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Optical Wireless Communication: A Candidate 6G Technology?

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SUMMARY We discuss herein whether an optical wireless communication (OWC) system can be a candidate for post 5G or 6G cellular communication. Almost once per decade, cellular mobile communication is transformed by a significant evolution, with each generation developing a distinctive concept or technology. Interestingly, similar trends have occurred in OWC systems based on visible light and light fidelity (Li-Fi). Unfortunately, OWC is currently relegated to a limited role in any 5G scenario, but the debate whether this is unavoidable has yet to be settled. Whether OWC is adopted post 5G or 6G is not the vital issue; rather, the aim should be that OWC coexists with 5G and 6G communication technologies. In working toward this goal, research and development in OWC will continue to extend its benefits and standardize its systems so that it can be widely deployed in the market. For example, given that a standard already exists for a visible-light beacon identifier and Li-Fi, a service using this standard should be developed to satisfy user demand. Toward this end, we propose herein a method for visible-light beacon identification that involves using a rolling shutter to receive visible-light communications with a smartphone camera. In addition, we introduce a rotary LED transmitter for image-sensor communication.

key words: *post 5G/6G, visible light communication, Li-Fi, IEC 62943 visible light beacon, rolling shutter, rotary LED transmitter*

1. Introduction

2020 was supposed to be the year that fifth-generation (5G) cellular mobile communications made its grand debut. Unfortunately, the coronavirus pandemic postponed this development. However, 5G communications remain the main technological focus for cellular mobile communications. In fact, research on wireless communication systems has already shifted from 5G to post 5G and 6G technologies. In this paper, we address the question of whether optical wireless communication (OWC) [1], [2] can be a candidate for post 5G or 6G technology, what form it should take, and what technical elements are required for such a scenario.

Almost once per decade, cellular mobile communication is transformed by a significant evolution, with each generation developing a distinctive concept or technology. For example, first-generation mobile communication introduced the cellular concept, and second generation technology transitioned from analog to digital, making the devices smaller and more affordable. Third-generation technology used multiple access systems such as code division multiple access (CDMA), and included data in addition to voice. The fourth generation adopted orthogonal frequency division multiplexing (OFDM) to allow high-speed data communication and multi-input multi-output (MIMO) to accelerate user connectivity for smartphone applications. Finally, 5G technology is now expanding beyond ultrafast data communications to autonomous driving control and the Internet of Things (IoT).

In mobile wireless communication, OWC has already been used in 2G technology in the form of an infrared data module. With this technology, terminals that are mainly used for voice communication are also used for data communication via infrared communication systems. However, with the rise of Bluetooth and wireless LAN, the adoption of OWC has stalled.

In this paper, we discuss whether OWC can be a candidate for post 5G or 6G communications. In particular, we look at the trends in cellular mobile radio communications and OWC and discuss what form, if any, OWC systems should take and what technical elements would be required in such a case. As a candidate technology, we introduce visible-light communication (VLC) with a camera also known as image-sensor communication (ISC) [3]–[5] or optical camera communication (OCC) [6]–[8]). We also introduce a rotary LED transmitter for ISC.

This paper consists of two parts: In the first part, we consider trends in cellular mobile radio communications and OWC and discuss the technical challenges to be resolved for OWC to be a candidate for post 5G or 6G technology. In the second part of the paper, we introduce the rolling-shutter method, which allows VLC using a smartphone camera and provides a visible light beacon (VLB) identification (ID) system. We also introduce a method that uses the smartphone camera and produces an afterimage by rotating the transmitter, thereby creating an effect similar to the rolling-shutter method.

2. Reviewing Trends in Mobile Radio Communications and Optical Wireless Communication

2.1 Timeline

Figure 1 summarizes the trends in mobile radio communications and OWC from 1980 to 2020. As seen from the figure, cellular radio communication technology has undergone a generational change every decade since 1980, with

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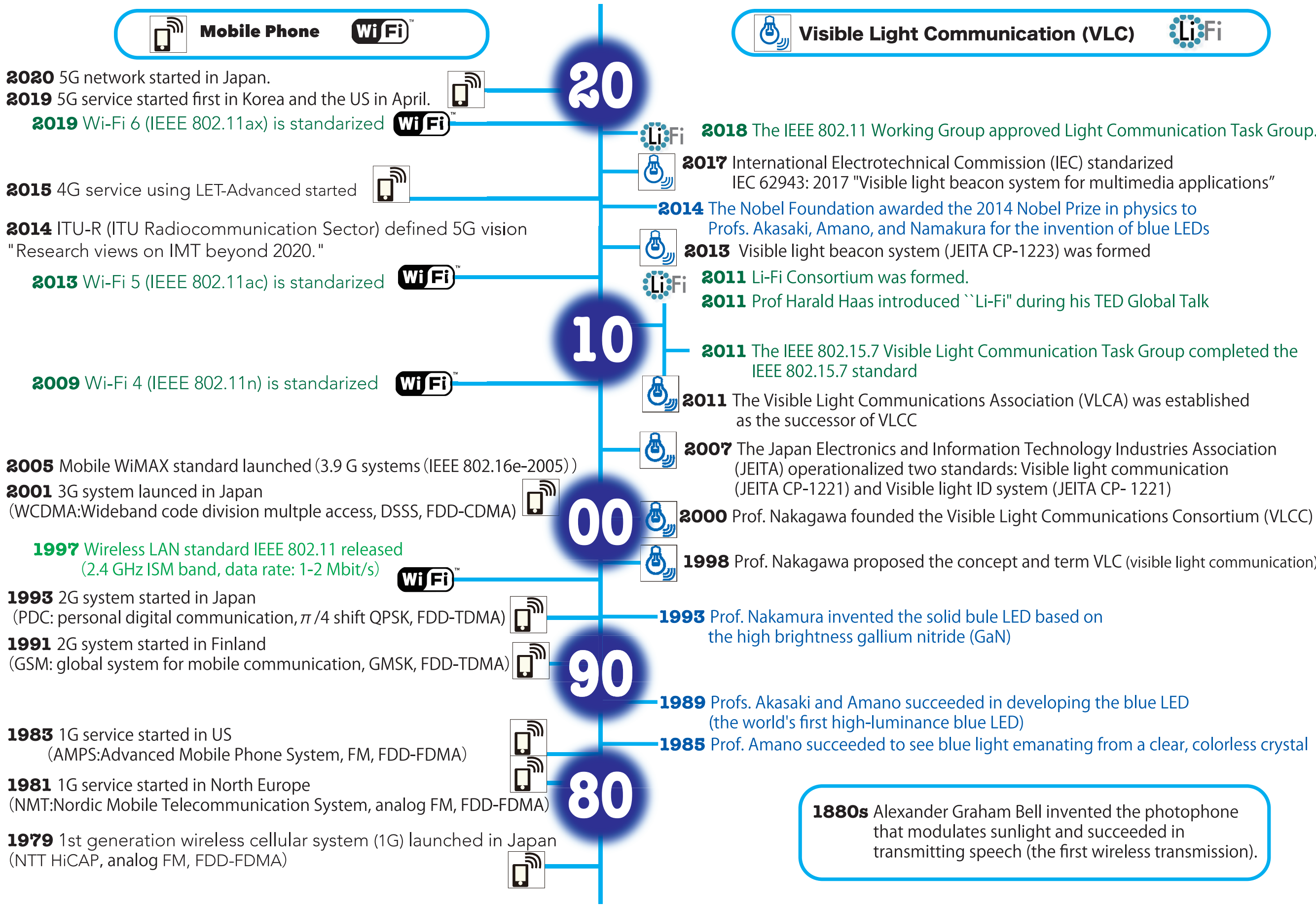

Fig. 1 Brief history of mobile phone systems, Wi-Fi, VLC, and Li-Fi. Cellular mobile radio and Wi-Fi, being mobile radio communication systems, are listed on the left side of the figure. On the right, we show the trends of VLC and light fidelity (Li-Fi) [9]–[11] as OWC systems. Note that we exclude IrDA [12]–[14], free-space optical (FSO) communication [15]–[18], etc. and focus only on VLC and Li-Fi. We also exclude Bluetooth from mobile radio communications.

VLC and Li-Fi concentrated after 2010.

We may also assume that, for VLC and Li-Fi, technological generational transitions will also occur roughly every ten years. VLC was first proposed by Nakagawa at Keio University at the end of the 1990s when white-light LEDs or phasor-coated blue-light LEDs first came on the market [19]–[22], which was almost ten years after Akasaki and Amano invented blue-light LEDs in 1989 [23].

Slightly over a decade later, in 2011, Haas at the University of Edinburgh proposed Li-Fi, which is a high-speed wireless communication system based on optical radiation transmitted along a line of sight [11]. Finally, in 2018, the IEEE 802.11 study group was established to form the wireless LAN standard.

Haruyama of Keio University then proposed the LED VLB as a standard for VLC. In 2007, the Japan Electronics and Information Technology Industries Association (JEITA) operationalized two standards: Visible light communication (JEITA CP-1221) [24] and Visible light ID system (JEITA CP-1222) [25]. Later, in 2013, the VLB system (JEITA CP-1223) [26] was formed. Ten years after the first standard in 2007, the International Electrotechnical Commission (IEC) produced the standardized IEC 62943: 2017, entitled “Visible light beacon system for multimedia applications” [27], and which we refer to herein as *IEC62943 VLB*.

Thus, based on the history of generational advances in OWC systems every ten years, we may expect breakthroughs in OWC systems to mature around 2030, which is when 6G communications will appear.

2.2 Research Trends in Optical Wireless Communications

We now discuss the research trends in OWC systems. Figure 2 shows the yearly number of research papers related to infrared communication (Ir), VLC, ISC (or OCC), Li-Wi, FSO communication, and others. Furthermore, Table 1 summarizes the classification and characteristics of OWC technologies.

As seen in Fig. 2, the number of research papers has increased since 2010. In particular, the VLC category grew remarkably and Li-Fi and ISC, which are derived from VLC, grew in tandem. Conversely, we count a constant and mod-

Table 1 Classification and characteristics of OWC technologies [28]–[32].

	Ir	VLC	ISC	Li-Fi	FSO
Transmitter	LED/LD	LED/LD	LED/Display	LED/LD	LD
Receiver	PD	PD/Camera	Camera	PD	PD
Data rate	kbps-Gbps	Mbps-Gbps	bps-Mbps	kbps-Gbps	Gbps
Range	<10m	<100m	<200m	<10m	>1km
Implementation complexity	Moderate	Moderate	Low	Moderate	High
Application	Optical USB, PAN (Personal Area Network)	Navigation, PAN ID, Underwater	Navigation, PAN ID, ITS	Indoor internet access	Backhaul, Space, Underwater
Standard	IrDA SIR (1994) IrDA MIR (1994) IrDA VFIR (1998) IrDA UFIR (2006) IrDA Giga-IR (2009)	JEITA CP-1221 (2007), JEITA CP-1222 (2007), JEITA CP-1223 (2013), IEC 62943:2017 (2017), IEEE 802.15.7 (2011), IEEE 802.15.7m (2018)	JEITA CP-1221 (2007), JEITA CP-1222 (2007), JEITA CP-1223 (2013), IEC 62943:2017 (2017), IEEE 802.15.7 (2011), IEEE 802.15.7m (2018)	Under discussion at IEEE 802.11 Light Communication Task Group	—

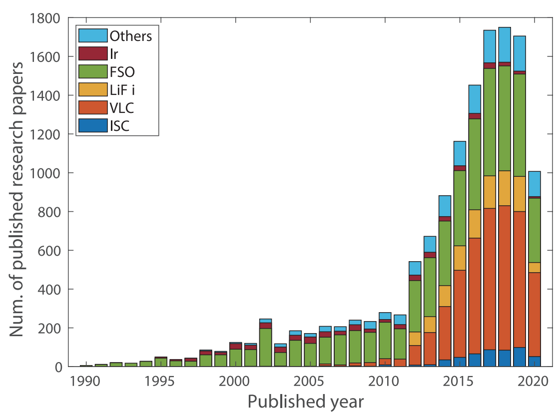

Fig. 2 The yearly number of published research papers by Nov. 17, 2020. These data were obtained by searching for each keyword in the Web of Science database, following which the articles were classified based on titles and keywords. We treat OWC as a generic term; in other words, Ir, VLC, ISC, Li-Fi, and FSO are all methods of OWC, but papers are only classified as belonging to the OWC category if the author specified "OWC" as a keyword or used it in the title.

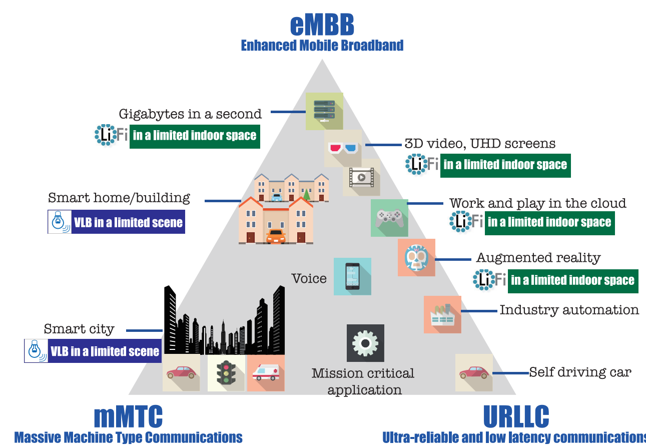

Fig. 3 Usage scenarios of 5G. Li-Fi and VLB adaptation in a limited scenario [34], [35].

erate number of FSO papers since 1990 with only a slight increase in number since 2010. FSO has been evaluated as a backhaul network technology and a certain level of demand for this type of technology is expected in the future. In the Ir category, although a certain number of publications appear every year, no growth trend is apparent. Ir uses near-infrared radiation and is a successful example of OWC. It was used in 2G devices and IrDA and set the standard [33] in 1993, when it was established. However, with the advent of smartphones, Bluetooth and Wi-Fi have been adopted, with Ir becoming less used. This explains why relatively few Ir papers have been published.

3. Can Optical Wireless Communication Systems be Candidates for Post 5G or 6G Technology?

3.1 5G Use Scenarios and Suitability of Optical Wireless Communication

The International Telecommunications Union Radiocommunication Sector started research on 5G at the workshop entitled "Research views on IMT† Beyond 2020" at Working Party 5D, held in May 2014. After a year and a half of work, they produced a draft vision recommendation [34], [35]. Because it took time to specify the frequency band for 3G and 4G technology and to examine how the system would work when using this frequency band, the draft also outlines the use of the 6–100 GHz frequency band and the system's requirements. For example, with 3G, it took seven years to identify the spectrum and 15 years to deploy the system. For 4G, it took about nine years from the 2003 vision recommendation to final approval of the radio interface for 4G systems (IMT-Advanced).

The recommendation for the 5G vision presents three typical use scenarios (see Fig. 3). Assuming that post 5G and 6G technologies will follow the extension of 5G, we also inherit the use cases shown here for post 5G and 6G. We now discuss the applicability of OWC to each of the following use scenarios.

(1) eMBB: Enhanced mobile broadband.

Enhanced mobile broadband is a people-centric scenario, where multimedia content can be accessed anytime, any-

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where. Unfortunately, it is challenging to ensure ubiquity when using OWC.

For a human-centered scenario, access must be guaranteed in all locations, including when moving. When the wavelength of the radiation is 1 mm or less, absorption by molecules in the air or at the surface of a material is likely. When the surface of an object is not sufficiently flat (relative to optical flatness), irregular reflection occurs, and radiation is rapidly attenuated. Therefore, the signal becomes weak, and communication is not possible if the radiation source is not visible. Conversely, radio waves have longer wavelengths than optical radiation and are easily transmitted beyond the field of vision because they are reflected from objects. It is also quite possible to envision, for example, the use of OWC in a limited indoor space; this is the scenario for which Li-Fi is considered.

Post 5G and 6G are expected to use higher-frequency bands than are currently in use. However, assuming the use of frequencies above 300 GHz, the wavelength would be 1 mm or less, making communications more susceptible to absorption in matter and air. Thus, the characteristics of the transmitting radiation would become closer to those of visible light. Because a sufficiently large frequency band is available for OWC, it may prove to be an excellent solution for implementing the ultrafast communications expected in post 5G and 6G. Therefore, one may consider that OWC is a viable candidate for post 5G and 6G.

(2) URLLC: Ultra-reliable, low-latency communication.

This scenario assumes wireless operation in the manufacturing industry, telemedicine surgery, smart grids, vehicle automation, etc. and requires precision from the viewpoints of throughput, delay, and reliability. Adoption of OWC is unlikely in this scenario because of the difficulty in ensuring ubiquity as described in Sect. 3.1 (1). However, it may be adopted as an alternative measure in places where radio waves are not used, such as at medical sites.

(3) mMTC: Massive-machine-type communication.

OWC is expected to only find limited use in this scenario. Since this scenario involves low-speed or immobile objects, line-of-sight communication is easily secured. In such an environment, OWC can play a significant role. In particular, VLC and Li-Fi use visible light as a transmission source so that communication paths can be visually determined, which would greatly facilitate designing the communication path. Conversely, the use of OWC would be limited because IoT devices installed outside the line of sight, for example, behind shelves, would be inaccessible.

3.2 Can Optical Wireless Communication be a Candidate for Post 5G or 6G?

As we have seen, the application of OWC in any of the 5G scenarios appears rather limited. However, users expect 5G and, later, post 5G and 6G, to provide flexibility over the network infrastructure for a variety of use cases. To accommodate this, 5G adopts a virtualization technology represented by network slicing, which could allow OWC to play an active role, even in limited use scenarios.

Furthermore, given that optical radiation does not interfere with radio waves, OWC can further expand its field of activity. If OWC can satisfy user demand in a limited use scene, it may find its place in communications other than cellular mobile communications. Since OWC does not use radio waves and the communication band is license-free, we can use any technology that coexists with or complements radio waves. Thus, adoption of OWC need not to be restricted to only post 5G and 6G technologies.

Although optical radiation can coexist with radio waves, and different systems can easily coexist, standardization is required, as already exists for VLC. For example, a VLB ID system has already been standardized, and Li-Fi is also being considered for standardization as a wireless LAN. Wireless LAN uses its own path with mobile phones and provides an essential function for user terminals such as smartphones. In view of the above, OWC should aim to coexist as a complementary technology in the post 5G or 6G world rather than aiming to be a standard technology.

In summary, the goal should not be that OWC be adopted for post 5G and 6G, but rather that it coexist with the other technologies. Research and development into OWC will continue to extend its benefits and to standardize it so that it can be widely deployed in the market. For example, standards such as VLB ID already exist, and the implementation of a service based on the standard to satisfy user demand would be a welcomed development.

4. Coexistence of Optical Wireless Communication with Cellular Mobile Communications

4.1 Visible-Light Identification, Visible-Beacons Systems, and Li-Fi

How can OWC coexist with post 5G or 6G? One of the solutions is Li-Fi, which provides indoor high-speed internet access. Li-Fi can provide multiple access with seamless handover and offers mobility [36] and no interference from a different radio spectrum. Therefore, it is suitable for implementing femto- or attocells as parts of the post 5G or 6G network and is easy to integrate into existing networks [37].

Another solution is a VLB ID, which serves as the starting point of internet connections in post 5G and 6G. Although the ID itself has a low data rate, the desired information can be fetched from a server on the internet associated with the received ID. With the directivity of LEDs, a reliable link can be established without interference from other sources simply by pointing the receiver to the target information source. Furthermore, OWC complements wireless communications, where radio waves are of limited use, such as underwater [38], in tunnels [39], in hospitals [40], etc. For these reasons, VLB ID is a critical solution and would allow OWC to coexist with post 5G and 6G technologies. Figure 4 illustrates services where OWC coexists with post

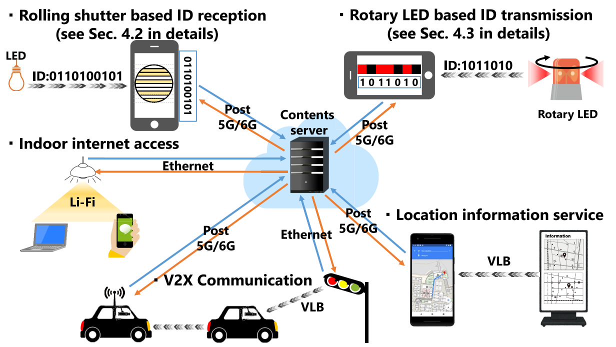


Fig. 4 Examples of services where optical wireless communication coexists with post 5G and 6G technologies. Visible light beacon (VLB) ID serves as the starting point of internet connections.

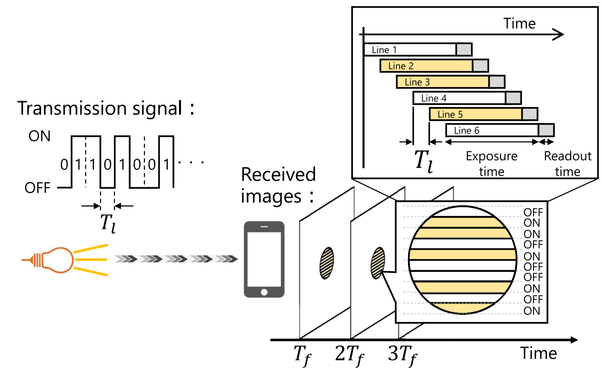


Fig. 5 Operation process of rolling shutter based ISC. Pixels are read out sequentially line by line, and each line is exposed with a different timing T_ls.

5G and 6G technologies.

4.2 Standard for Visible-Light Identification and Beacon Systems

To determine whether OWC can coexist with post 5G and 6G technologies, we focus on a VLB system for multimedia applications (i.e., IEC62943 VLB) [27]. In this system, a VLB sends a unique ID, and the receiver uses communication technologies other than VLC and ISC to download data from a content server linked to the ID. Thus, VLB ID serves only as a trigger to start a service. This VLB system is a good example of OWC coexisting with cellular mobile communications.

The IEC62943 VLB is modulated at 9.6 kHz. To receive beacons modulated at 9.6 kHz, the VLB system was originally designed to use a photo diode (PD) as a beacon receiver. However, very few applications exist that use PD-type receivers, and smartphones are not equipped with PDs, which would delay the spread of this technology.

To receive a beacon at this data rate with a smartphone image sensor would require a creative VLC transmitter and receiver. Toward this end, we introduce below in Sect. 4.3 the rolling-shutter ISC, which is actually used to receive visible beacons. Additionally, we present in Sect. 4.4 a unique device called a "rotary LED transmitter" to increase ISC rate on the transmitter side.

4.3 Reception of Visible-Light Beacon Using Rolling Shutter

The rolling-shutter-type image sensor, which uses the smartphone camera, creates a possible use of OWC in post 5G and 6G technologies. Cameras mounted on smartphones usually have framerates of 30–60 fps. Cameras operating at 30–60 fps cannot receive signals from VLB IDs modulated at 9.6 kHz. However, by focusing on the line-scan mechanism of the rolling-shutter camera, Danakis et al. proposed receiving high-speed modulated LED transmission signals by using a commercial off-the-shelf low-frame-rate smartphone camera [41]. This approach allows a VLB ID modulated at 9.6 kHz to be received by the image sensor, including the commercial off-the-shelf cameras in smartphones.

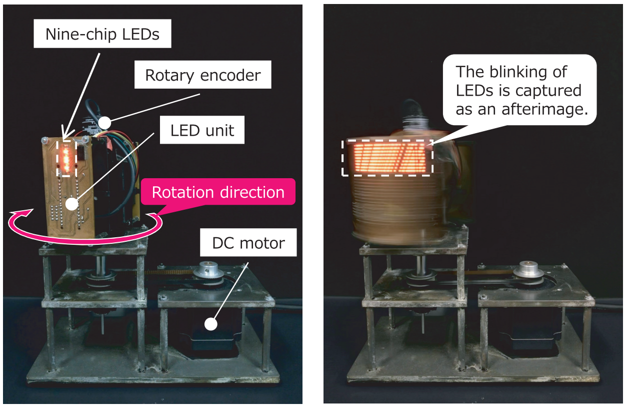
We now explain the basic principal of ISC based on the rolling-shutter method. In general, two types of camera imaging mechanisms are in use: one is called "rolling shutter" and the other is called "global shutter." As illustrated in Fig. 5, pixels are read out sequentially line by line in the rolling shutter method, whereas pixels are all read out simultaneously in the global shutter method. Although this sequential exposure mechanism distorts moving objects and degrades image quality, it offers substantial benefits for ISC in terms of data rate [42].

Specifically, as shown in Fig. 5, the transmission light source is modulated at the same rate as the line scan ($1/T_l$). Next, upon receiving the image, each line is projected as a striped pattern in the row direction by modulating the light source [43]. Data can be obtained by demodulating each stripe of the received image obtained by the rolling-shutter camera [44]. For example, assume that the receiver can capture images (columns × rows = 1920 × 1080) at a frame rate of $1/T_f$ = 30 fps. At this time, the maximum sampling rate is $1/T_l = 1/T_f \times$ rows $= 30 \times 1080 = 32.4$ kHz. In this way, the rolling-shutter method can receive signals modulated faster than the frame rate and can thus receive VLB IDs modulated at 9.6 kHz.

Panasonic started a service (with the commercial name "LinkRay") that uses this rolling-shutter method and that captures ID information simply by holding the smartphone over the light source that transmits the VLB ID [45]. With LinkRay, the VLB ID is repeatedly transmitted, and the ID can be acquired within approximately 0.3 s. In applications, LinkRay assumes that IDs are transmitted from lighting, signboards, and displays and provides public-transportation and facility information, shop-product information, and coupons.

4.4 Transmission of Visible-Light Beacon by Using Rotary LED Transmitter

One way to improve the data rate in ISC is to increase the number of LEDs on the transmitter and for each LED to independently transmit data; this method is called "paral-



(a) Structure of the transmitter. (b) State of the rotating transmitter.

Fig. 6 Prototype of rotary LED transmitter.

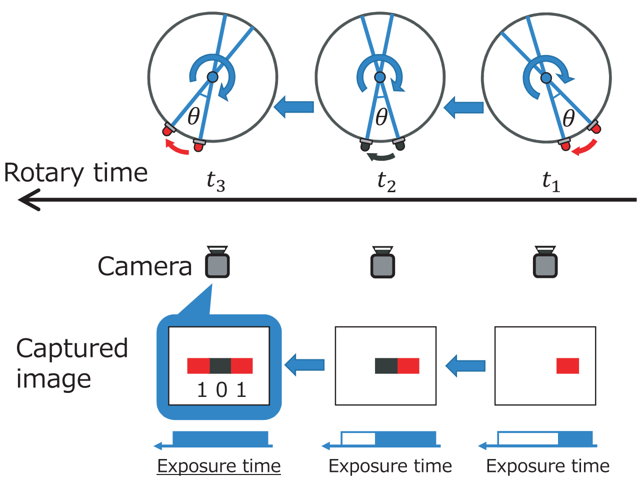


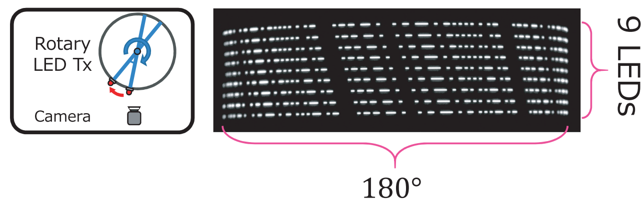
Fig. 7 Improving the amount of the received data per image by rotation.

lel data transmission" [46]–[48]. Rather than increasing the number of LEDs, increase the number of LEDs in the image by intentionally moving the LEDs during data transmission, which creates an afterimage of the blinking LEDs. This is called a "rotary LED transmitter" [49], [50].

Figures 6(a) and 6(b) show a prototype of the rotary LED transmitter, which comprises a LED unit, a rotary encoder, and a DC motor. Let us first explain the operation of the rotary LED transmitter. We first rotate the LED unit, which consists of nine LEDs arranged vertically. While rotating, the LEDs blink to communicate the data. Next, the image sensor detects the signal from the rotating-LED transmitter. Here, we assume that the exposure time of the sensor is significantly less than the period of rotation of the transmitter and greater than the blinking period of the LEDs. In this case, the image sensor can capture multiple LED blinks per image, as shown in Fig. 6(b). If the LED blinking depends on data modulated by on-off keying, then the receiver can obtain the blink state of LEDs per degree of rotation from a single image as a data sequence.

Figure 7 shows the mechanism used to improve the data rate. When the LEDs are fixed as in a conventional

(a) When the nine-chip LEDs remain fixed, each frame contains nine blinking LEDs.



(b) When the nine-chip LEDs are rotated in front of the camera during the exposure, the camera captures the blinking LEDs after 180° of rotation as afterimages in single frame.

Fig. 8 Actual images captured from fixed and rotary LED transmitter.

VLC transmitter, the receiver captures a single LED blink state per image. Conversely, the multiple blink states can be captured in a single frame if we rotate the blinking LED in front of the camera, as shown in Fig. 7. The change in the blinking LED is stored as an afterimage in the captured frame. Thus, the amount of data received per image can be increased by rotating the blinking LED.

We implemented this transmitter and verified its operation in a laboratory experiment. In this experiment, we set the rotation speed of the transmitter and the shutter speed of the image sensor to 300 rpm (rotations per minute) and 5 fps (frames per second), respectively. The nine-chip LEDs on the transmitter switched the blinking status per each degree of rotation. The transmitter and receiver were placed 1.0 m apart and arranged face-to-face with no interceding objects. The receiver captured the blinking of LEDs that were rotated by the transmitter and counted the number of captured LEDs per image.

Figures 8(a) and 8(b) show actual captured images of a nine-chip fixed LED and of the same nine-chip LED under rotation. When the nine-chip LEDs are rotated in front of the camera during the exposure, the camera captures the blinking LEDs after 180° of rotation as afterimages in a single frame. Here, we assume that the demodulation range is limited to the ±30° from the center of the captured image in Fig. 8(b). In this case, 540 blinking LEDs are captured (=9 LEDs × 60°; −30°–+30°). This result indicates that the image sensor can receive 540 bits of data per image in the case of on-off-keying.

An advantage of the rotary LED transmitter is that the increase in communication speed is independent of the image-capturing methods of the camera. Although the IEC62943 VLB is a technology standard based on a rolling-shutter-type camera, the rotary LED transmitter would satisfy the communication speed required by IEC62943 VLB even if using a global-shutter-type camera. If the beacon can be received regardless of the image-capturing methods of the camera, we could develop OWC technology suitable for the post 5G and 6G IoT because any camera, such as in-vehicle cameras and security cameras, could be used as the beacon receiver.

5. Conclusion

This paper discusses whether OWC systems can be candidates for post 5G or 6G technology. Unfortunately, the potential use of OWC in any 5G scenario is limited, with few cases of its use. However, whether post 5G or 6G technology adopts OWC is not the crucial question; rather, the technologies should be designed to coexist with each other. Research and development in OWC will continue to extend its benefits and standardize its systems so that it can be widely deployed in the market. For example, if a standard such as a VLB ID already exists, it would be preferable to develop a service that uses the standard to satisfy user demand. As one such candidate, we introduce the rolling-shutter method, which is a method to receive VLC via the smartphone camera and that can be used to implement a VLB ID system. The Panasonic LinkRay service has already started using such a system, and we can expect more from it. We also introduce a method that produces an afterimage in the smartphone camera by rotating the transmitter, which creates an effect similar to that of the rolling-shutter method.

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