Peter Adam Hoeher

Visible Light Communications

Theoretical and Practical Foundations

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Preface

"Data is the future of lighting"
Larry French

Visible light communication (VLC) is a fiberless data transmission technology based on visible light. VLC is an emerging field. One of the key motivations is the fact that light can be used simultaneously for illumination as well as for communication and/or positioning purposes. In return, due to this dual/triple functionality, no additional power supply is necessary for data transmission and localization. Endeavor to replace outdated light sources by LEDs can be combined with VLC technology. Compared to radio-based Wi-Fi, light-based data transmission systems – dubbed Li-Fi if fully networked – offer distinct features: they are human-friendly, provide higher data security on the physical layer, and permit low-cost hardware components. Light waves do not interfere with wireless radio signals and do not penetrate walls. Hence, the entire optical spectrum can be re-used in neighboring rooms or by using spatially separated spot beams. VLC systems are license-free world-wide and can be used in environments with strong electromagnetic radiation (as in fabrication halls and power plants), in electromagnetic-interference-sensitive areas (like aircraft cabins and hospitals), or as an alternative to Wi-Fi (for example in domestic, office, and retail/public surroundings). VLC technology is able to enhance smart lighting infrastructure and Internet-of-Things (IoT) applications in general. VLC is suitable for indoor as well as outdoor applications. LED-based Car-to-X communication is considered to be an enabling platform towards autonomous driving.

The emphasis of this textbook is on LED-based systems in the visible range of the radio spectrum and the adjacent ultraviolet and infrared bands. However, also aspects of laser-based **free-space optical** (FSO) communication are discussed. The entire range is covered, from theoretical considerations to system concepts, circuit design issues, and a selection of suitable commercially available off-the-shelf photonic devices. However, networking aspects and fiber optics are beyond scope.

The first (more background-oriented) part is devoted to goals and applications, fundamentals of illumination engineering, VLC and IR/UV channel modeling, optical intensity modulation schemes, as well as multiple-input multiple-output techniques for optical communications. Among the main challenges in **optical wireless communications** (OWC) to date are limited transmission rates, particularly in conjunction with off-the-shelf LEDs, and interference stemming from nearby illumination fixtures and from daylight. Considering these factors, focus is on advanced digital modulation techniques in order to improve spectral efficiency, but also on camera-based communication methods.

In the second (more practically oriented) part, OWC standards and ongoing standardization efforts, the software-defined radio concept and its application to VLC and FSO communication, selection criteria of photonic devices and high-speed amplifiers, fundamental circuit designs of OWC system components, selected VLC and FSO applications, and finally optical rangefinding and **visible light positioning** (VLP) techniques are presented.

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Disclaimer

Although the manuscript has been prepared carefully, typographical errors and mistakes are possible. The author is responsible for any flaw. Feedback by email to

VLC-book@web.de

is welcome.

Throughout this monograph, off-the-shelf products are pointed out, including LEDs, photodetectors, and computer platforms suitable for software-defined radio. These products are intended to serve as implementation guidelines. The author and his chair are not sponsored by any of the mentioned companies. The product selection is not intended to be complete. The author does not provide any warranty with respect to correctness and product changes. All product and company names are trademarks of their respective holders.

Kiel, Germany, May 2019 Peter Adam Hoeher

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1 Introduction

Learning Outcomes:

- What are the motivations and goals of visible light communication (VLC)?
- What are possible applications of VLC and related techniques?
- What are the advantages compared to radio communication?
- What are the drawbacks compared to radio communication?
- What is the current market situation?

1.1 Historical Background and Scope

Light has been used for data communication since a few thousands of years [Dar12]. Already in ancient times, smoke and fire signals were used for transmission of short messages, probably even over significant distances. It has been handed down that the Greek victory over Troja in the 12th century BC was delivered by means of **fire signaling** over a distance of about 555 km from Troja to Argos.

Later, signaling towers were built for the purpose of optical communication. On the island of Corsica for example (as well as in other Mediterranean places), visitors still are witnessing a ring of **signaling towers** along the coastal shoreline. In Corsica alone, about 150 Genoese towers were erected during the 16th century AD to defend the island from the menace of Barbary pirates. Upon alarm, optical signals were sent to the neighboring towers in the form of smoke or fire, possibly supplemented by acoustical signals. Although very successful, the message rates were quite limited. As a reminiscent, probably in all countries around the world with coastal access, lighthouses are still in use for the purpose of maritime navigation.

After the invention of the telescope, further technical progress was achieved. During the French revolution in the 18th century, the French engineer Claude Chappe invented an **optical telegraphy** device based on swivel-mounted signaling arms. With these signaling arms, a more efficient encoding/encryption and hence somewhat higher data rates could be achieved. Based on Chappe's invention, **semaphore systems** were implemented in France, Sweden, Denmark, England, and Prussia. Between 1832 and 1849, 62 telegraph stations were maintained between Berlin and the Rhine Province, covering a distance of almost 550 km. It is reported that a message could travel the complete distance of the Prussian semaphore system in much less than an hour. Swivel-mounted signaling arms are still used in railway signaling systems in many countries. It is interesting to note that semaphore signal detection corresponds to optical pattern recognition. In connection with a pixelated light source and a camera, this is currently an emerging technique for low-rate data transmission and localization purposes. The data rate depends on the cardinality of the signal alphabet and on the frequency of changing the pattern.

Semaphore systems were replaced by **Morse telegraphy** after the invention of the so-called Morse code by Samuel F.B. Morse in 1833, refined in 1838/1848/1865. In the 19th and 20th century, Morse signals were transmitted, amongst other methods, by the so-called **heliograph**, a wireless solar telegraph. Inside the heliograph, sunlight is reflected by a mirror. In order to digitally modulate the light beam, either a pivoting mirror or a shutter was applied. An predecessor to the heliograph is the **heliotrope**, invented by Carl Friedrich Gauss in 1821 for geodetic surveys. Heliographs were used by legal armies for a long time, and are nowadays used by irregular military and regional forces. Optical Morse signaling is still used on surfaced submarines, for example, using special signaling lamps.

In 1880, Alexander Graham Bell and Charles Sumner Tainter have patented the so-called **photophone**. The photophone is an early version of a telephone, but is based on modulated light rather than on a modulated current carried by a twisted cable. The main principle of the photophone is to modulate a collimated light beam by means of a flexible mirror. Stimulated by voice, the mirror becomes either convex or concave and thus bundles or scatters the light beam. As opposed to the heliograph, modulation is analog. At the receiver side, Bell and his assistant recovered the voice signal by a selenium photodetector connected to a loudspeaker.

Although the bulk of data nowadays is handled via high-speed/ultra-high-speed optical fiber transmission systems approaching up to 100 Gbps and beyond, **optical wireless communication** (OWC) is undergoing a revival [Hra05, Ram08, Arn12, Bou12, Gha12, Cha13, Lee15, Uys16, Cho18]. OWC is fiberless and covers the entire frequency range from ultraviolet (UV) via visible light (VL, VIS) to infrared (IR).

Based on the transmission distance, **OWC can be classified** as follows [Uys16]:

- **Ultra-short-range OWC** is employed in chip-to-chip communication in order to reduce the wiring overhead in multi-chips devices [Mil00]. Optocouplers also put ultra-short-range OWC into practice.
- **Short-range OWC** is employed in body area networks and related applications. Furthermore, optical interconnections in computer centers fall in this range order [Kac12].
- **Medium-range OWC** is suitable for WLAN-type of services and distances, both for indoor (e.g., home entertainment) and outdoor (e.g., car-to-car and underwater) applications. This distance range is commonly served by solid-state light emitting devices. Sometimes infrared light is used, e.g. in remote controls, otherwise visible light is applied in medium-range OWC. Ultraviolet light is rarely practiced. Most use cases addressed subsequently are instances of this range category.

- **Long-range OWC** is used as a last mile access or as a mobile backbone network technique. Potential applications are data links between tall buildings, base stations, ships, and so forth. Long-range OWC is laser-based, with a few exceptions. Long-range OWC is known as **free-space optical** (FSO) communication [Wil02, Bou04, Kar11, Maj14, Raj16, Maj19].
- **Ultra-long-range OWC** is traditionally used in inter-satellite and deep-space laser links [Hem06], because scattering is negligible in space. However, also satellite-to-earth links are potential use cases. The first commercial laser-based satellite-to-earth link has recently been implemented between a low-earth-orbit satellite directly to an earth-based optical ground station.

Generally speaking, **visible light communication** (VLC) is the branch of OWC employing white light or selected colors between violet and red. In a more strict sense, the key idea of VLC is to conduct joint illumination and data transmission by modulating the light source(s). This concept dates back to the beginning of this century. In 2001, Masao Nakagawa and members of his team at Keio University in Yokohama invented and explored the fascinating idea of using light simultaneously for illumination and communication purposes [Kom03, Kom04]. Quickly, researchers from all over the world began to investigate fundamentals and applications of VLC [Kom03, Kom04, Arn15, Dim15, Gha17, Wan17, Chi18]. In most cases light emitting diodes (LEDs) are utilized, which can be switched “on” and “off” more than a million times per second without significant impact on operating lifetime and aging. Medium-range VLC applications are dominant.

In this textbook, we are not just interested in VLC defined in the strict sense, because the main principles, modulation and reception techniques, circuit designs etc. can also be applied to other light sources (like laser diodes, organic LEDs, and micro-LEDs) and to the adjacent frequency bands, namely infrared and ultraviolet. However, we do not consider optical fibers in any case.

1.2 Motivations for Using Visible Light Communication

There are some **key features** which motivate using light for simultaneous illumination and data transfer:

- **Energy efficiency:** For data transmission, the same power spent for illumination can be re-used. Hence, no extra power is necessary for data transfer, despite some extra amount of power needed for digital signal processing. Therefore, VLC is an energy-efficient (“green”) technology. Power LEDs and LED arrays, which are typically used in VLC, are more energy efficient than traditional light sources. Efforts to replace outdated (incandescent/halogen/fluorescent) light sources by LEDs can be combined with VLC technology. Daylight harvesting and smart lighting can be combined with future VLC systems to reduce energy consumption and CO_2 emission even further.

Still, it is worth to mention that illumination requirements and communication requirements are not easy to combine. Illumination involves energy efficiency, color control, and flicker avoidance. Vice versa, communication targets are throughput maximization and outage minimization. These partly conflicting requirements can only be joined by properly designed modulation techniques, c.f. Chapters 4 and 5. Otherwise, data transmission would impact the color quality of illumination/lighting, treated in Chapter 2.

- **Tremendous unregulated bandwidth:** As a rough rule of thumb, the following wavelengths are usable in conjunction with LEDs: about 200-400 nm in the UV range, 400-800 nm in the visible range (more precisely 380-780 nm), and roughly 800-1600 nm in the IR range. Note that 1 nm equals one billionth of a meter. This translates into signal bandwidths of about 1500 THz (UV), 750 THz (VL), and 375 THz (IR). These figures extend available and future radio-frequency (RF) frequency bands by orders of magnitudes. Tremendous bandwidth converts into extremely large channel capacity and hence potentially Gbps data rates.

  For reasons of fairness, however, it is worth mentioning that it is difficult with today's LED technology to efficiently exploit the tremendous bandwidth. Typically, LEDs have a spectral linewidth of about 10-40 nm if they are not coated. Otherwise even wider. Hence, the number of channels is limited. The number of quasi-orthogonal channels can be increased by optical filters and/or digital signal processing. The former are lossy, angle-dependent, and sometimes expensive, whereas the latter option adds to computational complexity.

- **License-free operation:** VLC is license-free and light spectrum is globally harmonized, since international radio frequency spectrum regulation usually stops at 3 THz. Light spectrum is complementary to RF frequency bands. License-free operation is also possible in the industrial, scientific and medical bands (which are used for Wi-Fi and personal area networks, for example) – but the useful light spectrum is much wider than the classical radio spectrum.

- **High signal-to-noise ratio:** VLC systems making use of power LEDs or LED arrays provide a high signal-to-noise ratio at the receiver side in environments like office buildings, where a certain light intensity must be met according to regulations. In office environments not exposed to direct sunlight, a link margin of about 30 dB has been measured for distances between 2 m to 4 m. Again, constraints need to be taken into account: for eye safety average intensity restrictions apply, whereas LEDs are peak intensity limited.

  In other applications, for instance optical underwater communication (Chapters 3 and 10), the signal-to-noise ratio is often quite low, however. Sunlight and nearby light sources have a detrimental effect on the signal-to-noise ratio.

- **Interference immunity:** Unlike radio waves in the microwave regime, light does not penetrate walls. Hence, the whole light spectrum can be re-used in neighboring rooms, without causing interference. Frequency planning/frequency management is not necessary. From a cellularization point of view, perfect cell borders can be achieved by walls, i.e., there is no inter-cell interference between closed rooms. Furthermore, radio waves in the entire regime allocated by radio systems do not interfere with light. Both frequency ranges can be used simultaneously without causing any interference. (It has been observed that LEDs occasionally disturb radio reception. This effect is owed to non-certified LED drivers rather than the core

LED.) Hence, VLC provides enhanced reliability if line-of-sight between transmitter and receiver is given.

Interference due to light sources located in the same room can be decreased by spot beams. Interference caused by optical products partly occupying the desired light spectrum, e.g. IR remote controls for TV sets, can be optically filtered out, if necessary, or suppressed by means of digital signal processing. Novel alternatives of interference mitigation will be introduced in Chapter 9.

- **Area spectral efficiency:** VLC promotes the implementation of so-called attocells, i.e., cell sizes even smaller than pico/nano/femto cells familiar in RF-based cellular radio. Accordingly, a higher spatial user density is possible compared to RF communications. This fosters massive connectivity.
- **Low-cost hardware:** For data rates below approximately 1 Gbps, Tx and Rx hardware is much simpler than RF front-ends, see Chapters 7-9. Hence, low-cost consumer products are feasible. Moreover, VLC can be installed at a low cost since power supply is already available at the installation site ("dual-use of existing infrastructure"). Considering LED-based prototypes, data rates up to about 10 Gbps are reported under lab conditions [Wan15, Isl17].
- **Electromagnetic compatibility:** Visible light is not harmful to the human body, if eye-safety and flicker regulations are kept in mind in system design.

  However, light quality control is mandatory to prevent psychological and biological effects. Non-visible effects of light on human beings should not be ignored.
- **Data security:** Since light radiation is easier to constrain in a physical space and because light does not penetrate walls, especially in indoor applications data security is easier to maintain on the physical layer compared to radio communication. VLC offers inherent protection against eavesdropping. Also, jamming is more difficult to achieve.

  Often overlooked in the context of data security of OWC systems is the feeder link, however. Conventional data encryption at bit level, physical layer security, and optical quantum technologies are possible solutions.
- **Human centric lighting:** In the framework of human centric lighting (HCL), the goal is to match light color, light intensity, and timing of light exposure to our circadian rhythm. By carefully controlling the spectral distribution and the intensity of light sources, HCL affects health, productivity, and emotional comfort of people in a positive fashion. Although the combination of VLC and HCL has not yet been explored in detail, VLC seems to be an enabling technique towards personalizing light quality, coined **human centric Li-Fi** (HCLiFi) by the author in Chapter 2.

Conceptually, VLC is an alternative to RF communications. It may be used as a **complementary system**. Light communication may complement Wi-Fi (2.4/5 GHz), WiGig (60 GHz Wi-Fi), and LTE/5G cellular radio, similar as WiGig complements Wi-Fi. Power over Ethernet (PoE), powerline communication (PLC), or the digital addressable lighting interface (DALI) may serve as a wireline backbone infrastructure, see Fig. 1.1.

Data communication making use of steered collimated infrared beams, recently proposed in [Koo18], is an alternative to wide-coverage VLC based on LED illumination. This proposal predicts unshared high channel capacities to devices individually. However, precise and adaptive beam steering is not ready for the mass market yet.

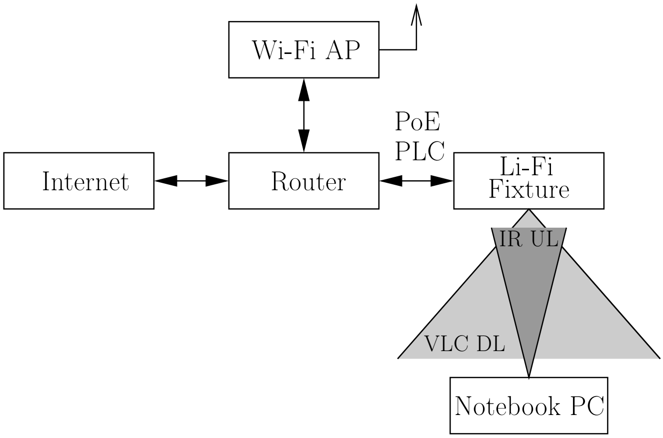


Figure 1.1 Possible system level architecture. VLC is used on the downlink (DL), IR on the uplink (UL) in this example. Li-Fi is complemented by a Wi-Fi access point (AP).

Like radio waves which can be used for communication and localization purposes, light can be used for communication and localization purposes as well. **Visible light positioning** (VLP) is an emerging topic, c.f. Chapter 11. VLP potentially affords guidance in airports and railway stations, shopping malls, supermarkets, stadiums, cinemas, concert halls, museums, and many other environments. On the one hand, customers may benefit from new traveling/leisure/shopping experiences, and on the other hand, VLP may be used as a tool for retail strategies. In the worst case, VLC/VLP can be used to intervene in personal rights.

Besides these structural advantages, there are a few **drawbacks** to be mentioned:

- **Deactivation and shadowing/blocking:** VLC (defined in the strict sense) only works when the illumination is activated. Without artificial light, for example when the sun exposure is bright enough or at rest times in the night, data transfer stops. Even more troublesome for customers may be non-line-of-sight scenarios. A mobile VLC device does not work when put in a pocket or bag. If communication capabilities are required without interruptions, a hybrid fall-back solution would be necessary. Generally speaking, non-line-of-sight scenarios are more critical compared to RF links.

  On the other hand, customers are able to intuitively track the best coverage positions, because the light sources are visible when light is switched on.
- **Artificial light vs. daylight:** Daylight harvesting is an efficient solution for energy savings. In daylight harvesting, artificial light is added onto the available amount of daylight. The intensity and spectrum of artificial light is adaptively matched in order to mimic the sun. Micro-spectrometers are useful to measure the combined contribution of artificial light and daylight. Closed-loop control schemes determine the dimming levels of luminaries to produce the right amount of artificial light. Alternatively, daylight sensing luminaries perform the dual function of illumination and daylight sensing in conjunction with an open-loop control scheme [Li16].

  On the other hand, daylight (plus light emitted by other luminaries) is biasing the modulated photocurrent at the receiver side. Furthermore, daylight causes additional shot noise in the photodetector. Therefore, daylight should be reduced before data detection. Otherwise, it may happen that daylight saturates the receiver input. Reducing daylight, however, is in conflict to the energy savings aspect.

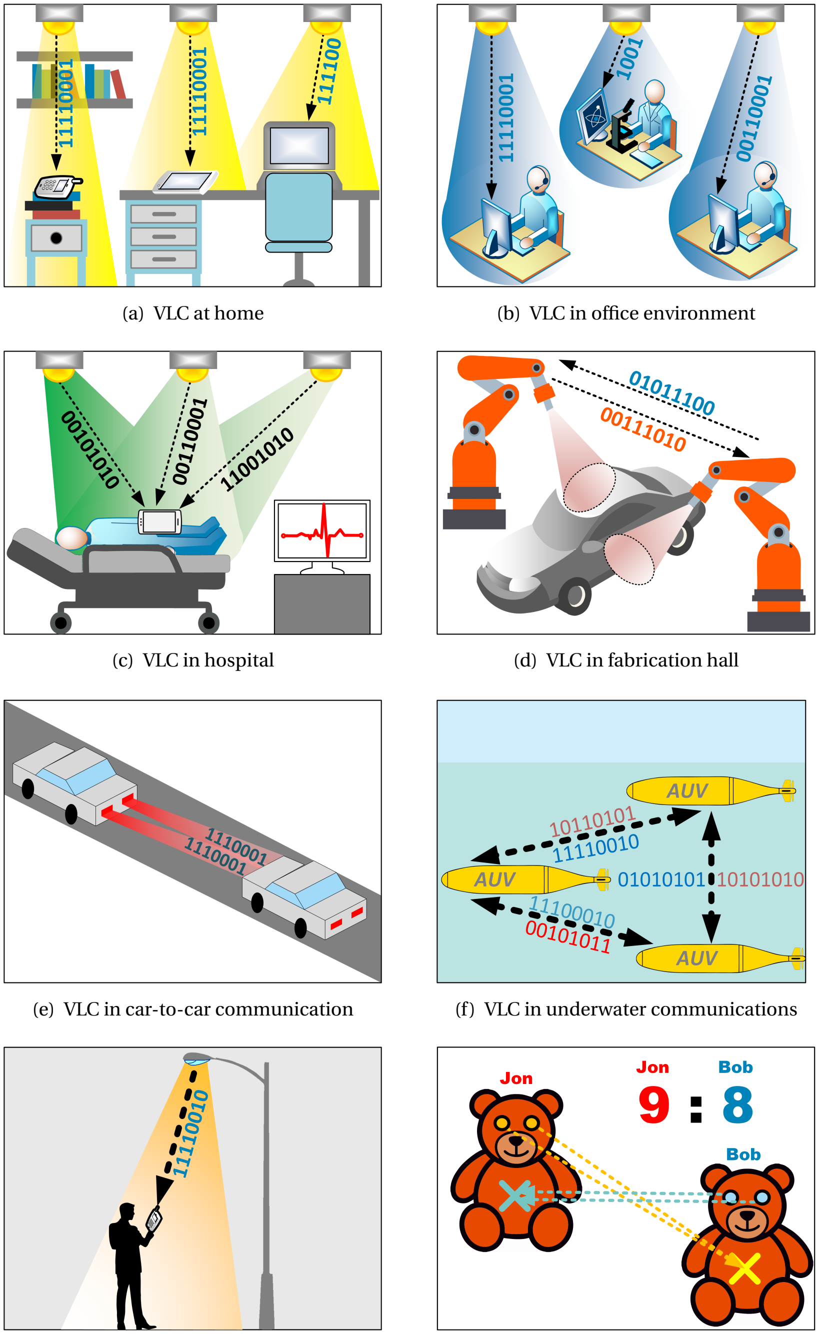
- **Return link, duplex communication:** Whereby the data link from the illuminating light source to the receiver is obvious, the return link (also called uplink) is not that obvious. One may use a different wavelength (for example infrared) on the return link, among other technologies like time-division duplexing or hybrid light/radio communication.
- **Optical relaying:** By nature, VLC is a short/medium-range concept. Optical relaying may be useful in scenarios with shadowing or for data links with strong attenuation. Optical relaying is an emerging technology, which is not well treated in literature so far as elaborated in Chapter 10.
- **User mobility and outdoor applications:** Support of mobile users and portable VLC devices is currently a research topic. Also, research on VLC outdoor use cases is challenging.
- **Limited bandwidth per LED:** Despite the tremendous bandwidth offered in the UV, VL, and IR bands, the bandwidth per LED is limited. The 3 dB bandwidth of off-the-shelf LEDs in the visible range does not exceed about 20 MHz. Hence, wideband VLC communication is only possible in conjunction with multichannel LED arrays and advanced signal processing.

Flicker avoidance and dimming support are issues, which have been solved in recent years. Furthermore, mitigation of multipath propagation effects is a well-studied topic. Color control is still an active research topic, particularly when VLC and HCL are treated jointly. The blue-light hazard, i.e. retinal damage potentially caused by blue LEDs with yellow phosphor coating, remains being a health risk [Bul00]. Particularly blue light also contributes to the global light pollution [Fal11].

1.3 Applications of Visible Light Communication

VLC applications are manifold, ranging from simultaneous illumination and data transfer (in the sense of dual functionality) to many other areas, see Fig. 1.2.

- **Li-Fi:** Light fidelity (Li-Fi), coined by Harald Haas in 2011, is a high-speed communication and networking variant of visible light communication (VLC) [Dim15]. Li-Fi is an alternative to Wi-Fi or may coexist with Wi-Fi. The light spectrum can be used to provide data off-loading and link aggregation capabilities. Prominent environments of Li-Fi personal area networks are apartment buildings, office buildings, classrooms, hotels, ports, trains, vessels, and retail areas like supermarkets, shopping malls, and restaurants. Li-Fi offers a wide signal spectrum that can be re-used in tiny cells as opposed to Wi-Fi, which is interference limited in hotspots nowadays. Details will be presented in Chapter 10.



(a) VLC at home
(b) VLC in office environment
(c) VLC in hospital
(d) VLC in fabrication hall
(e) VLC in car-to-car communication
(f) VLC in underwater communications
(g) VLC in street lighting
(h) VLC in toy market

Figure 1.2 Potential VLC applications.

- **Industrial applications, robotics:** Particularly in industrial environments like fabrication halls/manufacturing cells, a high immunity against interference is important. Machines for instance are prominent sources of electromagnetic (EM) radiation, but also power plants are strong EM emitters. Light is immune against EM radiation. Furthermore, high-rate ultra-low-delay VLC systems are feasible, which is an important feature in robotics and in cyber-physical systems, among other applications. Furthermore, light is suitable for areas exposed to explosion hazards, such as offshore platforms and oil/gas industry in general.
- **Aircraft cabins, hospitals:** Besides environments with high EM radiation, like manufacturing cells, the opposite use case is important as well: VLC is suitable for electromagnetic interference (EMI) sensitive areas. Aircraft cabins and hospitals, particularly areas around surgery theaters and magnetic resonance imaging scanners, are among the most frequently mentioned examples. Spacecraft cabins and military submarines are other applications. In contrast, radio communication is prohibited in these areas.
- **Car-to-X communication, traffic systems:** Some intelligent traffic signs and road charge systems are already based on VLC. LED-based Car-to-X communication is considered to be an enabling platform towards autonomous driving and swarm communication. In the future, in-car communication may be based on VLC as well.

  In-car Li-Fi communication as well as in-train Li-Fi communication may become an alternative to on-board WLAN installations. The mutual influence of in-car WLAN and fixed WLAN networks is likely to become a major concern. Currently few cars are equipped with WLAN, however this situation is expected to change soon as car manufacturers continue to improve infotainment systems and introduce autonomous driving. Connectivity may be one of the enabling technologies of autonomous driving. In return, it is predicted for example that hundreds of cars equipped with on-board WLAN parking near a hospital may seriously affect the wireless infrastructure in sensitive areas inside the hospital. This and related problems can be relieved by Li-Fi.
- **Sensor nodes:** Optical wireless communication is an interesting low-power high-speed alternative to radio links. Particularly, communication between sensor nodes and Internet of Things (IoT) applications may benefit from VLC technology. The ZigBee Light Link (ZLL) has been introduced by the ZigBee Alliance for interoperable and easy-to-use consumer lighting, supporting IoT applications.
- **Museums, street lights:** Museums and street lights are examples, where VLC promotes infotainment access in public areas. Particularly broadcasting type of services are simple to implement.
- **Mobile underwater communication:** LED-based underwater communication provides high-speed data links. Swarms of autonomous underwater vehicles and related instrumentation may benefit from optical communication.
- **Chemical industry, mining:** In petrol industry, chemical industry and mining VLC is an interesting candidate for safety reasons.
- **Toy and gaming market:** Interactive toys already virtue from LED links. Low-cost production is of primary concern in this market segment. For example, the same LED may be used for emission as well as for reception in order to reduce cost. Also, interactive games may benefit from high-capacity links.

- **Virtual and augmented reality:** On short term basis, virtual reality (VR) goggles can be connected via high-capacity links. In a longer time-frame, in-house virtual reality is a possible future market segment, which may be combined with VLC. Additionally, augmented reality (AR) can be supported by OWC, both for entertainment/educational purposes as well as for safety applications.

These short/medium-range use cases can be complemented with those known from the area of free-space optics, like wireless front-/backhauling.

By using the whole visible spectrum, achievable data rates on the order of 100 Gbps are predicted [Tso15]. Several VLC demonstration systems have been installed in recent years, offering data rates between a few kbps and several Gbps [Wan15, Isl17]. Besides lab experiments conducted in academic environments, mainly supermarkets and office buildings have been equipped in order to illustrate the main functionalities of joint illumination and data transmission/localization. However, the technologies used so far are proprietary – world-wide standardization efforts are important to proceed. Standardization is expected to help to accelerate an introduction of additional products to the market, see Chapter 6.

1.4 Smart Lighting and VLC Consumer Products

Smart lighting combines solid-state lighting, a communication interface, environmental sensing, and advanced control algorithms [Che17, Hig18]. Compared to classical light sources, LEDs have an improved luminous efficacy, lower cost per lumen, a smaller form-factor, and a longer operational lifetime [Cra09]. In wireless lighting, a ZigBee [Wan13], Wi-Fi, Bluetooth, or other communication chip is integrated into the LED/OLED driver enabling adaptable light tuning. Consequently, tone/contrast/color spectrum/color temperature of the light source can be controlled remotely. Environmental sensors comprise infrared and ultrasonic proximity detectors, as well as light sensors such as micro-spectrometers, etc. The benefits are manifold and include increased energy savings (notably in conjunction with daylight harvesting), increased light quality and aesthetics, as well as human centric lighting, among others [Hig18]. A plethora of smart lighting solutions is available on the market, see Table 1.1. As an IoT platform, wireless lighting is an ingredient of Smart Homes, Smart Offices, Smart Fabs, and related environments.

The first **commercial Li-Fi products** are available since 2018, see Table 1.2, others are announced at the time of writing. Typically, a USB dongle shall be connected to the mobile user equipment. This dongle performs processing for both directions, i.e., for DL and UL.

- **Firefly LiFi** initial product categories include office, outdoor, machine-to-machine, transportation, and vehicle communication. Their office product, for example, achieves up to 700 Mbps on the DL using visible light, and up to 1300 Mbps on the UL using IR. All data links are encrypted.

Table 1.1 Commercial smart lighting products [Che17, Hig18].

Product	Wireless connectivity
Belkin WeMo	Wi-Fi, ZigBee
Cree connected LED bulbs	ZigBee
Digital Lumens SiteWorx	Wireless Mesh Network
Elgato Avea	Bluetooth
FluxSmart WiFi LED Light Bulb	Wi-Fi
GE Link Smart LED	Wi-Fi, ZigBee
Gooee EcoSystem	Bluetooth
Ledmotive	Wi-Fi, Bluetooth, sub-GHz
LIFX	Mesh Wi-Fi network
LightWave RF	Wi-Fi, LightWave RF
Osram Lightify	Wi-Fi, ZigBee
Philips Hue	Wi-Fi, ZigBee
Samsung smartThings	ZigBee, Bluetooth

- **Oledcomm** sells Li-Fi indoor and outdoor equipment. The indoor product portfolio includes Li-Fi desk lamps, Li-Fi floor lamps, LED panels, and light bulbs. For instance, the IoT desk lamp MyLIFI supports bidirectional VLC links. On the DL, the achievable data rate is 13 Mbps, whereas it is 10 Mbps on the UL. An office solution called LIFIMAX provides secured high-speed (DL: 100 Mbps, UL: 40 Mbps) internet access through IR light for up to 16 users.
- **PureLiFi** has been pioneering Li-Fi research. Their first Li-Fi product is a starter kit (LiFi-XC), with a maximum data rate of 43 Mbps on DL and UL shared by up to eight users. Gigabit Li-Fi technology is currently announced by pureLiFi.
- **Signify**, formerly Philips Lighting, provides a Li-Fi system with a maximum data rate of 30 Mbps on the DL. An IR uplink offers a maximum data rate of 8 Mbps.
- **Velmenni** presently announces a LiFi-based mesh network solution.
- **VLNcomm** supplies a Li-Fi desk lamp as well as a Li-Fi ceiling light. The desk lamp supports data rates of up to 23 Mbps on DL and UL, the ceiling lamp up to 70/60 Mbps on DL/UL. VLC is used on the DL, IR on the UL. Multiuser functionality is provided. Recently, they launched a Li-Fi enabled lighting panel.

Besides first commercial Li-Fi products, numerous prototypes have been implemented particularly by research institutes. The **Heinrich Hertz Institute** at **Fraunhofer Gesellschaft** (FHG-HHI) in Berlin is among the leaders in OWC research. Their Li-Fi prototypes based on PLC chips have been demonstrated at various exhibitions and in field trials.

Table 1.2 Commercial Li-Fi providers at the time of writing. More than 20 companies, including global players, are currently working on Li-Fi products.

Product	Homepage
Firefly Lifi	www.fireflylifi.com
Oledcomm	www.oledcomm.com
PureLiFi	www.purelifi.com
Signify	www.signify.com
Velmenni	www.velmenni.com
VLNcomm	www.vlncomm.com

1.5 Chapter Summary

Although the origins of OWC date back many centuries ago, some principles are still used today, particularly for optical signaling purposes. Despite the popularity and efficiency of ultra-high-speed optical fiber networks, OWC is undergoing a revival. OWC can be implemented on different distance scales, from ultra-short-range OWC to ultra-long-range OWC.

VLC is the branch of OWC utilizing wavelengths resolvable by the human eye. VLC supports a triple functionality – illumination, communication, and positioning can be performed simultaneously on the DL. Among the motivations of studying and implementing VLC are energy efficiency and CO_2 reduction, tremendous unregulated bandwidth, license-free operation, potentially high signal-to-noise ratio, interference immunity, area spectral efficiency, low-cost hardware, electrosmog-free operation, data security, and human centric lighting. Conceptually, VLC is an alternative to RF communications. VLC can be combined with powerline communication and Power over Ethernet.

Besides the structural advantages, several drawbacks of VLC should not be forgotten. Artificial light sources must be active, even in the presence of daylight and during night hours. Even worse, daylight is likely to saturate the detector, causing outage of data reception. Any non-light-of-sight scenario should be avoided, including bags and pockets. The return link is an open research topic, unless IR is used on the UL. Optical relaying is auspicious, but not well treated in literature as well. Mobile and portable applications are challenging. Although the overall spectral bandwidth is tremendous, the bandwidth per LED presently is quite small.

Potential use cases of VLC are manifold – including apartment and office applications, public domain environments, interference-free areas, areas with heavy EM pollution, and outdoor applications like Car-to-X communication, among many others.

Smart lighting is a driving force of VLC, many smart lighting consumer products are available. The first commercial VLC products have been introduced in 2018. Given several ongoing standardization efforts in conjunction with a plethora of novel insights contributed by the research community, it is currently expected that VLC is a strongly emerging market.

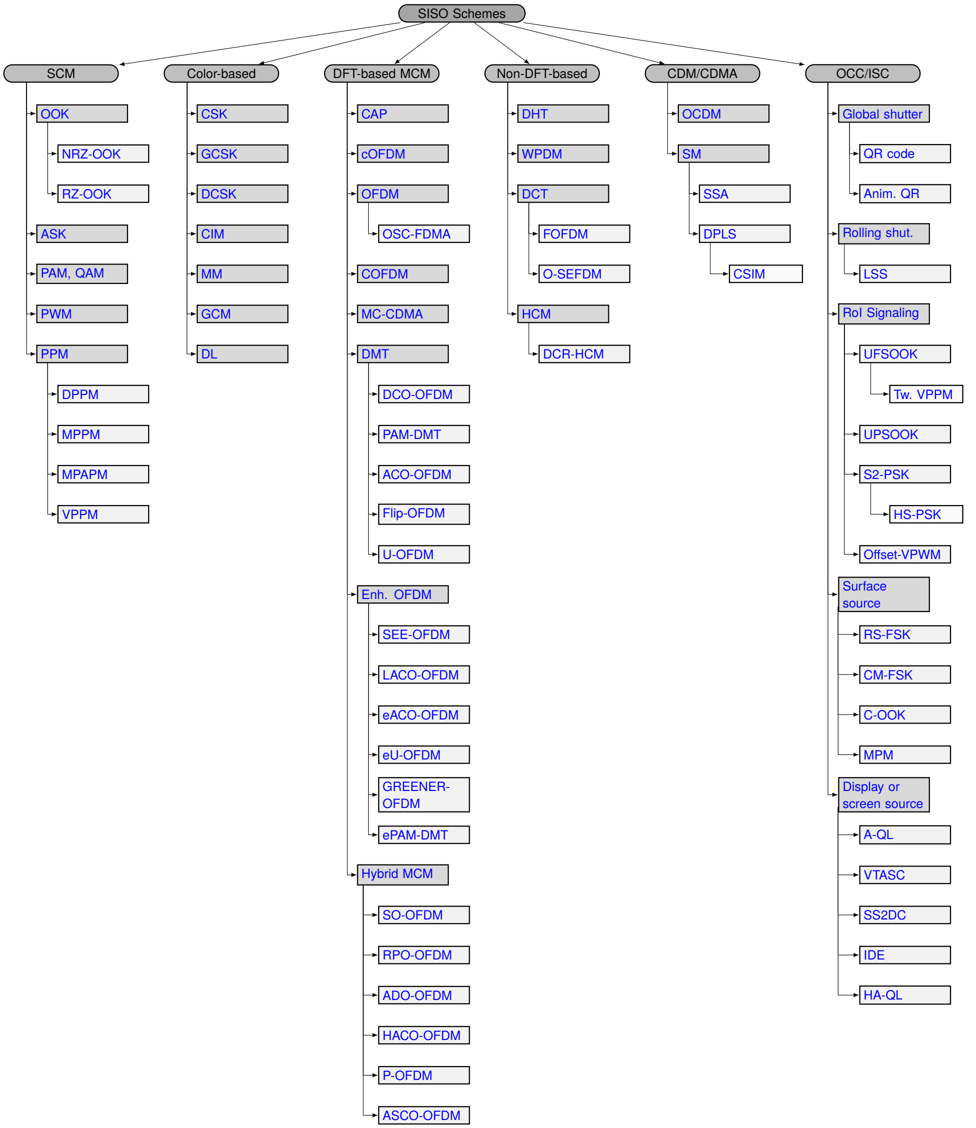


Figure 1.3 Classification of optical modulation schemes employing a single transmit aperture. For e-book readers: If you click on a selected abbreviation, you will be guided to the corresponding page.

1.6 Outline

The remainder of this monograph is organized as follows. Chapter 2 is devoted to fundamentals of illumination engineering. Focus is on color mixing, color spaces and photometric quantities, but also on eye safety issues and human centric lighting. Chapter 3 emphasizes on VLC channel modeling, considering free-space propagation, indoor multipath propagation, as well as optical communication in sea water. The chapter is complemented by IR/UV channel modeling. Modulation techniques suitable for optical wireless communications are studied in Chapter 4. Focus is on photodetector-based direct detection, but also camera-based detection concepts are treated. About eighty different intensity modulation schemes are appointed in this chapter, including single-carrier and multi-carrier modulation schemes, color-domain modulation techniques, and pixelated light sources in conjunction with two-dimensional image sensors. A classification of these schemes is depicted in Fig. 1.3. Optical multiple-input multiple-output (MIMO) techniques are reviewed in Chapter 5. In Chapter 6, OWC standards and current standardization efforts are introduced. Emphasis is on the 2011 release of the IEEE 802.15.7 VLC standard, which is the first VLC standard considering flicker mitigation and dimming support. In Chapter 7, the software-defined radio concept and its applications in the area of OWC are highlighted. Photonic devices and high-speed amplifiers are presented in Chapter 8. Based on this, elementary circuit design rules both with respect to the transmitter and the receiver side are figured out in Chapter 9. Chapter 10 is devoted to selected VLC and FSO applications, including Li-Fi, optical underwater communication, optical free-space Ethernet, and optical relaying. Finally, Chapter 11 introduces the reader to the interesting area of visible light positioning, and briefly deals with optical rangefinding.

Each chapter starts with selected learning outcomes and is concluded by a summary. These end-of-chapter summaries comprise the learning targets. As a supplementary, at the end of each chapter a selection of questions is formulated. These questions may be considered as homework problems, or they may inspire a profound reflection on the topic.

Problems

1-1 It is interesting to note that some antiquated optical wireless communication (OWC) principles are still in use or have inspired related techniques that are still applied. Please name a few.

1-2 Visible light communication (VLC) is a subset of OWC. Which OWC applications are beyond the scope of VLC?

1-3 Reflect on the advantages of VLC as given in the text.

1-4 Discuss the technical problems of VLC. A critical review is desirable.

1-5 Numerous advantages and some drawbacks of VLC are mentioned in the chapter. Latency, however, has not been addressed in the main text. How would you assess the latency of a VLC system compared to the latency of an RF system operating at a similar data rate?

1-6 In your opinion, what are influential applications of VLC?

1-7 VLC either utilizes single or multiple photodetectors at the receiver side, or a camera. In the latter case, pixelated sources are frequently used, like displays. Imagine how this latter concept works. Mention differences compared to a classical VLC setup employing a single light source and a single photodetector. Consider indoor and outdoor scenarios.

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