Visible Light Communications

Modulation and Signal Processing

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A comprehensive reference on modulation and signal processing for visible light communication

This informative new book on state-of-the-art visible light communication (VLC) provides, for the first time, a systematical and advanced treatment of modulation and signal processing for VLC. *Visible Light Communications: Modulation and Signal Processing* is a practical guide to designing VLC, linking academic research with commercial applications.

In recent years, VLC has attracted attention from academia and industry since it has many advantages over the traditional radio frequency, including wide unregulated bandwidth, high security, at a low cost. It is a promising complementary technique in 5G wireless communications, especially in indoor applications. However, lighting constraints have not been covered in current literature when considering VLC system design, and its importance has been underestimated. That's why this book—written by a team of experts with both academic research experience and industrial development experience in the field—is so welcome. To help readers understand the theory and design of VLC systems, the book:

- Details many modern techniques on both modulation and signal processing aspects
- Links academic research with commercial applications in visible light communications as well as other wireless communication systems
- Combines theoretical rigor with practical examples in presenting optical camera communication systems

Visible Light Communications: Modulation and Signal Processing serves as a useful tool and reference book for visible light communication professionals, as well as wireless communication system professionals and project managers. It is also an important guide for undergraduates and graduates who want to conduct research in areas of wireless communications.

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Preface

This book presents the state-of-the-art of visible light communication (VLC) focusing on the modulation and signal processing aspects. VLC has many advantages, such as wide unregulated bandwidth, high security and low cost over its traditional radio frequency counterpart. It has attracted increasing attention from both academia and industry, and is considered as a promising complementary technology in the fifth generation (5G) wireless communications and beyond, especially in indoor applications. This book provides for the first time a systematical and advanced treatment of modulation and signal processing for VLC and optical camera communication (OCC) systems. Example designs are presented and the analysis of their performance is detailed. In addition, the book includes a bibliography of current research literature and patents in this area.

Visible Light Communications: Modulation and Signal Processing endeavours to provide topics from VLC models to extensive coverage of the latest modulation and signal processing techniques for VLC systems. Major features of this book include a practical guide to design of VLC systems under lighting constraints, and the combination of the theoretical rigor and practical examples in present OCC systems.

Although it contains some introductory materials, this book is intended to serve as a useful tool and a reference book for communication and signal processing professionals, such as engineers, designers and developers with VLC related projects. For university undergraduates majoring in communication and signal processing, this book can be used as a supplementary tool in their design projects. Graduate students and researchers working in the field of modern communications will also find this book of interest and valuable. The book is organized as follows.

Chapter 1 provides an overview of the history of VLC, its advantages, applications, related modulation and signal processing techniques, and standardization progresses.

Chapter 2 investigates optical channel models and channel capacity subject to lighting constraints from light emitting diode (LED), where chromaticity control, dimming control and flicker mitigation are also discussed. The link characteristics including shadowing, direct versus indirect lighting and natural light are introduced. Typical optical channel models are addressed in detail. In addition, channel capacity under different lighting constraints is derived to achieve tight upper and lower bounds.

Chapter 3 reviews carrierless, single carrier modulations and some coding schemes for VLC systems. Modulation and coding techniques for dimming control and flicker mitigation are also introduced to satisfy illumination requirements.

Chapter 4 briefly reviews conventional optical orthogonal frequency division multiplexing (OFDM) schemes and then focuses on recent developments on optical OFDM including performance enhancement, spectrum- and power- efficient optical OFDM, and optical OFDM under lighting constraints. Comprehensive comparisons of the existing and proposed modulation techniques are provided as well.

Chapter 5 discusses multicolor modulation schemes under illumination requirements. The LED colorimetry is introduced as a measure for illumination quality, and various modulation schemes are explored to support both communication and high quality illumination.

Chapter 6 explains optical multiple-input multiple-output (MIMO) techniques for imaging and non-imaging VLC systems, including modern optical MIMO, optical spatial modulation, optical space shift keying, and optical MIMO-OFDM. Furthermore, multiuser precoding techniques for VLC systems are also introduced under lighting constraints.

Chapter 7 addresses the signal processing and optimization issues for VLC systems including pre- and post-equalization, interference mitigation and capacity maximization. The hybrid visible light communication and wireless fidelity (VLC-WiFi) system is also introduced to provide better coverage, and the system optimization problem is formulated and solved.

Chapter 8 introduces OCC fundamentals. It describes a typical OCC link, from the optical signal source, propagation path, to optical lens, filters, pixelated image sensors and the receiver. Different noise models such as ambient noise, temporal noise and fixed pattern noise are also addressed. Inter-pixel interference in the active pixel sensor, optical crosstalk due to diffraction and light diffusion, and the distortion due to perspective are introduced.

Chapter 9 discusses OCC modulation schemes and system design aspects. It also introduces various system impairment factors and mitigation techniques, including tracking and coding techniques to achieve synchronization. The off-line and real-time prototypes as well as the potential applications of smartphone cameras are illustrated.

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Introduction to Visible Light Communications

1.1
History

Visible light communication (VLC) is an age-old technique which uses visible light to transmit messages from one place to another. In ancient China, communication by flames was an effective way to relay signals from border sentry stations to distant command offices on the Great Wall. Similarly, lighthouses were distributed along seashore or on islands to navigate the cargo ships on oceans. Nowadays, visible lights are also mounted on modern skyscrapers to not only indicate its presence at particular locations, but also provide reference signals to pilots flying a plane.

Along with the evolution of telecommunication science and technology, using visible lights instead of other electromagnetic waves to transmit information started to attract attentions from scientists, tracing back to the famous photophone experiment by Alexander Graham Bell in 1880 [1]. In his experiment, the voice signal was modulated onto the sunlight and the information was transmitted over a distance of about 200 m. Efforts to explore natural lights and artificial lights for communication continued for decades. In 1979, F. R. Gfeller and G. Bapst demonstrated the technical feasibility of indoor optical wireless communication using infrared light emitting diodes (LEDs) [2]. Built upon fluorescent lamps, VLC at low data rates was investigated in [3]. As LED illumination industry advanced, the fast switching characteristic of visible light LEDs prompted active researches on high-speed VLC. A concept was first proposed by Pang *et al.* in 1999 [4], using the traffic light LED as the optical signal transmitter. Later on, a series of fundamental studies were carried out by S. Haruyama and M. Nakagawa at Keio University in Japan. They investigated the possibility of providing concurrent illumination and communication using white LEDs for VLC systems [5, 6]. Meanwhile, they not only discussed and analyzed effects of light reflection and shadowing on the system performance, but also explored VLC applications at relatively low rates [7, 8]. Using LED traffic lights to transmit traffic information was experimented based on avalanche photodiode (APD) and two-dimensional image sensor receiver, respectively [9, 10]. VLC and power-line communication (PLC) were coherently integrated to provide a network capability [11], where the performance of an advanced orthogonal frequency division

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multiplexing (OFDM) modulation format was evaluated [12]. Applications were extended to brightness control [13] and high-accuracy positioning [14] in addition to communications.

As mobile broadband grows rapidly, the demand for high-speed data services also increases dramatically. VLC emerges as an alternative to alleviate radio spectrum crunch. Higher rate VLC has attracted global research attentions, in particular, from European researchers at the beginning, by maximally exploring the LED capabilities and increasing the spectral efficiency. Using a simple first-order analogue equalizer, a data rate of 100 Mbps was realized with on-off keying non-return-to-zero (OOK-NRZ) modulation in 2009 [15]. Meanwhile, 125 Mbps over 5 m using OOK and 200 Mbps over 0.7 m using OFDM were reported by Vucic *et al.* [16, 17], where photodiodes (PDs) were used in those VLC systems to detect optical signals. By adopting a 2×1 array of white LEDs and an imaging receiver consisting of a 3×3 photodetector array, a multiple-input multiple-output OFDM (MIMO-OFDM) system could deliver a total transmission rate of 220 Mbps over a range of 1 m [18]. The data rate can be further increased if APD is adopted. In 2010, the data rate of the OOK-based system reached 230 Mbps [19] and the data rate of the OFDM-based system approached 513 Mbps with bit- and power-loading [20]. In 2012, the highest data rate of a single LED-based VLC system achieved 1 Gbps with OFDM [21]. Additionally, carrierless amplitude and phase modulation (CAP) was introduced into VLC systems, and a data rate of 1.1 Gbps was achieved [22]. Using an MIMO structure, a 4×9 VLC system achieving 1.1 Gbps was presented, where the parallel streams were transmitted by 4 individual LEDs and detected by a 3×3 receiver array [23].

In the previous studies, a phosphor-converted LED (pc-LED) was adopted as optical signal transmitter. The bandwidth of a pc-LED is however limited by slow response of the phosphorescent component. In 2014, a post-equalization circuit consisting of two passive equalizers and one active equalizer was proposed to extend the bandwidth from tens of MHz to around 150 MHz [24]. If other types of LEDs having higher bandwidth are employed, it has potential to increase the throughput significantly. For example, using micro LEDs as transmitters in VLC systems could be firstly attributed to McKendry *et al.* and a data rate of 1 Gbps was reported at a price of low luminous efficiency [25]. Multicolor LEDs, radiating particularly red, green, and blue lights, can provide high-rate transmission by wavelength division multiplexing (WDM). Data were simultaneously conveyed in parallel by different colors such as red, green, and blue lights. In principle, the data rate could be tripled in the absence of color crosstalk. An OFDM-based VLC system using a multicolor LED was realized supporting a data rate of 803 Mbps over 0.12 m [26]. Using multicolor LED as the transmitter and APD as the receiver, the data rate of OFDM-based VLC systems was increased from 780 Mbps over 2.5 m to 3.4 Gbps over 0.3 m, where WDM and bit- and power-loading techniques were jointly applied [27–29]. In another study [30], the bandwidths of multicolor LED chips were extended to 125 MHz and modulated by 512 quadrature amplitude modulation (QAM) and 256WDM, respectively, and the frequency domain equalization based VLC system finally reached a data rate of 3.25 Gbps. The data rate of CAP-based VLC systems using multicolor LEDs was increased up to 3.22 Gbps, also benefiting from WDM technology [31].

It is well known that lighting LEDs typically serve as transmitters for downlink information transmission to mobile devices. In 2013, an asynchronous bidirectional VLC system was demonstrated in [32] where a 575 Mbps downlink transmission was realized by red and green LEDs, and a 225 Mbps uplink transmission by a single blue LED. From a network perspective, a spectrum reuse scheme based on different colors was proposed for different cells in an indoor optical femtocell, where multiple users can share the spectrum and access the network simultaneously [33]. User-centric cluster formation methods were proposed for interference-mitigation in [34]. A VLC system can also be combined with a wireless fidelity (WiFi) system to provide seamless coverage after a judicious handover scheme was designed and applied [35].

In multicolor LED-based VLC systems, signals from three color light sources were transmitted independently in most experiments, leaving room for capacity increase. In 2015, Manousiadis *et al.* used a polymer-based color converter to generate red, green, and blue lights emitted by blue micro LEDs [36]. Three color lights were modulated and mixed for white light illumination. The aggregate data rate from three colors was 2.3 Gbps. Techniques to explore spatial and temporal capabilities of devices were also investigated. A MIMO VLC system employing different field of view (FOV) detectors in order to improve signal-to-noise ratio (SNR) was analyzed in [37]. An optical diversity scheme was proposed, where the original data and its delayed versions were simultaneously transmitted over orthogonal frequencies [38]. Data rate can be significantly enhanced by employing different degrees of freedom. Combining with WDM, high-order CAP, and post-equalization techniques, Chi *et al.* showed that a multicolor LED based VLC system could provide a data rate of 8 Gbps [39]. A novel layered asymmetrically clipped optical OFDM scheme was proposed to make a tradeoff between complexity and performance of an intensity-modulated direct-detection (IM/DD) VLC system [40]. Under lighting constraints, DC-informative modulation and system optimization techniques were proposed [41–43]. Some receiver design issues were particularly addressed in weak illuminance environments and several bidirectional real-time VLC systems with low complexity were reported [44, 45].

Besides individual research groups, there are also many large scale organizations and research teams worldwide that have contributed to the development and standardization of VLC technology. In Europe, the HOME Gigabit Access (OMEGA) project was launched in 2008 to develop a novel indoor wireless access network, providing gigabit data rates for home users [46]. The project members included France Telecom, Siemens, University of Oxford, University of Cambridge, and many other companies and universities. This project finally demonstrated a real-time VLC system using 16 white LEDs on the ceiling to transfer HD video streams at 100 Mbps. Another organization called OPTICWISE was funded by the European Science Foundation under an action of the European Cooperation in Science and Technology (COST), which allowed coordination of nationally funded VLC researches across European countries. Significant research results and professional activities were reported from its various groups [47].

In Japan, Visible Light Communication Consortium (VLCC) consisting of many Hi-tech enterprises and manufacturers in the areas of illumination and communication, such as Casio, NEC, and Panasonic, was founded in 2003. It was devoted to marketing investigation, application promotion, and technology standardization. After years of development, it evolved to Visible Light Communications Association (VLCA) in 2014 to collaborate various industries closely for realizing the visible light communication infrastructure, from telecommunication to lighting, social infrastructure, Internet, computer, semiconductor, etc.

In the United States, the Ubiquitous Communication by Light Center (UC-Light), Center on Optical Wireless Applications (COWA), and Smart Lighting Engineering Research Center (ERC), are notable VLC research groups. UC-Light focuses on efficient lighting, communication, and navigation technologies by LEDs, and aims to create new technological innovations, economic activities, and energy-saving benefits. COWA is dedicated to the optical wireless applications of communications, networking, imaging, positioning, and remote sensing. ERC concentrates on LED communication systems and networks, supporting materials and lighting devices, and applications for detection of biological and biomedical hazards.

In China, two sizable teams were built in 2013 to focus on the research of optical wireless communications over broad spectra, including visible light communication. One was funded by National Key Basic Research Program of China (973 Program), including about 30 researchers from top universities and research institutes. The other was funded by National High Technology Research and Development Program of China (863 Program). Both project teams have made tremendous efforts on theory breakthrough, technology development, and real-time VLC system demonstrations. The real-time data rate has reached 1.145 Gbps at 2.5 m to deliver multimedia services, and the highest off-line data rate of 50 Gbps was achieved at a shorter distance. To jointly prompt commercialization of VLC technologies, Chinese Visible Light Communications Alliance (CVLCA) was founded in 2014, which attracted universities and industries in lighting, telecommunication, energy, consumer electronics, and financing agencies.

1.2
Advantages and applications

Visible light communication has many attractive advantages compared to its radio frequency (RF) counterpart, which include but are not limited to the following aspects.

(1) Wide spectrum: As the demand for high-speed wireless services is increasing dramatically, RF spectrum is getting congested. The radio wave spectrum is limited, from 3 kHz to 300 GHz, while the visible light spectrum is at least 1000 times greater, which is from 400 THz to 780 THz [48].

(2) No electromagnetic interference: Since light does not cause any electromagnetic interference, VLC is suitable for communications in the electromagnetic interference immunity (EMI) environments, such as hospitals, nuclear power plants, and airplanes.