol

Created in 1993, the IrDA (Infra-red data Association) is an association of around one hundred and fifty members of different companies. As of 1997, this association suggested a recommendation allowing for a digital communication with inexpensive optical modules. This IrDA device is on many portable machines, including laptops, PDAs, and also on peripheral devices such as printers or camcorders.

Generally, the equipment has a short range infra-red port , mainly allowing for file transfers. They are usually made up of a transmitter/receiver working around 850 nm, and with throughputs of 1.5 Kbit/s to 16 Mbit/s over several meters and a divergence of +/− 15°.
The first protocol suggested by the IrDA in 1997 is called OBEX (Object Exchange), and allows for data exchange between devices that have an IrDA infra-red link. The communication process occurs between two devices in point-to-point configuration, as a session. The data exchange occurs according to the established rate, no obstacle whatsoever must disturb the communication. Upon completion of the file transmission, the connection is terminated and the session ends.

The following table shows the different characteristics for transmission modes and rates.



Signaling Rate	Modulation	Rate Tolerance % of Rate	Pulse Duration Minimum	Pulse Duration Nominal	Pulse Duration Maximal
2.4 kbit/s	RZI*)	± 0.87	1.41 µs	78.13 µs	88.55 µs
9.6 kbit/s	RZI*)	± 0.87	1.41 µs	19.53 µs	22.13 µs
19.2 kbit/s	RZI*)	± 0.87	1.41 µs	9.77 µs	11.07 µs
38.4 kbit/s	RZI*)	± 0.87	1.41 µs	4.88 µs	5.96 µs
57.6 kbit/s	RZI*)	± 0.87	1.41 µs	3.26 µs	4.34 µs
115.2 kbit/s	RZI*)	± 0.87	1.41 µs	1.63 µs	2.23 µs
0.576 Mbit/s	RZI*)	± 0.1	295.2 ns	434.0 ns	520.8 ns
1.152 Mbit/s	RZI*)	± 0.1	147.6 ns	217.0 ns	260.4 ns
4.0 Mbit/s Single pulse Double pulse	 4 PPM 4 PPM	 ± 0.01 ± 0.01	 115.0 ns 240.0 ns	 125.0 ns 250.0 ns	 135.0 ns 260.0 ns
16 Mbit/s	HHH (1.13)	± 0.01	38.3 ns	41.7 ns	45.0 ns

*) **RZI** = **R**eturn to **Z**ero **I**nverted

Table 3: Parameters of IrDA rates

The actual typical performance is shown in the table below.

Characteristics	Values
Delay	The detection and handshake time of the connection is between 250 and 650 ms
Latency	Typically L < 20ms, but can fall as low as 500 µs
Effective throughput	115 kbit/s link (PDAs, cellular phones): 80 kbit/s throughput (70%) 4 Mbit/s link (laptops, IrDA adaptors): 3.5 Mbit/s throughput (88%)

Table 4: Typical achieved performance of IrDA links

Several standards have been developed, and these offer increasing data rates.

SIR – Serial Infra-red- throughput of 9.6 to 155 kbit/s. Products are widely available and used

AIr (Advanced Infra-red) also called **FIR (Fast IrDa)** –up to 4Mbit/s at a range of 1m or can also provide LAN connectivity at a range of up to 10m at lower data rates. Products are available though less widespread use in portable appliances.

VFIr (Very Fast Infra-red)

Up to 16Mbit/s with some products available.

There has been some activity at higher data rates. Most recently KDDI proposed a standard as described below

Giga-IR users lasers to provide Gbit/s short range point and shoot links.

As well as work on physical layer standards their have also been efforts to tailor the standard to particular applications (**IrFM-**for financial transactions) and to improve the protocol stack **IrSimple.**

Although IrDa represents the largest installed base of Ir links perhaps the only relevance to the OMEGA project is the Giga-IR standard, in that this shows the perceived need for high-speed IR communications.

4.2 Existing Multi-access protocols

There are several existing standards designed for optical wireless physical layers, notably a standard within 802.11 which has not been commercially exploited, and a Japanese standard where prototypes have been fabricated, but again there is no widespread use.

Also of interest are protocols designed for systems that used a 60GHz carrier frequency, such as elements of the IEEE 802.15.3c draft standard documents. In addition the Very High Throughput (VHT) study group within 802.15 is also working to develop standards in this area. The VHT group are considering techniques such as beamforming, and the need to adapt the radiation pattern to find devices within the coverage area. This may be relevant to the high-speed IR where similar challenges exist. Work in the VHTSG is also relevant to the RF work within Omega.

Ethernet is also included in this study, as any device is likely to use an Ethernet connection to the optical wireless transceiver, or to the optical wireless MAC. Gigabit Ethernet over fibre offers a possible basis for the IR work also: replacing the fibres with free space links is attractive as it allows gigabit Ethernet components to be used, although further study is required to see whether it is a suitable protocol.

In the following sections more details of each of these protocols are given.

4.2.1 802.11 protocol

The 802.11 IR-PHY standard was developed in 1993, with a physical layer using diffuse infra-red radiation.
The broad specifications are

- Link length of 10-20m
- Transmitter wavelength between 850 nm and 950 nanometres.
- Pulsed emission power limited to 2 watts.
- Must be class 1 eye safe to IEC 60 825-1
- Throughput from 1 to 2 Mbit/s, then to 10 Mbit/s maximum,
- Modulation schemes as follows:16 PPM (Pulse Position Modulation) for 1 Mbit/s and Gray coded 4 PPM for 2 Mbit/s.

The standard also defined frame preambles, synchronisation procedures and other required elements.

4.2.2 ICSA protocol

The Japanese association’s standard proposal is an extension of the ARIB STB-T50 standard. This defined a multi-access communication protocol for an infra-red LAN system at 10 Mbits/s with an extension for 1000Mbit/s. This is designed to be compatible with Ethernet, using many of the parts of the Ethernet recommendations, and the optical sources must be class 1 eye safe. For the 1Gbit/s system a line of sight with a range of 1-10m is assumed. There is no specified wavelength, and a target BER of 1E-10.

4.2.3 802.15.3 protocol

The IEEE 802.15.3 created task group 3c (Task Group 3C or TG3c) in March, 2005. The TG3c (WPAN Millimetre Wave Alternative PHY) is developing an alternate physical layer using carrier frequencies from 25-100GHz offering throughputs of several Gbit/s. As mentioned earlier some elements of the standard may be useful to OMEGA due to the similar propagation characteristics of high-frequency RF radiation to light. It should be noted that there is no support for multiple access in the standard, which may limit its use. More relevant in this area may be the work of the Very High Throughput (VHT) study group of IEEE 802.11.

4.2.4 Ethernet protocol (IEEE802.3)

The most well-known protocol of multi-users is Ethernet. Its most common standards, with their main characteristics are as follows:

	Connectics	Max. distance	Time between frames	Min/max frame length	Modulation	Transmission
Ethernet 10 Base T full/half duplex (IEEE 802.3)	RJ45 twisted pairs cat 3– 2Tx + 2 Rx	100 m	9.6 µs	1518 bytes 64 bytes	Two levels	Manchester code baseband
Fast Ethernet 100 Base TX full/half duplex (IEEE 802.3u then 802.3).	RJ45 2 twisted pairs cat5 – 2Tx + 2 Rx	100 m	0.96 µs	1518 bytes 64 bytes	Three levels	Coding baseband 4B/5B and MLT-3
Fast Ethernet 100 Base FX full/half duplex (IEEE 802.3u then 802.3)	SC or ST multi-modes fibre connectors 2 twisted pairs cat5 – 2Tx + 2 Rx	412 m half duplex 2,000 m full duplex.	0.96 µs	1518 bytes 64 bytes	Two levels	Coding baseband 4B/5B and NRZI
Fast Ethernet 100 Base T4 half duplex	RJ45 4 twisted pairs cat3 – 2Tx + 2 Rx	100 m	0.96 µs	64 bytes 1518 bytes	Two levels	Coding baseband 8B/10B and NRZ
Giga Ethernet 1000 Base T full duplex	4 UTP twisted pairs cat 5E – 2Tx + 2 Rx	185 m	0.096 µs	64 bytes 1518 bytes (or 9018 bytes – Jumbo)	Five levels	Basebands 8B1Q4 and 4DPAM5 (Pulse Amplitude Modulation)
Giga Ethernet 1000 Base X full duplex	CX (4 copper wires – 2Tx + 2 Rx - RJ45), SX (fibre MM – 770 and 860 nm), LX (fibre SM – 1270 and 1335 nm)	25 to 1000 m	0.096 µs	64 bytes 1518 bytes (or 9018 bytes – Jumbo)	Two levels	Coding baseband 8B/10 and NRZ
10 Giga Ethernet 10 000 Base X full duplex	SR, SW, LR, LW, LX4, ER, EW	25 to up 40 000 m	0.0096 µs	64 bytes 1518 bytes (or 9018 bytes – Jumbo)	Two or three levels	Coding baseband 8B/10 and NRZ

Table 5: Ethernet protocols

Point to point links as reported in [SCH 06a] are implemented by making a direct electrical/optical conversion and vice versa of the Ethernet waveforms. In this case, the two-level modulation protocols should be favoured, as are found in the following protocols:

- Ethernet 10 Base T full/half duplex (IEEE 802.3)
- Fast Ethernet 100 Base FX full/half duplex (IEEE 802.3u then 802.3).

- Fast Ethernet 100 Base T4 half duplex only
- Giga Ethernet 1000 Base X full duplex

Any Optical Wireless MAC that is developed in OMEGA must be compatible with Ethernet, but the direct conversion of fibre-based Gb Ethernet to an analogous free-space version may not be suitable for the network, rather than point to point architecture that is required for OMEGA. In this regard the available Japanese standards provide a more relevant starting point for the MAC work within the project.

4.3 Other possible Multiple access techniques

4.3.1 Multiplexing, optical techniques

4.3.1.1 Wavelength Division Multiplexing(WDM)

The abundance of optical spectrum allows different wavelength sources, together with wavelength selective receivers to be used to increase data rates between two points by using more than one link, or to provide enhanced isolation between up and down links between terminals. Fibre systems use this technique routinely but the availability of components for free space systems, and challenges in the design of components optimised for free space reception and transmission make this unattractive in the short term.[MOR 96].

4.3.1.2 Space Division Multiplexing(SDM)

The ability to confine optical radiation to a specific field of view and to distinguish between angle of arrival at an optical receiver makes this an attractive technique for optical wireless. The need to use narrow field of view links to achieve the required link margins makes SDM an aspect likely to be used in all high bit rate systems, either at 1Gbits or higher rates. It also offers the potential for very high bit rates which do not have to be shared as an unshared link exists between all the users in the system. All high speed systems that have been proposed and offer wide field of view coverage use SDM, either with imaging[DJA 00], MIMO[OBR 06a] or angular diversity schemes[CAR 00].

4.3.2 Electrical multiplexing techniques

Multiple users accessing the shared optical channel require a means to do so efficiently, and the commonly used electrical techniques are as follows: TDMA – Time Division Multiple Access, the FDMA – Frequency Division Multiple Access, and the CDMA – Code Division Multiple Access.

4.3.2.1 Time Division Multiple Access (TDMA)

TDMA allows different users to access a shared channel and has the advantage that the power transmitted can be reduced if usage is low [MOR 96]. TDMA is efficient under the regular flow of information (relatively constant throughput), however, it may be more difficult to manage for transferring "bursts", which is a very high throughput over a short time period [PAH 95].

4.3.2.2 Frequency Division Multiple Access (FDMA)

In this approach, the frequency axis is split into portions of frequency bands where each channel fills a certain band. For reception, the receiver filters the desired signal frequency. The FDMA solution is efficient in applications with relatively constant throughputs [PAH 95]. However, the power efficiency from the FDMA technique becomes lower as the number of users increases. In other words, this solution is equivalent to WDM (optical multiplexing) with a distribution of power emitted in relation to the number of users or wavelengths (frequencies). Managing “bursts” is also a delicate issue in this approach.

4.3.2.3 CDMA

This technique assumes that each user has a different sequence of orthogonal codes to avoid any interference [MOR 96]. CDMA may be considered to be a hybrid combination of FDMA and TDMA where the users operate at the same time on the whole bandwidth [PAH 95]. The signals of each user are divided-up with their respective codes to modulate their signals, and are then regenerated by the receiver. There are two main CDMA techniques, the Direct Sequence DS-CDMA, and the method by Frequency Hopping FH-CDMA).

In the DS-CDMA method, the information is modulated with certain codes. Each user must be assigned a code so there is no interference among the users' signals. The receiver then regenerates the codes that are used to demodulate the information. DS-CDMA is built on a broad spectre of techniques.

In the FH-CDMA solution, the information modulates a group of frequencies that jump from one to the other according to a pseudo-random sequence with a synchronisation algorithm.

4.3.2.4 Discussion

The physical layer constraints on high-speed systems make it likely that multiple physical channels will be required to meet the data rate and field of view targets for OMEGA and similar systems. These are very well suited to SDMA type schemes with one channel being available for each terminal. However, it is equally feasible, and simpler to transmit the same data on different physical links, thus creating shared transmission paths. In this case some form of electrical domain multiplexing is required. This is likely to be the case if two terminals are within the field of view of one of the links, even if SDMA is used. Therefore OMEGA requires electrical multiplexing in all cases, but there is the option to incorporate SDMA techniques as the physical layer architecture permits this.

5 The optical wireless ‘landscape’

In this section the characteristics of optical wireless communications are compared with their RF based alternatives, both generally and in the context of the available standards. Table 6 shows a comparison between RF and optical wireless. It can be seen that the major advantage of optical wireless is the abundance of unregulated spectrum, but as has been seen in the previous chapters the challenge is to create robust and reliable systems that can use it. To some extent these encompass some of the same challenges that 60GHz LOS RF technologies face (such as blocking) but additionally include the major challenge of poor link margin.

Characteristics	**Radio**	**Optical**
Spectral availability	Limited, especially in low frequency bands	Abundant (though effective usage of multiple wavelengths is a major challenge)
Spectral Regulation	Highly regulated	No regulation (other than eye safety)
Financial charge for allocation of spectrum	Varies (no charge for the radio technologies mentioned above)	Not at present
Security of data	Requires encryption	Signal confined by room
Multipath fading	Major issue (needs spreading or OFDM-like techniques)	None
Inter-Symbol Interference	Weak	Potentially important to high bit-rate
Electromagnetic Interference created	Possible	None
Sensitive to Electromagnetic Interference	Possible	None
Dominant noise source	Other users	Natural and artificial light, amplifier noise at very high data rates
Inter-connectivity	Electrical (Cable, PLC) or radio or optical (FTTx)	Electrical (Cable, PLC) or radio or optical (FTTx)
Effect of humans	No evidence	No evidence
Quality of service	Best effort QoS in evolution	Best effort

Table 6: Comparison between the radio frequency and optical wireless transmission

5.1 Comparison between existing and proposed wireless communications standards

5.1.1 Radio communications

OW is significantly less advanced than RF wireless communications, so to some extent the comparison is not 'like for like'. In the next section a range of different standards is summarized, and Table 7 compares these.

Bluetooth 1.0:

- Used for data exchange between portable devices.
- Data rates approximately 1Mbits/s, around 723 kbits/s net rate download and 57 kbits/s upload (maximum 433 kbit/s).
- Range is approximately 10 to 30 metres, up to 100 metres for some devices
- Bluetooth is principally designed for home networks (WDAN – Wireless Domestic Area Network)
- There is the start of a collaboration within the WiMedia (UWB) Forum to develop a standard in the 6-9 GHz band.

WiFi: "IEEE 802.11":

- Ubiquitous worldwide standard for wireless LAN, promoted by the WECA (Wireless Ethernet Compatibility Alliance). WiFi offers WLAN services.
- Data rates:
  - 802.11a: typical bit-rate of 30 Mbits/s with a range of 10 m in the 5 GHz frequency band
  - 802.11b: typical bit-rate of 6 Mbits/s with a range of 50 m in the 2.4 GHz frequency band
  - 802.11g: typical bit-rate of 26 Mbits/s with a range of 27 m in the 2.4 GHz frequency band
  - 802.11n: typical bit-rate of 100 Mbits/s to 90 m on the frequency band of 2.4 and 5 GHz and MIMO technology.
- The maximum range is approximately 50 to 100 metres depending on the environment

UWB:

- Promoted by the WiMedia Alliance (http://www.wimedia.org) forum. The recommendation phases are carried out in collaboration with the ECMA since December 2005 and with ISO since March 2007. Work is still underway in CEPT (CEPT/ECC TG3) in order to define regulations in Europe in the 3.1-4.8 GHz and 6.0-8.5 GHz bands. ECMA and ISO already released a WiMedia standard.
- Data rate: approximately 480 Mbits/s up to a range of 3 m or 110 Mbits/s to 10m.

5.1.2 Optical free-space transmission

A number of different standards are in use or development, and these are described below.

IrDA (Infra-red data association):

- IrDA links are used to communicate over short ranges between portable appliances such as PDAs
- The bit-rates of 2.4 kbits/s to 4 Mbits/s are accepted (16 Mbits/s is also proposed - IrDA-V VFIR).

IrSimple

- A modification of the IrDA. Allows high bit-rate infra-red communication between portable devices

- Supports bitrates up to 16 Mbits/s (VeryFast IR) with planned rates of 100 Mbits/s (UltraFast IR).

ICSA

- Created in 1996, the ICSA (Infra-red Communication Systems Association) is a Japanese association which aims to favour the standardisation and use of optical communication systems in free-space; and to promote this wireless communication technology in the infra-red domain.
- Specifications of a 100Mbit/s infra-red LAN system compatible with the 100 Mbits/s Ethernet standard are available. Current work in ICSA is on specifications for a 1Gbit/s system compatible with the Gigabit Ethernet standard.

5.1.3 Comparative studies

	Standards						
	Radio			**Optical**			
	802.11		**UWB**	**IrDa**	**IrSimple**	**ICSA**	**Giga-IR**
	g	*n*					KDDI
Version/ Status	IEEE approved	In progress	In progress	approved	n/a	n/a	approved
Medium Access	CSMA/CA and other medium access mechanisms	CSMA/CA and other medium access mechanisms	CSMA/CA and other medium access mechanisms	IrPHY	CSMA	CSMA/CD	n/a
Band Frequency/ Wave length	2.4GHz (ISM)	2.4 and 5 GHz	3.1-10.6GHz	850/900 nm	850nm	Visible and Infra-red	Infra-red
Modulation	OFDM with BPSK up to 64-QAM	OFDM with BPSK up to 64-QAM	QPSK and DCM	HHH (1,13)	n/a	n/a	n/a
Bit rate Mbits/s (not including overheads)	54	600	480-110	16	100	1000	1000
Range (m)	30	90	1-10	0.1-1	10	10	1
Encryption	Option	Option	Yes				
QoS	802.11e *	802.11e *	yes for multimedia (with DRP)	no	no	yes	n/a
Protocol type	Ethernet	Ethernet	WiNet	PPP	Ethernet	Ethernet	n/a
Availability/status	Worldwide	Still in standardizaion (Sep 2009)	Available (USA)	Worldwide	Available	Japan	Japan

*: There is virtually no implementation of the relevant mechanism (PCF). Furthermore, 11e is not sufficient in case of multiple multimedia applications.

Table 7: Table summary of wireless technology standards: radio and optical

5.2 Potential uses of indoor Optical Wireless

The indoor wireless optical communication systems can be defined according to two approaches:

WDAN: Wireless Domestic Area Network or Home Network :
Many appliances have the ability to be controlled remotely. A low bit-rate optical wireless network might be used to provide control to all of these devices, creating an automatic home. This subject is well presented in the Omega project public document: D1.1 Final Usage Scenarios report.

WLAN: Wireless Local Area Network: The widespread success of WiFi has led to a growing demand for wireless networks. Optical Wireless has the potential to compete with high-speed LOS alternatives such as 60GHz communications.

WPAN: Wireless Personal Area Network: Communications using IRDA transceivers fall in the WPAN category, and OW may be able to provide higher data-rate communications.

Hotspot/Refuelling or SAN:
Networks that offer ‘hotspots’ of high data rate coverage, combined with broader area WiFi coverage are an area of research interest. The ability to confine optical radiation and the potential to provide high data rates using simple communications transceivers makes this an attractive area of application for OW.

IdP: Indoor Positioning: Radio Frequency positioning techniques such as GPS do not function well in indoor environments. VLC allows individual lighting units to broadcast position information, so that receivers close the the lights can determine their location.

5.3 Organisations active within indoor and short-range optical wireless

The following paragraphs present an overview of manufacturers for optical wireless communication products for indoor applications, spanning from commercially available products to prototypes. We also provide an overview of academic institutions active in this field and of organisations with ties to optical wireless indoor communications.

5.3.1 Manufacturers

Optical wireless data transmission using infra-red radiation is an established and even standardised technology, and several IR-based communication devices are thus commercially available.

Clarinet Systems offers several "EthIR LAN" (Ethernet LAN over IR) products that are based on IrDA. They offer infra-red links of 115 kbits/s (SIR) to 4 Mbits/s (FIR) in line of sight and over an average distance of 50 cm. These can be used for a network link using Ethernet 10/100 or WiFi (802.11b) protocols.

The Japanese company **JVC – Panasonic** sells two IR products (see chapter 1):

- VIPSLAN – point-to-multipoint infra-red WLAN at 10 Mbit/s,
- Luciole – Point-to-point transmission of uncompressed HDTV at 1.5 Gbit/s.

InfraCom markets integrated low-cost semi-conductor circuits for wireless short-range communication. Their transmission scheme is based on diffuse infra-red links, referred to as IrGate. InfraCom claim a bit rate of up to 10 Mbit/s. This product was developed for wireless audio connectivity to Hi-Fi speakers.

The **Kyosemi Corporation** developed a prototype called the "Infra-red Powered Solar Cell" enabling FM radio transmission by aid of infra-red LEDs;

The **KDDI company** demonstrated a link they called ‘Giga-IR’, an infrared communication standard with a data rate of 1Gbit/s. The technology could be used for forwarding music and video data stored in mobile phones at high speeds to other mobile phones, PCs, TVs, DVD recorders and printers etc. KDDI developed this communication format and is aiming to complete standardization at the Infrared Data Association. Unlike most infrared communications using LEDs, Giga-IR uses semiconductor lasers.

VLC is less well developed, with several prototype products being developed in Japan, as part of the Visible Light Communications Consortium (VLCC).. Examples of publicly displayed prototypes include [NAK 07]

- Indoor positioning with ceiling lights (NEC, Matsushita)
- Telematics (traffic light to car; Nippon Signal)
- Long-distance links (200 m and larger; Casio)

Another important manufacturer active in this field is Samsung. Prototypes presented by this company include [WON 08a]

- Point-to-point communication between mobile devices (up to 100 Mbit/s)
- Data broadcast with illumination devices (data rates in the kbit/s range)
- Telematics-traffic light to handheld device (data ratesin the kbit/s range)
- Point-to-point links between infrastructure and mobile devices (data rates in the Mbit/s range)
- Information broadcast with LED displays (data rates in the range of 10s of Mbit/s)

5.3.2 Academic Institutions

Incoherent optical wireless communications for indoor applications was pioneered by Gfeller and Bapst, with a first publication in 1979 [GFE 79]. In 1997 Kahn and Barry presented a comprehensive review paper on IR wireless indoor communications [KAH 97]. VLC has been pioneered by the group of Prof. Nakagawa at **Keio University** who play a leading role within the Visible Light Communications Consortium (VLCC). Among their recent results include an integrated system of white-LED communication and power-line communication [KOM 03], and an indoor positioning technique that uses ceiling lights [NAK 07].

The Department of Engineering Science of the **University of Oxford** (England) has developed a retro-reflecting communications system that uses visible light. In this case a liquid crystal shutter is used to modulate a beam of light that is returned from a retro-reflecting ‘tag’. The reader and tag offers bi-directional communications at several kbit/s. It also reported the first 2D cellular optical wireless system demonstrations, and the first 2D integrated cellular components[OBR 05].

France Telecom and the engineering institute **ENSSAT** (France) have developed a prototype optical wireless communication system that uses multi wave-length infra-red transmission (WDM). One of the features of the prototype is the use of each wave length of a WDM signal as a channel unique to a user or device. Thus, it is possible to obtain many users in simultaneous connection and each of the channels offers a guaranteed bit rate of a few Mbit/s to some tens of Mbit/s.

The Photonic Research Laboratory at the **University of Northumbria** pursues both optical fibre and wireless optical communications. In the latter field they presented a prototype for diffuse infra-red optical wireless communication based on digital pulse-interval modulation. Data rates of 2.5 Mbit/s in a 6.85 x 6.64 x 2.8 m room were demonstrated [ALD 05].

5.3.3 Institutions

There are a number of institutions with interest in the regulation of the optical spectrum, or its exploitation for communications. Figure 25 shows a diagram that illustrates this.

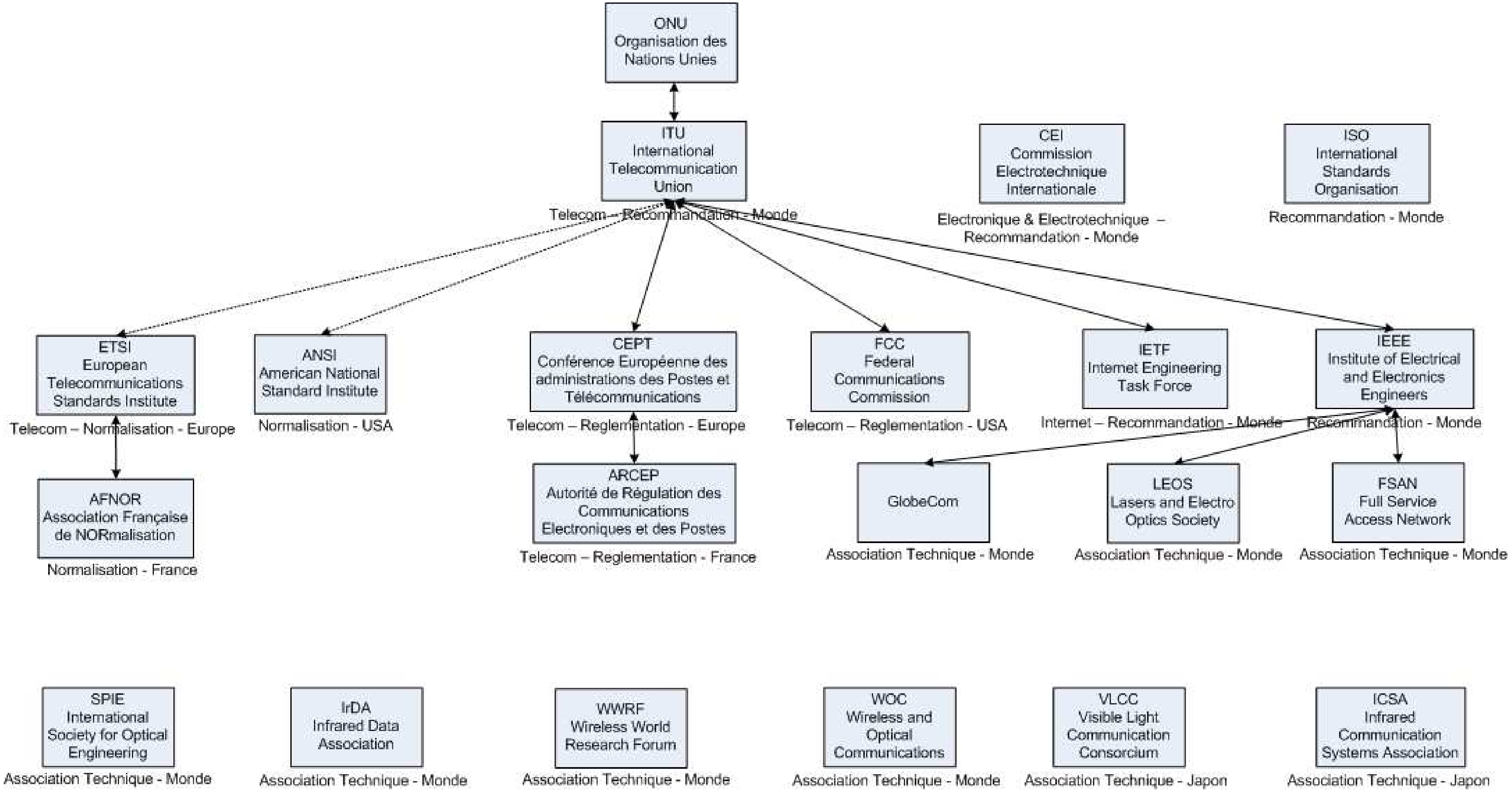


Figure 25: The institutional actors

5.3.3.1 ITU - International Telecommunications Union

The ITU is an agency of the United Nations, within which the States and the private sector coordinate the global telecommunication networks and services.
The ITU is structured in three distinct sectors:

-ITU-D: Development - Concrete initiatives and projects for the development of the information society-

-ITU-T: Standardisation –creating standards and recommendations covering all the fields of telecommunications
In March 2006, ITU-T created their in the domain of free space optics (FSO). This recommendation defined the usage for FSO "outdoor" systems of which the characteristics are the following: usage of lasers or of LED, transmission of data in line of sight up to 2km, bit-rate up to 1.25 Gbit/s, free spectrum and independence of the protocol.

-ITU-R: Radio communication – Regulation in the field of radio communications
The *commission of the THIS 3 study* works principally on the propagation of radio waves. In the domain of FSO, numerous contributions in the field of FSO have been proposed, principally from France and Japan, and these are largely concerned with outdoor propagation models.
The *commission of the THIS 5 study* controls the fixed service. There is a plan to launch of a process of recommendations for optical wireless systems with an objective to achieve this by 2010 [ITU 08].

The revision of frequency plans and sharing of the spectrum is carried out during the global radio-communication conferences (Conférences Mondiales des Radiocommunications: CMR) which are held at the end of each cycle of work of ITU-R.

(It is important to mention that currently there is no spectral regulation in the optical frequency range (from 10 to 1 000 THz) .

5.3.3.2 IEEE

The Institute of Electrical and Electronics Engineers (IEEE) has published a series of standards for local wireless networks (IEEE 802.11), and for personal-area networks (IEEE 802.15). The IEEE 802.11 standard contained an optical wireless component, but this has been superceded by RF base standards (802.11 a/b/g). There has been recent interest in VLC with 802.15, and a study group is currently preparing the documents required to start standards development VLC [WON 07]

5.3.3.3 CEPT

In Europe CEPT (Conférence Européenne des Postes and Télécommunication) regulates telecommunications, using the framework provided by ITU-R. The Electronic Communication Committee (ECC) uses these regulations to fix frequency allocations within the EU. Currently FSO is unregulated as there are no ITU-R recommendations.

5.3.3.4 ETSI

ETSI is the European Telecommunications Standardisation Institute creates European and global standards for telecommunications. It plays no role in free space optics at present, as there is no demand from its members for standards.

5.3.3.5 IEC

The International Electro technical Commission (IEC) is a standardisation and regulatory body concered with electrical, electronic and related areas. Eye safety regulations, highly relevant to optical wireless and free-space optics are published by the IEC.

5.3.4 Organisations

VLCC - *Visible light Communication Consortium*

VLCC is a Japanese association, whose objectives are to research and develop optical wireless communication technologies based on visible-light emitting LEDs. The partners in this consortium have engaged in academic research, development and presentation of prototypes, as well as drafting national standards for VLC [NAK 07].

FSAN - Full *Service Access Network*

The mission of FSAN is to drive the application of existing standards in commercial services and products. It has produced several whitepapers in the field of FSO, and it may be that indoor optical wireless could become an area of future interest.

WWRF - *Wireless World Research Forum*

This organisation is a forum for visions of future wireless communication and is in close contact with wireless technology associations such as: MITF in Japan, l'UMTS Forum in Europe, the NGMC Forum in Korea, and the FuTURE project in China. Whitepapers in the area of optical wireless communications, as well as visible light communications have been produced in the short-range wireless communications working group (WG5) and their have been numerous presentations on this topic.

6 Conclusions

6.1 Infra-red communications

A number of complete experimental systems have been fabricated, and commercial point to point links operating at 1Gbit/s have been demonstrated. These both demonstrate the feasibility and the challenges for OMEGA. The data rates required are challenging to achieve with the fields of view required in a typical home environment-perhaps 90 degrees at both transmitter and receiver. The narrow field of view available is a function of the link margin, due to the incoherent receivers used in OW, and to some extent the limited transmission power. The choice of the operating wavelength offers some degrees of freedom and potential to improve the link margin, but this is also mitigated by commercially available, rather than technically feasible, components within the context of the project. In all cases multiple links will be required to cover the required field of view, and the control and management of these is thought to be where most of the innovation in OMEGA lies, as the state of the art is relatively undeveloped. It is interesting to note that similar challenges are being studied in the context of 60GHz carrier RF networks, both within OMEGA and in the context of the IEEE study group in this area. This study of the state of the art therefore indicates that building a successful physical layer is feasible, but that OMEGA correctly focuses on the integration and control of the potentially complex and highly capable physical layer. It also indicates that techniques to integrate the complex physical layer components exist and to scale the data rates in the future are available.

6.2 Visible light communications

VLC is a relatively new area of communications, and a working 100Mbit/s broadcast system will represent a substantial improvement in the demonstrated state of the art. The key challenge for VLC is the modulation bandwidth of the LEDs, and the state of the art is demonstrated transmission at 100Mbit/s (at short range). This indicates the feasibility of the project, although substantial scaling is required. In addition there has been little significant development of higher layers for this application and OMEGA will undertake this. In addition the use of VLC in combination with IR and other RF wireless standards should allow the seamless reliable coverage that has been lacking from previous demonstrations.

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