Enabling Technologies and New Challenges in IEEE 802.15.7 Optical Camera Communications Standard

Huy Nguyen, Ida Bagus Krishna Yoga Utama, and Yeong Min Jang

The authors present a tutorial on recent optical camera communication technologies that deploy light-emitting diodes and image sensors.

Abstract

In this article, we present a tutorial on recent optical camera communication (OCC) technologies that deploy light-emitting diodes (LEDs) and image sensors. The article contains a discussion on the amendment of the IEEE 802.15.7-2018 standard, termed the IEEE 802.15.7a (TG7a) Higher Rate, Longer Range OCC Task Group, which has a significant influence on the advancement of OCC technology. In addition, the tutorial article presents the enabling technical issues in TG7a and a comparison with the existing standard. The current status, new challenges, and future directions of research and development are also discussed.

Introduction

Communication systems based on radio frequencies (RFs) have experienced substantial growth over the last decade. Qualcomm, the telecommunication company, predicts that upcoming wireless communication technologies will need to increase their capacity by a factor of a thousand [1]. However, conventional RF systems may not be able to adequately match the expected network traffic growth in the future. Hence, there is a need to explore innovative solutions that can operate within spectra that require no license (e.g., light waves). Light waves are situated at the higher end of the electromagnetic spectrum, do not contain any electromagnetic radiation, and have a bandwidth that extends considerably beyond the entire RF spectrum. Moreover, light waveforms support remarkable line of sight (LoS) separation features and can provide economical augmented-reality user experiences. Because of the increasing demands placed on wireless communication systems (such as speed, reliability, and security), the developers of wireless communication technologies are focusing on light wave communication due to the benefits of light waveforms. Accordingly, optical wireless communication (OWC) is expected to become a crucial wireless technology in the near future.

In 1880, visible light communication (VLC) systems were proposed by Alexander Graham Bell in Washington, D.C., where speech was transmitted with sunlight over hundreds of meters [2]. However, the first demonstration of a VLC system was conducted in Japan (2004) with a high-speed communication system that used photodiodes. The Visible Light Communication Consortium (VLCC) proposed the first standardizations for VLC systems in 2008. This field of research has received increasing attention since the IEEE Standards Association released the IEEE 802.15.7-2011 standard (related to VLC) in 2011 [3]. In addition, the Short-Range Optical Wireless Communications Standard (IEEE 802.15.7-2018) was proposed in 2014 and published in 2019 [4].

The VLC technology standards were published by the IEEE Standard Association, which includes three Physical Layer (PHY) modes for VLC technology [3]. Moreover, the Short Range Optical Wireless Communications Standard [4] was proposed to amend IEEE 802.15.7-2011 by including three PHY modes related to optical camera communication technology. In this revised version, several OCC technologies were proposed for short-range communication, including high framerate processing, region of interest (RoI) signaling, rolling shutter, and screen or projector-based techniques. Nevertheless, despite the advances in OCC technologies, their commercialization has been slow due to the lack of a suitable app for OCC. Instead of using photodiodes to receive data from light sources in Light Fidelity (LiFi), OCC use image sensors as receivers. Thanks to advancements in image processing, which includes computer vision and deep learning, as well as signal processing techniques, the deployment of OCC systems offers several advantages over LiFi/VLC. These advantages encompass extended communication ranges, easy application with Multiple Input Multiple Output technology, and support for mobility in outdoor applications, such as vehicular communication and drone networks. Given the extensive market potential and viability of OWC technology, many companies and research institutes are actively pursuing its commercialization. For example, Panasonic (Japan) has developed and released the LinkRay app, which delivers OCC information by reading IDs from an LED transmitter and includes displays, signboards, or spotlights. In addition, Casio has released the Picalio app, which is an indoor positing system that uses Casio's unique camera. Here, an LED represents the OCC signals based on color-change patterns, and the ID and position information are collected via the camera. Panasonic and Casio also proposed these contributions in [4]. To amend the IEEE 802.15.7-2018 standard,

ISSN: 0163-6804
Digital Object Identifier: 10.1109/MCOM.002.2300289

The authors are with Kookmin University, South Korea.

researchers from industry and academia in multiple countries (including Korea, Japan, and the United States) collaborated to improve both the data speed and communication range of OCC technology. Collectively, this body is referred to as the IEEE 802.15.7a Task Group (TG7a). By applying certain technologies, such as Orthogonal Frequency Division Multiplexing (OFDM), Multiple-input multiple-output (MIMO), Non-orthogonal multiple access (NOMA), hybrid modulation, and deep learning algorithms, TG7a will likely be able to increase the data rate and communication distance of OCC systems compared to the existing IEEE 802.15.7-2018 standard.

IEEE 802.15.7A TG Scope, Purpose, and Milestones

Scope

The TG7a optical range includes the following wavelengths: infrared (7001000 nm), visible light (400700 nm), and ultraviolet (100400 nm). The technical consideration document (TCD) of TG7a [5] serves as the basis for the standard and has two functions: It provides a summary of OCC applications, and It depicts their fundamental requirements. The final version of the TCD was issued on the May 12, 2021. It provides a summary of the applications of OCC, which encompass indoor localization, vehicle-to-vehicle (V2V) communication, vehicle-to-infrastructure (V2I) communication, infrastructure-to-infrastructure (I2I) communication, relay communication, underwater communication, seaside communication, Internet of Things (IoT) applications including Machine-to-Machine (M2M), Device-to-Device (D2D), and Smart Factory Monitoring, as well as eHealth applications. Moreover, the TCD conducted a comparison between TG7a and the existing IEEE 802.15.7-2018 standard. This comparison focused on achieving higher data rates, extended communication ranges, and improved mobility support through the utilization of MIMO techniques, OFDM, and Artificial Intelligence (AI) algorithms.

Timeline

The TG7a webpage provides updates on the current status of TG7a [6]. The draft standard is expected to be ready for the third Letter Ballot Recirculation by July 2023, with the goal of finalizing the standard by the mid of 2024. For the most up-to-date information on the milestones and schedule, the latest updates can be found online [7].

OCC Features and Applications

In the following section, we discuss the utilization of different OCC receiver sets (except for VLC and LiFi). While there is no universally accepted definition of VLC, it typically involves the use of LEDs. The IEEE 802.15.7-2011 standard is referred to as the VLC specification. The LiFi foundation with bidirectional high-speed VLC brings many benefits to OWC. Because VLC, LiFi, and OCC depend on optical wavelengths (1001000 nm), they do not interfere with radio frequencies. The IEEE 802.15.7-2018 standard is an extension of IEEE 802.15.7-2011 that particularly pertains to OCC technology with its low rate and short range. However, LiFi modes were transferred to other task groups (IEEE 802.15.13 Multi-Gigabit/s Optical Wireless Communications Task Group and the IEEE 802.11bb Task Group on Light Communication) in 2017. Table 1 shows the main difference between LiFi, VLC, and OCC. With VLC, we only use Visible Light (VL) for transmitting data, while LiFi/OCC can use not only VL but also Infrared (IR) and Utraviolet (UV) light to transmit information.

	LiFi	VLC	OCC
Receiver	Photodiode	Photodiode/Camera	Camera
Spectrum	IR/VL/UV	VL	IR/VL/UV
Security	High	High	High
Environment	Indoor	Indoor	Indoor/Outdoor
Distance	10 m	20 m	200 m
Limitations	Short distance and no reliable mobility support	Short distance and no reliable mobility support	Lower data rate than LiFi/VLC

TABLE 1. Comparison table of LIFI/VLC/OCC [8].

The IEEE 802.15.7a OCC TG amendment extends the IEEE 802.15.7-2018 standard to provide a solution that focuses on vehicular applications considering high data rates and long-range OCC. This amendment offers several benefits:

- Utilization of a spectral range that requires no license
- Usage of MIMO, AI-based PHY, and MAC layers
- Secure data delivery through optically opaque walls
- It can be used for purposes beyond traditional communication, such as illumination, indication, and localization.

These attributes are expected to be valuable in emerging markets, including commercial and business settings.

The majority of the IEEE 802.15.7-2018 standard focuses on defining the signal format and includes ideas to facilitate designing simple receivers for individual implementers. In contrast, the higher rate, longer range OCC specification aims to allow interoperability with a variety of cameras without changing the hardware. Therefore, the design of OCC systems must consider the limitations imposed by appropriate cameras in suitable settings as well as cameras features. Furthermore, the OCC channel's maximum capacity is constrained by the low frame rates of typical cameras with adequate image resolution. For these reasons, OCC system design remains a serious challenge.

In the TCD document, a number of potential OCC applications were presented. Fig. 1 represents the promising applications of OCC services for drone networks and vehicular applications. Here, V2V, V2I, and I2I systems receive signals from image sensors and smart lighting in vehicles and buildings that are connected to mobile base stations. Currently, drone communication [8] is a developing area of research that may be utilized for transportation, military, and civilian applications. Moreover, drones can support V2V, V2I, and I2I systems, as displayed in Fig. 1. In these systems, street lights, strobing lights in drones, and vehicular rear/head-lights would be able to operate as OCC transmitters and help reduce the overall costs of the system. Figure 1 shows a hybrid network that uses OCC technology with Radio Frequency (RF) technology in a

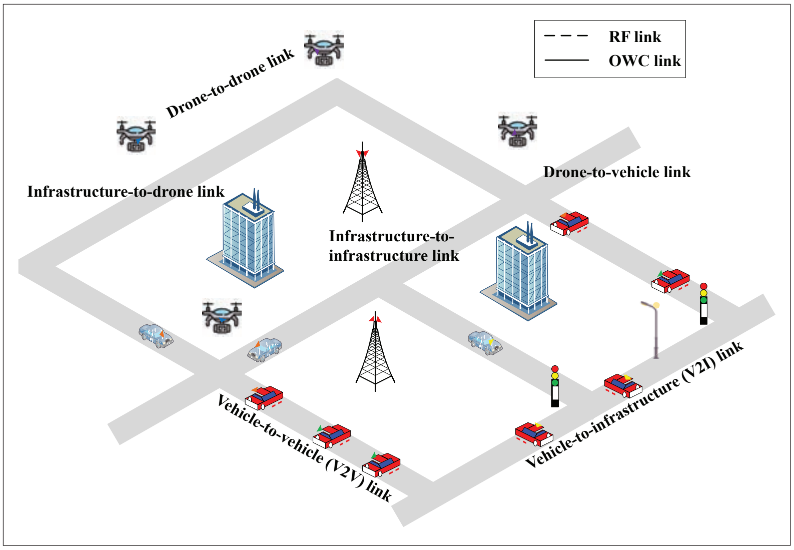

FIGURE 1. Example of OWC services utilizing 6G and beyond technology.

6G system. For base station (BS) to base station communication, RF technology should be used, while OWC should be used for V2V, V2I, and drone applications because of OWC's advantages over RF. During the IEEE 802.15.7a TG meeting, committee members proposed vehicular applications that use OCC technology using the rolling shutter effect to address mobility requirements at a distance of 30 m distance. For the future, we propose a laser-OCC concept, which uses a laser sensor instead of normal LEDs to enable communication distances of up to 100 m. It will be proposed for Next Generation Optical Camera Communication.

IEEE 802.15.7a TG PHY Modes and Related Works

To ensure that OCC systems achieve high performance, a good modulation and coding scheme is essential. Accordingly, TG7a has made a significant investment in the PHY layer. The addition of one new specification mode of the PHY specification modes (PHY VII in Table 2) was originally accepted by the TG7a committee based on technical proposals conducted in March 2022 and discussions held through TG7a meetings up until July 2023 [6]. The examination of these initial PHY modes is under review.

The current TG7a draft specification introduces numerous modulation methods that focus on a wide range of multi-carrier modulation techniques for OCC applications. In comparison, the IEEE 802.15.7-2011 standard relied on basic technical schemes (OOK, VPPM, and CSK [3] as show in Table 2) for VLC technology, while the IEEE 802.15.7-2018 standard relied on a low data rate OCC modulation scheme [4]. Various modulation methods have already been researched in TG7a, including some techniques for increasing the data rate and communication distance, such as OFDM technology, MIMO technology, and NOMA technologies [6]. In addition, deep learning has been applied to increase the performance of OCC systems for decoder algorithms.

OFDM Technology

In communication systems, inter-symbol interference (ISI) can limit the ability to increase the data rate and manifests in two ways: As a multipath phenomenon, and as a blur phenomenon. To improve the data rate in communication systems, researchers need to find methods to eliminate the ISI effect. OFDM is a modulation method to encode data using multiple carrier frequencies. It is an crucial modulation scheme in high data rate communication systems for reducing the channel-distorting effect of ISI. Rolling-shutter cameras are advantageous for OCC technologies compared to global shutter cameras because the rolling-shutter camera successively exposes the pixel lines to the receiving LED with a high sampling rate. The receiver sampling rates of these systems correspond to the rolling shutter's pixel row sampling rates and are often several kilohertz (or more) higher than the selected optical clock rate, which satisfies the Nyquist rate. Moreover, rolling shutter cameras are easy to deploy with OOK scheme. However, using the OFDM method for intensity modulation or direct detection (IM/DD) modulations is extremely challenging [9]. The OFDM technique based on the rolling-shutter effect is shown in the PHY VII specifications of Table 2 and referred to as RS-OFDM.

MIMO Technology

It is easier for OCC systems to deploy the MIMO technique instead of VLC/LiFi. This can resolve the major problem in OCC systems of simultaneous links with multiple light sources. By applying image processing methods, OCC systems can use many light sources simultaneously. For example, the IEEE 802.15.7-2018 standard proposed regions of interest (RoI) algorithms for detecting and tracking. Currently, deep learning is gradually replacing RoI for detecting and tracking light sources because it operates in real-time using both short processing times and high accuracy, which aids MIMO in OCC systems [6]. In TG7a, MIMO is used for OCC systems to increase the data rate and number of users, both of which were limited in IEEE 802.15.7-2018.

NOMA Technology

To improve the capacity of communication networks, NOMA has emerged as a promising candidate for RF and OWC systems. Code domain NOMA (also known as CD-NOMA) and Power domain NOMA (PD-NOMA) are two fundamental types of NOMA [10]. Instead of sharing time or frequency slots for multiple users, PD-NOMA shares the transmission power using the same time and frequency slots through superposition coding. In addition, CD-NOMA also shares the same time and frequency slots for multiple users through sparse dispersion or non-orthogonal low cross-correlation sequences [10]. In TG7a, the NOMA technique was proposed for the PHY VII modes of Table 2. It is referred to as Optical-NOMA (O-NOMA).

Hybrid Technology

Hybrid OCC systems have been proposed to transmit two data streams (high and low data rates) from the same light source simultaneously [6]. This can reduce OCC deployment costs while providing several services to multi-users via a low-complexity component. Moreover, energy is saved because the required number of light

PHY	Description	Modulation schemes	Optical Clock rate	Technology	Data rate	Mobility
I	IEEE 802.15.7-2011 [3]	• OOK • VPPM	20–0400 kHz	VLC	~ hundred kb/s	None
II	IEEE 802.15.7-2011 [3]	• OOK • VPPM	3.75–120MHz	VLC	~ hundred Mb/s	None
III	IEEE 802.15.7-2011 [3]	• CSK	12–24 MHz	VLC	~ hundred Mb/s	None
IV	IEEE 802.15.7-2018 [4]	• UFSOOK • Twinkle VPPM • S2-PSK • HS-PSK • Offset-VPWM	0.01–10 kHz	OCC	~ several kb/s	None
V	IEEE 802.15.7-2018 [4]	• RS-FSK • C-OOK • CM-FSK • MPM	10–12.5 kHz	OCC	~ several b/s	None
VI	IEEE 802.15.7-2018 [4]	• A-QL • HA-QL • VTASC • Invisible data-embedding	10–30 Hz	OCC	~ hundred kb/s	None
VII	IEEE 802.15.7-2024 [6]	• RS-OFDM • MIMO C-OOK • O-NOMA • MIMO-OOK • Hybrid modulation	1.5–40 kHz	OCC	~several Mb/s	~10 km/h

OOK: On-off keying
VPPM: Variable pulse position modulation
CSK: Color shift keying
UFSOOK: Undersampled frequency shift on-off keying
S2-PSK: Spatial 2-phase shift keying
HS-PSK : Hybrid spatial phase shift keying
Offset-VPWM: Offset variable pulse width modulation
PWM/PPM: Pulse width modulation/ pulse position modulation
CM-FSK: Camera multiple frequency shift keying
C-OOK: Camera on-off keying
RS-FSK: Rolling shutter frequency shift keying
VTASC: Variable transparent amplitude shape code
A-QL: Asynchronous quick link
HA-QL: Hidden asynchronous quick link
RS-OFDM: Rolling shutter orthogonal frequency division multiplexing
MIMO-COOK: Multiple input multiple output camera on-off keying
O-NOMA: Optical non-orthogonal multiple access
MIMO-OOK: Multiple input multiple output on-off keying

TABLE 2. IEEE 802.15.7A TG operating modes.

sources for the communication system is reduced. Due to its many advantages, hybrid modulation schemes were proposed in TG7a, which were categorized within the PHY VII modes as listed in Table 2.

Deep Learning Decoder

IEEE 802.15.7-2018 proposed RoI-signaling as a promising candidate for tracking and detecting light sources. However, RoI-signaling proved ineffective in high-mobility environments and with massive light sources (distinguishing between transmitting and non-transmitting light sources). Accordingly, new detection technology will need to be used in next-generation OCC systems to address these challenges. Currently, thanks to the advances in manufacturing, deep learning has emerged as a promising candidate for detecting and tracking objects with high precision and high reliability in real-time. As demonstrated in [11], utilizing You-Only-Look-Once (YOLO) in the OCC Rx (receiver) improves the data-reception rate when compared to conventional techniques.

In addition to detecting and tracking light sources, deep learning can be used for decoding data to improve OCC performance. Furthermore, in OCC modulation schemes that use the rolling shutter technique, striped patterns overlap on the receiver side due to factors such as the mobility effect, interference from other light sources (when using MIMO), and long distances. Under these conditions, the OCC signal can become distorted and cause errors while decoding data. As demonstrated in [12], using a deep learning model in the decoder increases the OCC data rate and decreases the bit error rate (BER).

PHY and MAC Frame Format and Configuration

PHY Frame Format

This section discusses the PHY layer, which includes PHY mode specification and the physical protocol data unit (PPDU) format. These problems have been addressed in the third recirculation letter ballot, which was submitted to the IEEE Review Committee in July 2023. The PPDU of the VLC PHY mode in the IEEE 802.15.7 Standard largely uses PHY header fields. However, the PHY header fields were removed in most OCC operating modes in IEEE 802.15.7-2018 to optimize the transmission overhead experienced in the low data rate OCC operating modes. The aim of these low data speed modulations was to simplify the PPDU format and PHY header field to increase the PHY service data unit (PSDU) length.

The IEEE 802.15.7a Task Group has several operating modes that can function with a single light source at high rates. These are similar to the existing IEEE 802.15.7-2018 PPDU format, including an O-NOMA and RS-OFDM. However, other modes (such as MIMO-COOK, Hybrid modulation, and MIMO-OOK) work with multiple light

<table>
<tr><td rowspan="2">Frame control</td><td rowspan="2">Sequence Number</td><td>Destination OWPAN Identifier</td><td>Destination Address</td><td>Source OWPAN Identifier</td><td>Source Address</td><td rowspan="2">Auxiliary Security Header</td><td rowspan="2">Frame Payload</td><td rowspan="2">FSC</td></tr>
<tr><td colspan="4">Addressing fields</td></tr>
<tr><td colspan="7">MHR</td><td>MAC Payload</td><td>MFR</td></tr>
</table>

FIGURE 2. Frame format of the MAC protocol [4].

	IEEE 802.15.7a TG	Next Generation OCC
PHY layer	Unidirectional communication	Bidirectional communication
	Single communication	Joint communications and sensing
	Ordinary IR/VL/UV Light	IR/VL/UV Laser
MAC layer	Unslotted ALOHA and CSMA/CA	Full duplex operation

TABLE 3. Summary of IEEE 802.15.7A TG and next generation OCC.

sources and are designed for long-range communication. Accordingly, they require a simplified PPDU format, which needs careful consideration. TG7a proposes a configuration based on PHY-layer personal area network information-based (PIB) attributes that can support multiple PHY operating modes with a non-PHY header field.

MAC Frame Format

The proposals for TG7a OCC include a medium access control (MAC) layer. Since the OCC operating modes in TG7a primarily support unidirectional communication, the MAC super-frame has been minimized, and the beacon frame is unnecessary for TG7a. A simple unslotted ALOHA algorithm was proposed for the multiple-channel access method.

TG7a uses the existing 802.15.7-2018 MAC for the added OCC modes. In addition to the PPDU field being configured by the PHY PIB attribute values, the MAC protocol data unit (MPDU) was determined by the MAC PIB attributes [6]. Fig. 2 displays the general frame format of the MAC protocol. The TG7a committee members agreed to add MAC PIB attributes that were tantamount to the MAC header subfields (MHR) to optimize the MAC overhead. In the future, the MAC protocol specifications, MAC frame format, and MAC command frames will be taken into consideration for proposals in the next-generation OWC systems, with a focus on accommodating full duplex operation.

Challenges and Future Directions

As mentioned previously, the IEEE 802.15.7a Task Group is regarded as the first step in bringing high-rate, long-range OCC to the IEEE 802.15.7 standard, which currently only offers basic VLC and low-rate, short-range OCC technologies. Moreover, many promising directions are being placed on hold for future standards, as displayed in Table 3. One such feature is bidirectional OCC. The current TG7a specification document only focuses on unidirectional OCC technology, which can only broadcast OCC information to another device and has lower reliability than bidirectional communication. Since OWC and RF have complementary qualities, combining them into one application is thought to be a potential way to sustain modern communication systems (6G and beyond). Hybrid RF/OWC and hybrid LiF/OCC systems are promising ways to overcome the drawbacks of standalone systems and combine the best aspects of both technologies. Quantum technology is also considered for future use by the OCC Standard through Quantum Key Distribution (QKD), which is suitable for military applications that require very high security. TG7a does not support joint communication and sensing, a feature expected to be crucial in future 6G networks [13]. By applying joint communications and sensing through OWC (in general) and OCC (in particular), the commercialization of OCC for 6G (and beyond) systems becomes a more realistic proposition. Moreover, the concept of Intelligent Reflecting Surfaces (IRS) is also a good candidate to improve the performance of LiFi and VLC systems using photodiodes. By integrating metasurface structures that can be programmed and altered to create an accurate response to the incident signals, IRS technology promises [14] a paradigm shift regarding enhancing wireless communication capabilities. However, we need to design new IRS materials to use IRS in OCC, which collects data from image sensors. In addition, the effect of the IRS on the OWC channel model also should be considered in the future. Ordinary IR/VL/UV lights are not feasible for increasing the communication distance and enabling communication over several kilometers because their signal intensity decreases rapidly with distance. Therefore, laser sensors have emerged as a candidate for next-generation OCC systems. However, the major drawback of laser communication is sensitivity when used in mobile environments. Nevertheless, integrating deep learning for tracking and object detection can offer substantial benefits for laser OCC. When combined with laser sensors, this approach can enable OCC technology and achieve communication over several kilometers. It will be proposed for the next OCC standard after completing TG7a in 2024. Moreover, the optical channel effects from laser sensors to the image sensor need to be considered in OCC systems to resolve complex noise problems, such as blur, irregular attenuation, and interference. Because bidirectional communication technology was proposed in the PHY layer, a new MAC protocol needs to be proposed in future OCC features. In addition, full-duplex optical MAC (FD-OMAC) [15] will be helpful for the next generation of OWC.

Conclusion

In this study, we analyzed the current state of the development process for IEEE 802.15.7a (the amendment standard for IEEE 802.15.7-2018) and related unsolved problems. Some significant attributes and promising applications of OCC were clarified, and the scope and timeline of TG7a were introduced. The PHY VII specification mode was compared with relevant works from outside TG7a. Furthermore, the PHY/MAC frame formats and the configurations selected in recent TG7a meetings were discussed. The TG7a relies on the established 802.15.7 PHY and MAC framework, which will facilitate the integration of future OCC technology into the mass market. In addition, we analyzed IEEE 802.15.7a TG's core PHY and MAC innovations. In addition, we highlighted the unresolved problems related to the upcoming next-generation OCC standard. We also detailed several potential future characteristics of the next-generation OCC standard, including a PHY layer (bidirectional, joint communications and sensing, and the laser concept in OCC) and a MAC layer (full duplex). We aspire that our study will draw the attention of the research community to the IEEE 802.15.7 standard and inspire their contributions to enhance OCC/OWC technology through comprehensive research and practical solutions.

Acknowledgment

This research was supported by the Ministry of Science and ICT (MSIT), South Korea, under the Information Technology Research Center (ITRC) support program (IITP-2023-2018-0- 01396), supervised by the Institute for Information and Communications Technology Planning and Evaluation (IITP), and the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIT) (no.2022R1A2C1007884).

References

[1] T. Nguyen *et al.*, "Technical Issues on IEEE 802.15.7m Image Sensor Communication Standardization," *IEEE Commun. Mag.*, vol. 56, Feb. 2018, pp. 213–18.

[2] A. A. B. Raj *et al.*, "A Review–Unguided Optical Communications: Developments, Technology Evolution, and Challenges," *Electronics*, vol. 12, no. 08, Mar. 2023, p. 1922.

[3] *IEEE Standard for Local and Metropolitan Area Networks — Part 15.7: Short-Range Wireless Optical Communication Using Visible Light*, IEEE Standard 802.15.7-2011, 2011.

[4] *IEEE Standard for Local and Metropolitan Area Networks — Part 15.7: Short-Range Wireless Optical Communication*, IEEE Standard 802.15.7-2018, 2018.

[5] IEEE 802.15.7 Rev. Technical Consideration Document v. 8; https://mentor.ieee.org/802.15/dcn/21/15-21-0065-08-007a-technical-considerations-document.docx; accessed May 3, 2023.

[6] IEEE Mentor 802.15.7a Task Group docs; https://mentor.ieee.org/802.15/documents?is_group=007a; accessed May 3, 2023.

[7] IEEE Mentor 802.15 VAT IG documents; https://mentor.ieee.org/802.15/dcn/20/15-20-0265-00-0vat-suggested-15-7a-schedule-and-milestones.pptx; accessed May 3, 2023.

[8] M. Z. Chowdhury *et al.*, "A Comparative Survey of Optical Wireless Technologies: Architectures and Applications," *IEEE Access*, vol. 6, 2018, pp. 9,819–10,220.

[9] J. K. Lain *et al.*, "Experimental DCO-OFDM Optical Camera Communication Systems with a Commercial Smartphone Camera," *IEEE Photon. J.*, vol. 11, no. 6, Dec. 2019, pp. 1–13.

[10] Mohsan *et al.*, "NOMA-Based VLC Systems: A Comprehensive Review," *Sensors*, vol. 23, no. 8, 2023, p. 7815.

[11] X. Sun *et al.*, "An LED Detection and Recognition Method Based on Deep Learning in Vehicle Optical Camera Communication," *IEEE Access*, vol. 9, May 2021, pp. 80,897–905.

[12] O. I. Younus *et al.*, "Data Rate Enhancement in Optical Camera Communications Using an Artificial Neural Network Equaliser," *IEEE Access*, vol. 8, 2020, pp. 42,656–65.

[13] X. Fang *et al.*, "Joint Communication and Sensing Toward 6G: Models and Potential of Using MIMO," *IEEE Internet Things J.*, vol. 10, Mar. 2023, pp. 4093–4116.

[14] Y. Ata *et al.*, "Intelligent Reflecting Surfaces for Underwater Visible Light Communications," *IEEE Photon. J.*, vol. 15, no. 1, Feb. 2023, pp. 1–10.

[15] A. Gupta *et al.*, "FD-OMAC: A Novel Full-Duplex Optical Media Access Control for IEEE 802.15.7," *IEEE Access*, vol. 9, Nov. 2021, pp. 148,894–910.

Biographies

Huy Nguyen earned his B.Sc. degree from Hanoi University of Science and Technology (HUST), Vietnam, in 2017. He received Master and Ph.D. degrees both in Electronics Engineering from Kookmin University, South Korea, in 2020 and 2023 respectively. He is now working as a Postdoc Researcher at KMU. His research interests include optical wireless communications, deep learning, and augmented-reality services. Since 2020, he has been the Technical Editor of IEEE 802.15.7a Higher Rate and Longer Range OCC TG.

Ida Bagus Krishna Yoga Utama received a B.Eng. degree from Universitas Indonesia, Depok, Indonesia, and an M. Sc. degree from the Kookmin University, Seoul, South Korea. He is currently working toward a PhD with the Wireless Communication and Artificial Intelligence Laboratory, Kookmin University, Seoul, South Korea. His current research interests include optical wireless communication, sensor fusion, intelligent Internet of Things, and machine learning.

Yeong Min Jang received his doctoral degree in computer science from the University of Massachusetts in 1999. Since 2002, he has been with the School of Electrical Engineering, Kookmin University. In 2019, he was the President of KICS. He was also the IEEE 802.15.7m Optical Wireless Communications TG from 2015 to 2019. Since 2020, he has been the Chairman of IEEE 802.15.7a Higher Rate and Longer Range OCC TG. He is also the Editor-in-Chief of ICT Express (indexed by SCIE). His research interests include AI mobility, optical camera communication, 5G/6G mobile communications, and the Internet of Energy.