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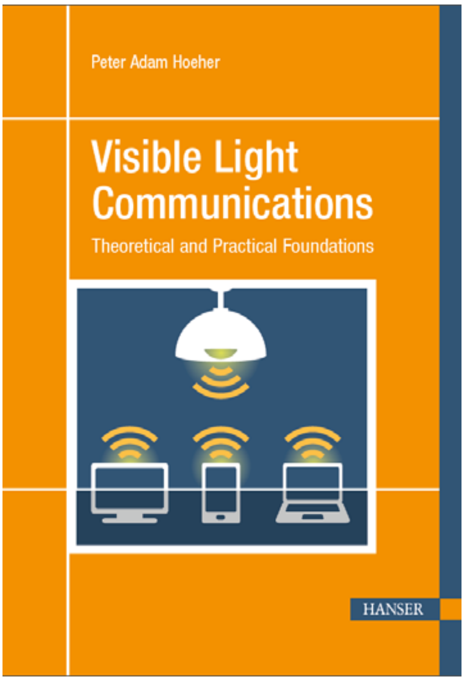

Sample Pages

Visible Light Communications

Theoretical and Practical Foundations

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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 Endeavor to replace outdated light sources by LEDs can be combined with VLC technology.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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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.

Subject Index