Visible Light Communications

Modulation and Signal Processing

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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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1
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 powerline 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.

(3) Easy implementation: VLC modules can be made small and compact, so that they can be easily implemented into the existing lighting infrastructure. The modulation unit, digital-to-analog converter, and driving circuit can be integrated into LEDs. The photodiode, analog-to-digital converter, and other signal processing units can be manufactured as a portable external receiver, or embedded into the lighting infrastructure.

(4) Low cost: The implementation of a VLC system is relatively simple. Instead of designing an entire wireless communication system, it reuses the ubiquitous lighting infrastructure, and only a few additional modules are added to the lighting system. As LED industry is rapidly developing, the cost of massively producing VLC transceivers is expected to decrease.

(5) High energy efficiency: As green lighting devices, LEDs have been recognized as the next generation lighting devices, which can reduce the energy consumption of traditional lighting sources by 80% [49]. If all the lighting sources are replaced by LEDs, the global electricity consumption is expected to reduce by as much as 50% [50]. According to a recent report from the U.S. Department of Energy, by the year of 2025, it is possible to save the amount of energy up to 217 terawatt-hours (TWh) with the adoption of LED lighting technology [51].

(6) Health safety: Unlike infrared LED and laser having concentrated optical power within a narrow beam, lighting LED is a diffusive light source. Therefore, it is intrinsically safe for many application scenarios with large emitted optical power. Since lighting LED does not generate radiation as radio frequency or microwave devices do, no obvious health hazard is incurred to the environment and end users.

(7) Information security: Security is an important issue to RF communication because radio waves can penetrate walls, causing information leakage. Since light cannot penetrate opaque objects, VLC can be confined in an indoor, enclosed space and more secure communication links are ensured.

The aforementioned features help to yield various indoor and outdoor VLC applications. The most desirable application, perhaps, is indoor high-speed Internet access for smart phones and computers. People usually spend much more time staying indoors than outdoors, in offices and homes for study, work, entertainment, etc. It would be convenient to access the Internet by simply using LED lighting devices on the ceiling. The inherent modulation bandwidth of LEDs (orders of MHz to hundreds of MHz) is able to provide much higher data rate than WiFi and existing mobile networks. Equipped with advanced techniques, such as multicarrier modulation, wavelength multiplexing, and equalization, the VLC data rate can be increased up to gigabit per second.

Besides offices and homes, electromagnetic sensitive environments also require safe and reliable wireless services. Visible light does not cause any electromagnetic interference to the existing electrical equipment, and is thus ideal for communication in those environments. In a hospital, for example, some sophisticated and expensive medical equipment, such as magnetic resonance imaging equipment, must be insulated from electromagnetic interference. The electronic devices radiating the electromagnetic waves are prohibited in an airplane cabin during takeoff and landing because those waves might cause equipment malfunction. In a nuclear plant, it is also very restrictive to use a mobile phone. It is evident that VLC becomes a safe technology for communications in such EMI environments.

In some cases, users would like to directly communicate to each other at high speed, without routing messages through a network, such as machine-to-machine (M2M) and device-to-device (D2D) communications. Two VLC transceivers such as smart phones or laptops can realize point-to-point communication directly. Light communication becomes a feasible solution as well.

It is well known that LED is a natural transmitter and can easily broadcast information, which can be embedded in LED displays and screens in different public areas, such as waiting hall at the airports and train stations, and sent to passengers. If an image sensor in a camera is used as signal detector, optical camera communication (OCC) could receive the broadcasting information [52]. Also, in shopping malls and outlets, merchandise and advertisement information can be broadcasted to customers through lighting LEDs or signage. Exhibitions, galleries, and museums are also ideal places to use LEDs for seamless information broadcasting.

Besides that, people could take the advantage of densely distributed LEDs for location references and use triangularization algorithms to forecast device positions. As a result, highly accurate indoor positioning and navigation come true by LEDs, like GPS in outdoors by satellites. LEDs could also send control signals to an intelligent robot and guide its precise movement along a route to reach its predefined destination [53].

Since there are a large number of LEDs deployed/used outdoors as well, street lights, traffic lights, and vehicle lights are also applicable for establishing VLC wireless links among vehicles, vehicle and roadside lighting infrastructure, vehicle and traffic lights [9, 10, 54]. Since the vehicle is usually equipped with an image sensor array, it can predict its relative motion together with data transmission [55–57]. Underwater VLC is also a competitive communication technology for ocean exploration.

The aforementioned indoor and outdoor applications span a variety of fields, which could gradually penetrate different markets for various services, from low rate communication and positioning, to high-rate communication, and intelligent transportation. As words “visible light” indicate, VLC will have a bright future in our modern life.

1.3 Overview of modulation and signal processing

For VLC systems, LEDs and photodiodes are used as alternative transceivers to convey information via visible light. Accordingly, modulation and signal processing for

VLC systems possess new features and new challenges, compared to their RF counterparts. Normally, LED works under a forward bias while photodiode is driven by a reverse voltage. Since LED is used for lighting and communication simultaneously, its chromaticity and nonlinearity have to be investigated in VLC systems. As for the photodiode, key parameters such as absorption coefficient, quantum efficiency, and responsivity are considered in the system model. Based on whether there exists a line-of-sight (LOS) link between the transmitter and the receiver, optical wireless propagation links can be classified into two categories: LOS link and non-line-of-sight (NLOS) link. Besides, noise from other devices and surrounding environment should be considered. Based on the dominant noise in practical scenarios, three common optical wireless channel models are discussed, i.e., free-space optical intensity channel, discrete-time Poisson channel, and improved free-space intensity channel. Since there are no analytic expressions of channel capacity, several upper and lower bounds have been illustrated. Considering these specific channel models of VLC systems, several modulation and signal processing schemes have been demonstrated.

Single carrier modulation and carrierless modulation schemes are addressed firstly. Pulse amplitude modulation (PAM) is a simple modulation format widely used in VLC systems. When multipath channel is considered, PAM together with frequency-domain equalization is utilized to combat inter-symbol interference (ISI). Besides, several implementation schemes are introduced in order to overcome the effect of LED nonlinearity, i.e., PAM can be implemented with multiple LEDs, where each LED is modulated by OOK. Pulse position modulation (PPM) is another simple modulation format for VLC systems and PPM together with decision feedback equalization could eliminate the ISI. Since PPM has low data rate with only one pulse in a single symbol duration, several modified schemes have been proposed including differential PPM, multipulse PPM, overlapping PPM, and variable PPM. Besides, CAP is also adopted in VLC systems due to its high spectral efficiency and simple implementation, which can also be extended to multi-dimensional CAP. Meanwhile, various modified modulation and coding schemes have been proposed for dimming control in single carrier VLC systems, which could support communication and illumination simultaneously.

Optical OFDM techniques have been investigated in order to realize broadband and high-rate transmission. Since IM/DD methodology is used in VLC systems, the amplitude of optical OFDM signals is constrained to be real-valued and non-negative. Therefore, the conventional OFDM method is not feasible for intensity modulation and several optical OFDM schemes have been proposed to satisfy the specific signal constraints in VLC systems, such as DC-biased optical OFDM (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM), pulse-amplitude-modulated discrete multitone (PAM-DMT), and unipolar OFDM (U-OFDM). Similar to conventional RF systems, optical OFDM suffers from high peak-to-average power ratio (PAPR), which might introduce severe nonlinear distortion and impair the performance of VLC systems. There are several techniques to enhance the performance of optical OFDM by optimizing DC bias and scaling factor, mitigating the nonlinear effect of LED, and PAPR reduction. Besides, some recently proposed power- and spectral-efficient optical OFDM methodologies, such as hybrid optical OFDM, enhanced U-

OFDM, and layered ACO-OFDM have shown great potential for future VLC systems. In addition, seamless integrations of OFDM modulation and dimming control are discussed, including pulse width modulation, reverse polarity optical OFDM and asymmetrical hybrid optical OFDM, which have shown that dimmable OFDM can support a wide dimming range with a relatively small throughput fluctuation.

Multicolor modulation is an interesting candidate for VLC systems, compared to the traditional RF modulation methods. White LEDs are usually classified into single-chip LEDs and RGB-type LEDs. The single-chip LEDs use a single blue LED that excites a yellow phosphor to create an overall white emission, while the RGB-type LEDs combine light from LEDs of three primary colors of red, green, and blue. They are preferable to single-chip LEDs since the transmission rate can be improved owing to their faster response time. Moreover, three wavelengths corresponding to the three primary colors can be used to carry multiple data streams independently and thus offer the possibility of WDM. Accordingly, multicolor modulation schemes under illumination requirements for VLC systems with RGB-type LEDs have been illustrated, whereby color shift keying (CSK) is developed and adopted in the IEEE 802.15.7 standard. Furthermore, the optimal design rules of CSK constellation as well as Qual-LED CSK are provided to achieve superior capacity, while CSK with coded modulation is introduced for practical scenarios. Moreover, WDM system combined with channel coding is detailed, and a receiver-side predistortion is proposed before channel decoding, which has shown significant performance gain.

Despite the fact that the spectrum of visible light is as wide as several THz, the bandwidth of off-the-shelf LED is limited, which makes it very challenging to achieve high-rate transmission. Meanwhile, in order to provide sufficient illumination, multiple LED units are usually installed in a single room. In such scenarios, MIMO techniques can be naturally employed in indoor VLC schemes to boost the data rate. Typically, there are two optical MIMO approaches for VLC systems, namely non-imaging MIMO and imaging MIMO. For non-imaging MIMO systems, each receiver collects the surrounding light with its own optical concentrator, and optical MIMO, optical spatial modulation, and optical space shift keying can be used. For imaging MIMO systems, an imaging diversity receiver is utilized to distinguish the light from different transmitters. Meanwhile, in order to support data transmission for multiple users simultaneously, precoding techniques are employed to eliminate the inter-user interference under the lighting constraints in VLC systems. Moreover, MIMO-OFDM is introduced for single-user and multiuser VLC systems, which provides high spectral efficiency and robust reception.

Due to the special characteristics of transceivers and channels for VLC systems, several signal processing and optimization issues for VLCs have been discussed. For multi-chip-based multiple-input single-output VLC system, an electrical and optical power allocation scheme is introduced to maximize the multi-user sum-rate in consideration of the luminance, chromaticity, amplitude, and bit error rate constraints. Considering the vulnerability of VLC LOS links, heterogeneous VLC-WiFi systems offer a solution for future indoor communications that combines VLC to support high-data-rate transmission and RF to support reliable connectivity. In such heterogeneous systems, vertical handover is critical to improve the system performance and a dynamic approach is adopted to obtain a tradeoff between the switching cost and the delay requirement, where the vertical handover is formulated as a Markov decision process problem.

For VLC systems with narrow FOV, the PD shot noise modeled by Poisson statistics is signal-dependent since it originates from the quantum nature of the received optical energy rather than external noises, which is in contradiction to the conventional signal-independent additive white Gaussian noise model. Therefore, novel signal processing and estimation techniques are illustrated to guarantee the transmission performance. OCC is a new form of visible light communication, which employs pervasive image sensors assembled in consumer electronic devices as the receiver. The advantages of OCC include the wide spectrum compared to the conventional VLC systems, the pervasive optical light sources including illumination LED, display and traffic light, and the pervasive consumer cameras having natural multicolor sensitivity, the feasibility of massive MIMO and anti-interference image-sensor-based receivers. With these advantages, OCC combined with mobile computing could realize novel forms of sensing and communication applications, such as indoor location, intelligent transportation system, screen-camera communication, and privacy protection. However, there exist also challenging issues to be addressed, including the limited frame rate, synchronization issue, non-negligible shot noise, perspective distortion, pixel misalignment, and blur effect.

To investigate the channel characteristics and system performances of OCC systems, the pixel-sensor structure and its operation procedure for CMOS image sensors have been addressed and the noise composition, including photo shot noise, dark current shot noise, fixed-pattern noise, source follower noise, sense node reset noise, and quantization noise at high illumination, is illustrated and analyzed. A plurality of experimental results demonstrate that the noise in a CMOS image-sensor-based receiver can be modeled as Gaussian noise, such as signal-independent electrical thermal noise as well as the signal-dependent and signal-independent shot noise. Based on these noise models, the SNR in OCC systems should be redefined, and accordingly, a unified communication model is proposed for OCC systems. Moreover, channel capacity of OCC systems has been investigated and the asymptotic upper bound and the tight lower bound with peak and average power constraints have been addressed. The capacity bounds indicate that a spectral efficiency of 8–11 bit/s/Hz is achievable under an ideal channel with diversity structure, and there is room for improvement using the today's OCC prototypes.

According to specific OCC channel characteristics, the modulation schemes, synchronization issues and several technical challenges in a real-time OCC system have been addressed. Based on the signal-dependent noise model, a capacity-achieving discrete nonuniform signaling scheme has been designed for OCC systems. However, it requires the feedback link, which possesses high complexity. Alternative modulation schemes which convey signal on different domains are adopted in OCC systems, including the under-sample-based modulation schemes in time/frequency domains, the rolling-shutter-effect-based modulation schemes in time/frequency domains, color-intensity modulation (CIM) in color space, and the spatial OFDM/WDM in spatial/frequency domains. Moreover, the effect of nonideal factors, such as linear misalignment, geometry distortion, blur effect and vignetting, and the corresponding mitigating schemes, are discussed, including equalization, perspective correction, adaptive coding, and modulation. For a practical OCC wireless link, synchronization is important and several methodologies have been discussed. The per-line tracking, inter-frame coding, and rateless coding could tackle the synchronization issues by decoding imperfect frames and recovering any lost frames.

Furthermore, a real-time CIM-MIMO OCC prototype has been realized, which utilizes spatial, color, and intensity dimensions to generate a high-dimensional signal constellation and parallel wireless links, leading to an increased data rate and improved bit error rate performance. Several technical challenges including unstable frame rate, joint nonlinearity and crosstalk, flicker noise, and rolling shutter, have been tackled.

For a real-time OCC system, commercial CMOS cameras are used as receivers. The corresponding products can be used in near-field screen-camera communications and indoor visible light positioning. If the sensor is equipped with an external optical lens, the transmission distance between the light source and the sensor can be significantly extended, which makes the system suitable for other applications, for example, capturing signals from a distant traffic light, or information broadcasting displays in a public area such as shopping mall and transportation hub.

1.4 Standards

With rapid evolution of VLC technologies, it is imperative to develop the corresponding standards to harmonize the physical layer (PHY) protocols and media access control (MAC) layer protocols, and help to transfer technologies into applications promptly, which has attracted much attention from various international and national standardization bodies.

The first international VLC standard, that is IEEE 802.15.7, was published by IEEE 802.15.7 working group for wireless personal area networks in 2011 [58]. The standard clearly specifies the PHY and MAC layers for short-range optical wireless communications using visible light for indoor and outdoor applications. IEEE 802.15.7 accommodates three different PHY layer types, i.e., PHY I, PHY II, and PHY III, respectively. PHY I supports lower rate (11.6–266.6 kb/s) and long-distance outdoor applications, PHY II supports higher rate (1.25–96 Mb/s) systems working in indoor infrastructures and point-to-point applications, and PHY III is designed to support the same rate (1.25–96 Mb/s) with multicolor light sources/detections. PHY I and PHY II adopt OOK and VPPM, which is a combination of two-pulse position modulation and pulse width modulation (PWM). A color shift keying modulation format, generated by using three-color light sources out of the seven-color bands, is also defined. Different forward error correction (FEC) schemes and run length limited (RLL) codes are added to meet various channel conditions and to guarantee the lighting brightness. In the MAC layer, IEEE 802.15.7 supports three different topologies, namely star, peer-to-peer, and broadcast. The MAC layer is also responsible for the following major tasks: initiating/maintaining procedures, association/disassociation procedures, color-function support mechanism, illumination and dimming support mechanism, mobility support mechanism, color stabilization, etc.

In 2014, a new working group 802.15.7r1 was formed to make revisions on the previous standard. The new standard, called as IEEE 802.15.7r1, is expected to be published in 2017 [59]. IEEE 802.15.7r1 will specify the following three different application scenarios depending on various data rates and devices. First, LED-ID is low-rate photodiode-based communication sending identification information through various LEDs. Second, OCC is an image-sensor-based communication which offers positioning/localization, message broadcasting, etc. Accordingly, three different source types have been defined, i.e., discrete source (15 bps–4 kbps), surface source (90 bps–8 kbps) and two-dimensional screen source (40 bps–64 kbps). At current stage, the modulation formats are still under on-going discussions. As a related application, a new interest group, called as IEEE 802.15 Vehicular Assistant Technology (VAT), was formed in January 2017 for OCC-based long range vehicular applications. Smart automotive lighting in vehicle safety systems has been also investigated in [60]. Third, light fidelity (LiFi) is high-rate photodiode-based communication that can support Gbps data stream, bidirectional and multiple access, mobility, and handover. The technical specifications focusing on modulation, coding, bandwidth, and optical clock rate have been intensively discussed. Although IEEE 802.15.7r1 has not been finalized, the endorsed reference channel models were presented in [61], where four different reference scenarios, including work place, office room with secondary light, living room, and manufacturing cell, are emulated by a powerful software Zemax to describe the channel impulse responses.

Besides IEEE 802.15.7 and IEEE 802.15.7r1, International Telecommunication Union (ITU), established a study group (named as SG15) to standardize the VLC technology within the G.vlc framework in September 2015. Research community together with key industrial members, such as Huawei and Marvell, are constructively and jointly developing a high-speed VLC standard. So far, G.vlc has been specifying VLC modulation format, dimming control, channel and source models, band plans, and network topology. Recently, SG15 decided to start a new G.occ framework (Gbps OCC) in order to cover various aspects of optical wireless applications.

In addition to international efforts, there are also national organizations focusing on VLC standardization. In Japan, VLCC was established in November 2003, whose members were major electronic companies and research centers. VLCC tried to merge VLC technology into LED lightings in offices and homes, commercial displays, traffic signals, and small lamps on home appliances. The Visible Light ID System was standardized by Japan Electronics and Information Technology Industries Association (JEITA), for commercial applications including indoor navigation and POS/client data exchange. In 2014, VLCA was established as the successor to VLCC, to facilitate various industrial collaborations and further develop the application and business of VLC technology.

Globally, China becomes the largest LED manufacturer and consumer market, and owns the most complete LED industry chain. Its VLC technology has bloomed in the recent decade, where lighting, wireless communication and automobile industries are all actively participating in the technology development and standardization of VLC systems. In March 2017, Smart Visible Light Industrial Technology Innovation Association was established in Guangdong Province, China, with over 20 industry members, including ZTE, Philips Lighting, and Audi. Its main goal is to publicize, popularize, and standardize the VLC technology in various industrial and commercial sectors. The Chinese VLC standard is being drafted by China Electronics Standardization Institute (CESI), and its first version will be released soon.

The above on-going standardization activities will prompt successful and rapid applications of various VLC technologies, which span from positioning, accurate control, low rate communication, to information broadcasting, and high-speed indoor and outdoor communications, for mobile devices, robotics, vehicles, and even new forms of terminals and applications such as drones, unmanned underwater vehicles, and virtual/augmented reality [62].

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2
Visible Light Communications: Channel and Capacity

In this chapter, the channel and capacity of visible light communication (VLC) are introduced. Specifically, the characteristics of light emitting diode (LED) as the transmitter and photodiode as the receiver are described in Section 2.1. When LED is employed for lighting and communication simultaneously, its nonlinearity and lighting constraints are investigated in Section 2.2. Besides, absorption coefficient, quantum efficiency, and responsivity of the photodiode are demonstrated in Section 2.3. Furthermore, different propagation links between the transmitter and the receiver are analyzed in Section 2.4. Since the dominant noise might be different in various application scenarios, three optical wireless channels are addressed including free-space optical intensity channel, discrete-time Poisson channel, and improved free-space intensity channel in Sections 2.5 and 2.6. Considering there exist no analytic expressions of the channel capacity, the state-of-the-art upper and lower bounds are presented in Section 2.6 as well.

2.1
LED characteristics

One of the first red LEDs was developed in 1962 based on GaAsP [1]. Compared to conventional lighting sources such as fluorescent and incandescent lights, LEDs have many advantages including energy efficiency, light density, lifetime, and reliability. Benefiting from the refinement of III-V alloy and the development of the epitaxy methods, LEDs have gained significant performance improvement over the last fifty years. The efficiency of commercial LEDs has been dramatically increased from 0.1 lm/W to a level that is above 100 lm/W. Currently, LEDs can emit the light covering all visible spectrum from short wavelength (i.e., violet) to long wavelength (i.e., red). As a result, LEDs have been widely applied in our daily lives, such as general lighting, traffic lights, and flat panel display. The market share of LEDs in global commercial lighting is continuously growing and the revenue from commercial LEDs sales would exceed 20 billion US dollars in the coming years. Although the price of LEDs is relatively higher than conventional light sources at present, it is foreseeable that the commercialization of LED associated with the advancement of

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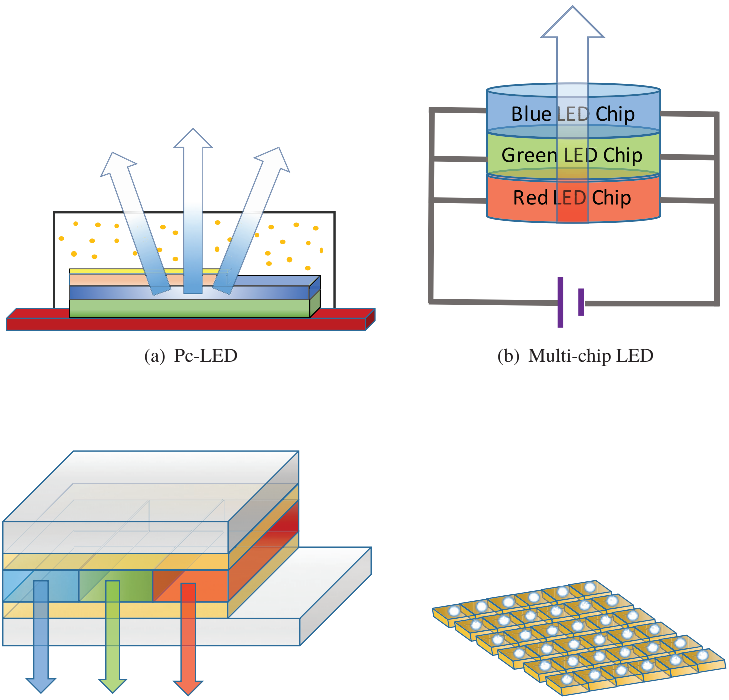
the fabrication technique would further reduce their costs.



(a) Pc-LED (b) Multi-chip LED

(c) OLED (d) μLED

Figure 2.1 Different LED types.

Until now, there are various types of LEDs such as phosphor-converted LED (pc-LED), multi-chip LED, organic LED (OLED), and micro LED (μLED), which are shown in Fig. 2.1. Pc-LED and multi-chip LED are two common types of white LEDs for lighting, which use two or more different wavelength lights to generate the white light. In pc-LED packages, one or more visible light-emitting phosphors are coated on an LED chip emitting short-wavelength light. The pc-LEDs employ some of the short-wavelength light to pump the phosphors and produce long-wavelength light while the rest of the short-wavelength light is leaked out. By mixing these different wavelength lights together, the white light could be generated. Typical commercial pc-LEDs utilize the cerium doped yttrium aluminum garnet (Ce:YAG) phosphor to produce the yellow light and mix it with the blue light emitted by the gallium nitride based LED chip [2]. Due to the development of modern manufacturing technology, the luminous efficacy of pc-LED has been improved to above 150 lm/W [3]. However, the intrinsic modulation bandwidth of pc-LED is limited to several MHz due to the slow relaxation time of the phosphor [4]. On the other hand, multi-chip LEDs ex-