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Editorial

Advances in Visible Light Communication

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1. Introduction

Visible light communications (VLC) have been a highly popular area of research in recent years [1]. With the ongoing advancement of various crucial technologies, the research community anticipates that VLC will play a significant role in future wireless communication systems [2]. The rapid recognition of VLC can be attributed to the development of various important technologies. First, thanks to the invention of semiconductor-based light sources, either light-emitting diodes (LEDs) or lasers, high-transmission bandwidths can be achieved to support Gbps data rates [3,4]. The use of state-of-the-art photodetectors and advanced optics at the receiver also contribute significantly to the development of VLC systems [5]. Furthermore, smart signal processing algorithms and multiplexing techniques have been widely investigated to boost the data rate and/or improve the reliability of transmission [6,7]. In recent research, we also see a trend of using data-driven machine learning techniques in different VLC scenarios, showing very promising performances [8].

Regarding their applications, VLC and optical wireless communications (OWC) show great potential in many distinct application scenarios, such as in the following: indoor optical wireless, which has the potential to greatly enhance existing WiFi infrastructures [1]; underwater OWC, which facilitates otherwise impossible high-speed data transmission in aquatic environments [9]; vehicle-to-vehicle (V2V) communication, which enables wireless communication between vehicles with minimal interference [10]; and indoor visible light positioning (VLP), which can be utilized to build highly accurate localization or positioning systems in indoor environments where global positioning system (GPS) signals may be unreliable [11].

Despite these many application scenarios for VLC techniques, there remains a noticeable gap between the highly encouraging results achieved in lab-based environments and their practical application in real-world settings. In this Special Issue, we aimed to gather papers that exhibit high academic quality and/or have a strong connection to real-world applications.

2. An Overview of Published Articles

In this Special Issue, we have published 21 papers covering the aforementioned important topics. These papers are listed in the 'List of Contributions' attached at the end of this editorial. Among these 21 papers, 14 are research articles and 7 are review papers. Notably, authors from various countries and well-known universities have contributed. Among these papers, some provide very detailed theoretical analysis and simulation results, while many others present high-quality experimental findings. In comparison to many other Special Issues in *Photonics*, a noteworthy aspect of this Special Issue is that we have invited and published many high-quality reviews, offering valuable insights into recent advancements in VLC or OWC. In the following, we briefly introduce these papers based on their specific focuses and topics, as well as their article types. The classified categories are signal modulation, photon counting detection, visible light positioning, transmission systems, and review articles.

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Signal modulation: In recent years, non-orthogonal multiple access (NOMA) has become a popular modulation technique in VLC for supporting multiple users [12]. In Alqahtani et al.'s article (contribution 1), NOMA is studied for the VLC downlink. In particular, the authors calculate the symbol error rate (SER) considering the influence of multi-user interference, which is the primary interference issue in NOMA. Subsequently, a decoding-order-based power allocation (DOPA) method is proposed to determine the optimal power allocation that minimizes the SER. In Li et al.'s article (contribution 2), a hybrid form of optical orthogonal frequency-division multiplexing (OFDM) is introduced and integrated with NOMA. This work makes a contribution by introducing a signal modulation scheme which is shown to effectively mitigate the error propagation effect commonly encountered in both hybrid OFDM and NOMA systems. Multiple-input and multiple-output (MIMO) is another important signal transmission technique for boosting the transmission data rate [13]. In Zhong et al.'s article (contribution 3), a deep-learning-based MIMO system named DeepGOMIMO is proposed. In this technique, the transmitted information bits are mapped onto both the index of the active LEDs and the signals directly transmitted by these active LEDs. Moreover, a deep neural network (DNN) is incorporated into the system for signal detection so that the channel state information (CSI) is not required at the receiver. In Wu et al.'s article (contribution 4), a liquid crystal (LC)-based optical receiver is analyzed for a multiple-input single-output (MISO) transmission system via simulations. The main contribution of this work is the formation of an optimization task to obtain the refractive index of LC which can maximize the MISO capacity. In Saied et al.'s article (contribution 5), a modified form of OFDM modulation, named discrete Fourier transform spread-optical pulse amplitude modulation (DFTS-OPAM), is proposed and its application is discussed for a visible light network for connecting vehicles.

Photon counting detection: The performance of a VLC transmission link highly depends on the sensitivity of the photodetector. The most sensitive possible photodetector is one that can accurately count the number of photons arriving at the sensor within a short period of time. These types of sensors are commonly known as photon-counting detectors, which are now widely considered for detecting light signals in environments with low light intensity levels, such as underwater OWC and eye-safe laser-based systems. Recently, one specific type of photon counting sensor, known as silicon photomultipliers (SiPM), consisting of a large array of single-photon avalanche diodes (SPADs), has shown a very promising performance [14]. In Matthews and Collins's article (contribution 6), both experiments and Monte Carlo simulations are used to study the non-linearity of a SiPM sensor. This allows for the determination of the maximum photon counting rate of a SiPM and also an evaluation of the impact of its non-linearity on transmission performance. In Zhang et al.'s article (contribution 7), the performance of a SiPM is analyzed by considering OFDM modulation. Moreover, the SiPM's bandwidth is studied via an equivalent circuit model of the SiPM. It provides very useful information for guiding the use of SiPMs with OFDM modulation. In Yang et al.'s article (contribution 8), a neural-network-based synchronous clock recovery method is proposed for an underwater OWC system when SPADs are used. The effectiveness of this method is validated through experimental measurements.

Visible light positioning: VLP is another important research topic that employs LEDs as positioning beacons for object positioning or localization, particularly in indoor environments where signals may be unreliable [11,15]. In Yang et al.'s article (contribution 9), a camera-based VLP system was examined, utilizing a single square LED luminaire. The use of the square LED enables the extraction of the receiver's rotation angle, consequently correcting the geomagnetic angle acquired from a geomagnetic sensor, and thereby enhancing the positioning accuracy. In recent studies, there has been a notable trend towards utilizing machine learning (ML) techniques in VLP for improving positioning accuracy. For instance, both Yang et al.'s article (contribution 10) and Deng et al.'s article (contribution 11) investigate ML-based three-dimensional VLP systems, incorporating multiple LED lights and multiple photodetectors. Moreover, both studies account for the influence of both line-of-sight (LOS) an·d non-line-of-sight (NLOS) links on the received signals. Yang et al.'s article (contribution 10) employs gated recurrent unit (GRU) neural networks, whereas Deng et al.'s article (contribution 11) uses convolutional neural networks (CNN). Notably, both approaches demonstrate positioning accuracy at the centimeter level. While many studies on VLP primarily concentrated on analyzing the positioning accuracy performance, they often neglected to consider the illumination aspects of these integrated systems. In Menéndez and Steendam's article (contribution 12), a noteworthy contribution was made by also examining the illumination aspects, based on the main illumination characteristics defined in the European Standard EN 12464-1. This research provides invaluable insights for the development of a combined illumination and positioning system that complies with established illumination standards.

Transmission systems: In Yang et al.'s article (contribution 13), a very interesting laser-based OWC system is constructed. On the transmitter side, an all-fiber configuration is considered by connecting the single-mode fiber (SMF) directly from the fiber access network to a multi-mode fiber (MMF). The MMF then emits the light into the free space. At the receiver, light first passes through a collimator, and is subsequently coupled into another MMF, which is linked to a photodiode. To mitigate fiber coupling losses at the receiver, the collimator's focus is adjusted. Additionally, to maximize the received optical power, controlled perturbations are applied to the MMF at the transmitter side for beam shaping. In Li et al.'s article (contribution 14), the performance of a real-time display-camera communication (DCC) system is studied. Compared to the previous approaches, the transmission distance of this work is increased by clustering multiple adjacent LED display points for information transmission.

Review articles: This Special Issue also includes seven high-quality review articles. In Shi et al.'s article (contribution 15), a comprehensive review is presented on the application of various artificial intelligence (AI) techniques in VLC systems, addressing diverse transmission challenges, particularly those resulting from nonlinearity issues in electronic devices. Both Geng et al.'s article (contribution 16) and Loureiro et al.'s article (contribution 17) focus on reviewing popular VLC techniques, specifically different modulation methods and application scenarios. In Liu et al.'s article (contribution 18), recent significant advancements in optical injection locking for visible light communication applications are summarized. In He and Chen's article (contribution 19), a thorough review is provided on summarizing the different transmitter and receiver technologies used in LED-based VLC systems. Fang et al.'s article (contribution 20) surveys various high-speed underwater OWC systems, highlighting how ML techniques can enhance signal processing for improved transmission efficiency. Lastly, in Huang and Yamazato's article (contribution 21), a comprehensive survey is presented on imaging sensor-based VLC systems. It particularly emphasizes techniques based on rolling shutter cameras and global shutter high-speed cameras.

3. Conclusions

VLC or OWC will certainly play a pivotal role in future networks. Nevertheless, there remain many technical and regulatory challenges to overcome. We hope this Special Issue will be a valuable contribution to the growing VLC research community, driving the use of VLC techniques in practical real-life applications.

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List of Contributions

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