Оптический журнал

Оптическое приборостроение

УДК 001; 001.8; 001.18

Optical camera communications: practical constraints, applications, potential challenges and future directions

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Submitted 02.08.2021

DOI:10.17586/1023-5086-2021-88-12-68-86

Mobile wireless communications mainly rely on radio frequency to transmit data. However, its congested spectrum cannot meet the growing requirements for future high data rate applications. Recently, optical wireless communication techniques have opened up a vast optical spectrum and emerged as a cost-effective and practical alternative to congested radio frequency wireless technologies. As a supplementary technique of high-speed optical wireless communication, optical camera communication has become very attractive due to recent developments in communications hinging on camera or image sensors in smart devices with low implementation complexity. In conjunction with the ubiquity in consumer electronics such as pads and smartphones, optical camera communication takes advantages of an image sensor or camera in areas such as intelligent transportation, vehicular communication, motion capture, indoor localization and internet-of-things. Optical camera communication and visible light communication are considered within IEEE 802.15.7m standardization. Optical camera communication based on camera and organic/inorganic light emitting diodes (LEDs) offer localization and low-rate transmission in indoor as well as outdoor applications. This paper presents a comprehensive survey of optical camera communication, principles and recent standardization activities. This survey covers multiple aspects of optical camera communication such as transceivers, multi-input and multiple-output (MIMO) and diversity. It outlines various applications of optical camera communication. It also addresses some practical constraints, modulation schemes and error correction coding techniques for optical camera communication systems. Finally, in the last section of this survey, potential challenges and future research directions are presented.

Keywords: *optical wireless communication, optical camera communication, radio frequency, visible light communications, image sensor, camera.*

OCIS Codes: *040.0040; 040.1490; 230.0230; 060.4510.*

Оптические камеры связи: практические ограничения, приложения, проблемы и направления на будущее

Syed Agha Hassnain Mohsan

Передача данных при мобильной беспроводной связи, как правило, использует радиочастотный диапазон. Однако перегруженность его спектра не может удовлетворить растущие требования

перспективных приложений с высокой скоростью передачи данных. В последнее время развитие оптической беспроводной связи (optical wireless communication (OWC)) сделало передачу в широком оптическом спектре рентабельной и практичной альтернативой перегруженным радиочастотным беспроводным технологиям. Наряду с повсеместным использованием в бытовой электронике (планшеты и смартфоны), развиваются методы, основанные на оптических камерах связи (ОКС) (OCC — optical camera communication) и датчиках изображений (image sensor, IS), перспективных для использования в таких областях, как интеллектуальный транспорт, автомобильная связь, технологии захвата движения, локализация расположения объектов как внутри, так и вне помещений, а также доступ в Интернет Вещей. Недавние разработки в области связи, комбинирующие камеры или датчики изображения с интеллектуальными устройствами с низкой сложностью реализации, делают оптические камеры связи очень привлекательными как дополнительных устройств в каналах высокоскоростных линий оптической связи.

Представлен всесторонний обзор оптических камер связи, принципов их работы и недавних мероприятий по стандартизации. Этот обзор охватывает несколько аспектов оптических камер связи, таких как приёмопередатчики, многоканальные системы (multiple-input multiple-output, MIMO) и диверсификацию. В нём описаны различные применения ОКС. В нём также рассматриваются некоторые практические ограничения, схемы модуляции и методы кодирования с исправлением ошибок для систем ОКС. Наконец, в последнем разделе этого обзора представлен анализ проблем и направлений будущих исследований.

Ключевые слова: *оптическая беспроводная связь, оптическая камера связи, радиочастота, связь в видимом свете (VLC), датчик изображения, камера.*

1. INTRODUCTION

Over the recent decades, traditional RF technologies have been significantly developed and utilized in communication. Although it is yet early to predict what the future technologies will provide, they aim at lower cost, lower power consumption, higher network capacity, enhanced spectral efficiency, lower latency and higher transmission speeds [1]. The rapidly growing digital services such as video contents, social media and pervasive connectivity of IoT has overgrown the demand for mobile data communications. According to Ericsson report, it is envisaged that total mobile traffic will increase at an annual growth rate of 42%, and monthly global mobile data rate will cross 100 exaBytes (EB) [2]. This rapidly growing data and demand for capacity has caused RF spectrum congestion. Moreover, we have witnessed incommensurate bandwidth as well as spectral efficiency due to growing traffic demands in RF domain. In a futuristic perspective, it is envisaged that high capacity and high data rate RF communications coexist with unlimited bandwidth, offloading and affordable wireless communications. In order to alleviate the RF spectrum congestion, higher frequency bands such as millimeter wave [3], terahertz [4] and petahertz [5] are under consideration. Under such circumstances, OWC has gained significant research interest due to well-controlled communication security, independent regulation, high-energy efficiency and large spectrum (350 nm – 1550 nm). OWC has emerged as a potential alternative to existing RF based communication systems. OWC is mainly divided into three technologies: light fidelity (LiFi), visible light communication (VLC) and optical camera communication (OCC). OWC technologies use infrared (IR) [6], ultraviolet (UV) [7] and visible light (VL) [8] frequencies for communication purpose. OWC offers massive bandwidth of 20 THz (IR), 320 THz (visible) and 30 PHz (UV) as shown in Fig. 1 [9].

In the visible light spectrum, VLC technologies have gained significant research interest. By considering light-emitting diodes (LEDs), it can serve for both communication and lighting applications including underwater OWC for autonomous underwater vehicles (AUVs), vehicular communication, indoor positioning and indoor high-speed internet access. Nevertheless, VLC technology suffers from both interference and limited coverage. Increasing the field-of-view (FOV) of LEDs can enhance coverage; however, it increases interference as well. In contrast to other optical sources, LEDs provide data transmission, which can be picked up by image sensors or photodiodes. Different from VLC, light-

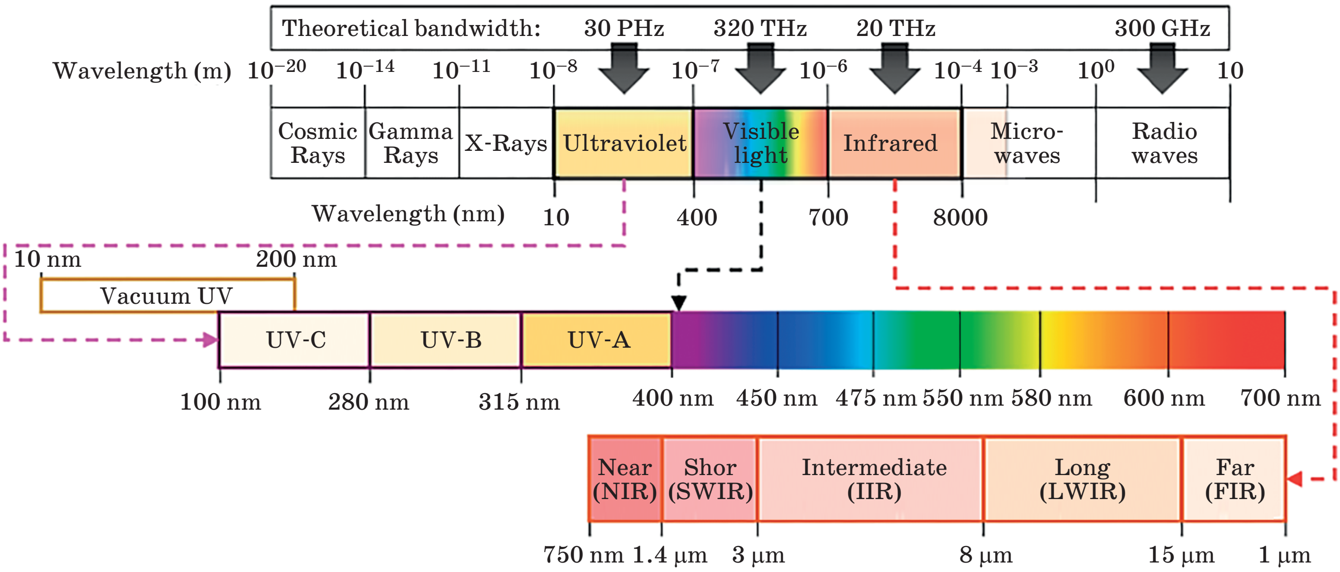

Fig. 1. The electromagnetic spectrum [9].

Table 1. Comparison between VLC and OCC

Characteristics	VLC	OCC
Protocol	IEEE.802.15.7	IEEE.802.15.7r1
Wavelength	VL	UV, IR, VL
Transmission range	Low	Up to several km
Data rate	11.67 kbps — 96 Mbps	Lower than VLC (in kbps)
Receiver	PD	Camera
Signal-to-noise ratio (SNR)	Low	High
Decoding	Low complexity	High complexity
MIMO implementation	Difficult	Easy

fidelity (LiFi) uses VL in the forward path and IR, VL or UV in the backward path. LiFi offers point-to-multipoint bidirectional communication and seamless terminal mobility. However, LiFi is vulnerable to long-distance outdoor applications. Here, free-space optics (FSO) appears as a promising candidate to achieve flexible coverage, ultra-high data rates and long-distance transmission by beamforming technologies [10]. FSO uses IR laser diode (LD) [11] as transmitter rather than LED in LiFi and VLC. However, it has high sensitivity to link alignment under physical obstructions, atmospheric turbulence and weather conditions. Consequently, the cost of FSO transceivers is high. Also, the atmospheric turbulence can be reduced by using accurate pointing and tracking methods [12–14], robust modulation techniques [15, 16] and statistical channel modeling [17, 18].

The ubiquity of smart devices integrated with cameras motivates researchers to explore several aspects of optical camera communication (OCC) [19–21]. It uses camera or image sensor in consumer electronics, such as iPads and smartphones, as an alternative to avalanche photodiode (APD) or photodiode (PD) receiver. As a pragmatic approach of VLC and owning to information carrying capability, OCC enables several services in IoT, internet of vehicles, device-to-device communication, underwater communication, in-flight service, digital signage, eHealth, color code, augmented reality, indoor positioning and localization [20–22]. However, mostly OCC systems reported in literature are used for indoor applications due to low intensity of ambient light [20]. Table 1 summarizes different characteristics and limitations of VLC and OCC [22].

Table 2. Comparison between different OWC technologies

Characteristics	FSO	VLC	OCC	LiFi
Standard	Well developed	IEEE 802.15.7	IEEE 802.15.7 m	IEEE 802.15.11 LC SG
Spectrum	IR/VL/UV	VL	IR/VL	IR/UL/UV
Transmitter	Laser	LD/LED	Screen/LED	LD/LED
Receiver	APD, PD	Camera, PIN, APD, PD	Camera	PD
Distance	>1 km	<100 m	Up to km	<10 m
Data rate	~Gbps	Mbps ~Gbps	bps ~Mbps	Kbps ~Gbps
Modulation	OAM, OFDM, PM, IM, OOK, etc.	CSK, OFDM, PM, IM, OOK, etc.	CSK, OFDM, PM, IM, OOK, etc.	CSK, OFDM, IM, OOK, etc.
Robustness to interference	–	Moderate	High	Moderate
Path loss	High	Moderate	High	Moderate
Complexity	High	Moderate	Low	Moderate
Limitation	Sensitive to turbulence and weather	Vulnerable to mobility, limited range	Low data rate	Limited range, limited use in outdoor

Compared to other OWC technologies, OCC owns unique characteristics including cost-effectiveness, wavelength separation ability and larger receiver field-of-view (FOV). In some applications like remote controlling, vehicle steering, motion over camera and navigation, accuracy and cost may be the major factors rather than data rate. However, OCC has some limitations such as random block, unstable frame rate and out-of-focus effect. The research fraternity has proposed several solutions to overcome these limitations. Therefore, the aim of this study is to facilitate novice readers about various limitations in OCC and solutions. Furthermore, technical aspects such as coding, modulation and channel modeling have been discussed. Besides, potential challenges and future directions have been discussed. Table 2 summarizes a comparison of different OWC technologies [23].

2. RELATED WORK

At a global level, a number of companies including China Telecom (China), Huawei Technologies (China), LG Electronics (Korea), Electronics and Telecommunications Research Institute (Korea), Casio (Japan), Panasonic (Japan), Intel (United States) and Fraunhofer Heinrich Hertz Institute (Germany) have been working on OCC [20]. In recent years, research interest in OCC is growing as a number of research surveys have been published on different aspects of OCC systems [9, 19–22]. In 2015, Saha et al. published a survey covering challenges and opportunities of OCC [19]. In 2017, Nguyen et al. published a survey on OCC targeting novel architecture, transmissions access, multiple-input and multiple-output (MIMO) diversity and new spectrum for 5G wireless networks [20]. In 2017, NT Le t al. provided an extant research study on the design and implementation of OCC [21]. In another survey published in 2019, Saeed et al. [22] provided a broad overview of use cases, challenges and future directions of OCC. Authors provided comprehensive discussion about OCC based intelligent transportation system, motion capture, navigation and localization. Finally, in a recent survey published in 2020, WA Cahyadi et al. [9] discussed principles and standardization activities in OCC. Authors have investigated key technical issues such as performance enhancement, interference, coverage and mobility. While this survey presents a comprehensive overview of OCC focusing on principles and modulations, together with practical constraints, research challenges, applications and future research directions. This study aims to extend practical implementation of OCC, while

Table 3. Comparison between different studies on OCC

Reference	Year	Research contribution
[19]	2015	Design and implementation of OCC
[82]	2016	Real-time CIS-MIMO OCC system
[20]	2017	OCC targeting novel architecture, transmissions access, multiple-input and multiple-output (MIMO) diversity and new spectrum for 5G wireless networks
[21]	2017	Design and implementation of OCC
[83]	2017	Smartphone image receiver architecture for OCC
[84]	2017	OCC for internet-of-vehicles (IoV)
[85]	2017	MIMO architecture for OCC
[86]	2018	Modulation and coding techniques
[87]	2018	Undersampled based modulation schemes for OCC
[88]	2018	OCC architecture and applications
[89]	2018	Performance analysis and improvement in OCC
[22]	2019	Use cases, challenges and future directions of OCC
[70]	2019	OCC for IoT based on organic LEDs
[71]	2019	OCC based monitoring system for a smart factory
[62]	2019	OCC for 3D indoor localization
[9]	2020	Key technical issues in OCC such as performance enhancement, interference, coverage and mobility
[23]	2020	Practical constraints and solutions for OCC
[90]	2020	CNN based decoding scheme for mobile OCC
[66]	2020	5G eHealth architecture based on OCC
[91]	2020	Analytical and simulation tools for OCC
[72]	2020	Vehicular Optical Camera Communication (VOCC)

disseminating emerging OCC technologies and future challenges. This work will be a good contribution for novice readers to understand OCC. Table 3 provides a comparison between different studies on OCC.

3. OPTICAL CAMERA COMMUNICATION

3.1. OCC Overview

Optical camera communication has emerged as a promising technology for the VLC systems. Different characteristics of OCC as compared with VLC and other OWC technologies are summarized earlier in Table II. It is worth noting that large transmission distance, low complexity and low cost features make OCC unique among OWC technologies. OCC was initially presented in 2001 when Leibowitz et al. [24] demonstrated FSO communication using a camera receiver. Since the past decade, several research studies have been presented on OCC for efficient designs, implementation scheme, to improve transmission range and data rates. As a standalone technique, OCC is sub-divided into three configurations as shown in Fig. 2.

In first configuration (LED2C), a single LED is used as a transmitter and a camera is used as a receiver. In second configuration (LEDA2C), LED array is used as a transmitter and a camera is used as a receiver. Second configuration is also referred as visual MIMO [25]. In third configuration (S2C), a screen is used as a transmitter and a camera is used as a receiver. Based on above three configurations, the possible transmitter in OCC systems are car lights, traffic lights, monitor screens, projectors, television screen and LEDs. A generalized block diagram

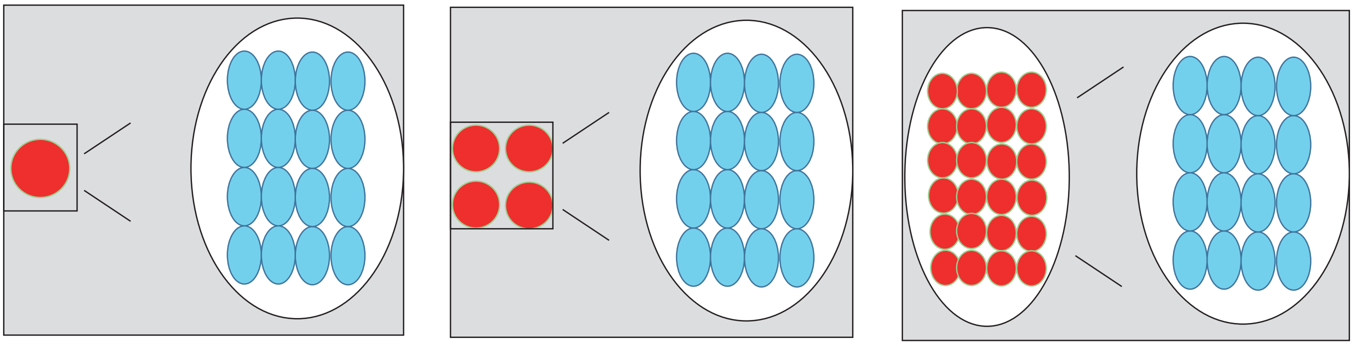

Fig. 2. Three configurations of OCC.

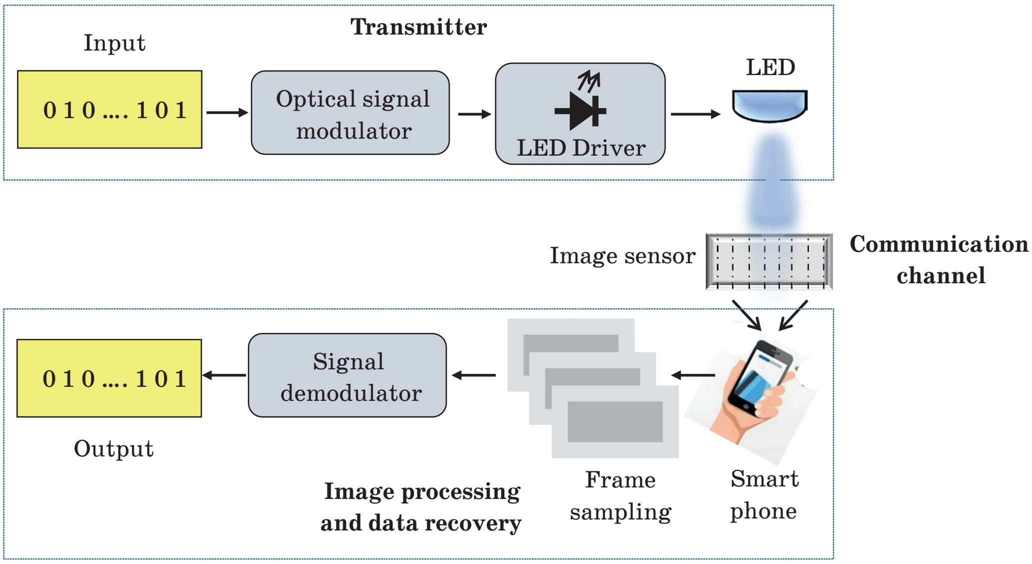

Fig. 3. Block diagram of OCC system.

of OCC system is shown in Fig. 3. Modulation technique is used to modulate data and LED driver is used to activate LED. The optical beam passes through a wireless channel and arrives at the image receiver. A shutter is used to control the exposure of the image sensor. Signal demodulation is carried out to obtain data.

3.2. OCC Principles

OCC system uses a single or multiple-camera setup as receiver, which can be seen in various mobile devices such as vehicles, tablets, laptops, smart watches and mobile phones. Existing VLC systems face limitation due to visible light spectrum while OCC systems employ different cameras to utilize entire light spectrum from VL, NIR to UV-C band. In OCC systems, camera receiver is used to capture images or video streams of the modulated light sources such as LED, multiple LEDS and digital screens. Thus, OCC can be implemented in both indoor and outdoor scenarios for an extensive range of applications [19]. Moreover, the latest complementary metal-oxide semiconductor (CMOS) sensor technologies have enabled a new era of high-speed built-in cameras [19], [21]. These high-pixel-resolution cameras support a F_R of thousands of fps [19].

3.2. OCC Transceivers

3.2. 1. OCC Transmitters

Among different light sources such as LED, halogen lamp, incandescent light bulb and fluorescent lamp, only LED is suitable for visible light communication. LEDs are perfect light sources for localization and VLC due to fast rate of on-off switching. LEDs offer a wide range of color, long lifespan, small size and high-energy efficiency. As a result, LEDs are employed in various lighting fixtures in streetlights, traffic lights, shopping malls, offices and homes. There are different ways to produce white LEDs such as:

• Blue LED + yellow phosphor—the white light is produced due to yellow photoluminescence (PL) emission and blue electroluminescence (EL) emission.

• Ultraviolet LED + red green blue (RGB) phosphors — here white light is produced due to RGB phosphors excitation by UV LED.

• RGB LEDs — here individual red, green and blue LEDs form white EL emission.

RGB LEDs enable parallel transmission of three independent signals. However, it requires three PDs for VLC communication. Thus, it makes parallel transmission bulky and complex. On the other side, camera based receiver can easily separate RGB channels and image sensor (IS) has a built-in color filter. These features make RGB LEDs suitable for OCC systems.

3.2.2. OCC Receivers

The selection of OCC receiver impacts the choice of transmitted signal formats by LEDs. Notably, different types of cameras are commercially available which limit the performance of OCC system. Thus, appropriate cameras must be chosen on the basis of below mentioned characteristics on the communication performance.

• The primary mechanism of signal acquisition by the camera is frame rate. Smartphone camera operates at a lower frame rate of 30 fps while high-speed cameras may reach up to 1000 fps or higher.

• The shutter mechanism decides the pixels exposure in an image. Cameras are classified into rolling and global shutter classes on the basis of shutter mechanism. Rolling shutter cameras require fast sampling in order to detect the change of light intensity in the rolling images. Whereas global shutter cameras require fast frame rate in order to detect the changing light intensity modulated in the consecutive images.

3.3. MIMO and Diversity

MIMO, diversity and multiplexing are promising techniques to enhance performance of any communication system. These techniques can also be incorporated to achieve better performance. An additional light source is utilized to enhance throughput in multiplexing and transmission robustness in diversity. The receiver obtains a better signal with a higher SNR. Image sensor based communication systems have more benefits with MIMO techniques. Image sensors can be used as multiple receivers. A computer algorithm can be operated to separate transmitter sources. OCC systems have the capability of MIMO implementation. An overview of a visual MIMO OCC is displayed in Fig. 4. With a proper directional view, it mitigates interference and noise from ambient light sources. The performance of OCC system can be enhanced by MIMO functionalities. MIMO functionalities offer multiple access conveniences and higher data rate through spatial multiplexing. Luo et al. [26] stated that communication distance can be significantly enhanced by MIMO through RGB LEDs. MIMO capability makes OCC suitable for various applications such as scene detection, shape detection and range estimation.

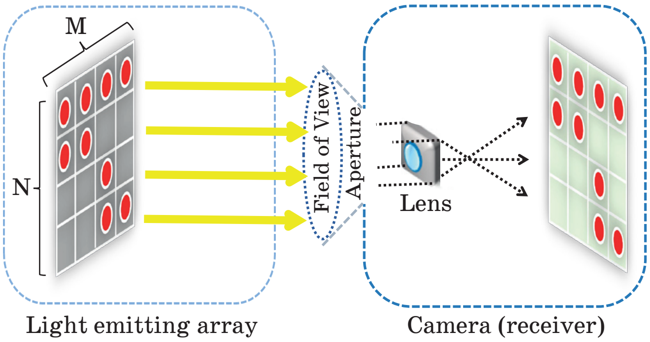

Fig. 4. Visual MIMO OCC.

3.4. IEEE Standardization Issues for OCC

Technical considerations document (TCD) is an essential aspect of IEEE specification as it covers guidelines for important specification requirements. It provides application scenarios and fundamental requirements for practical implementation in any proposed architecture. The IEEE standards for optical spectrum are IEEE 802.15.13 (Li-Fi), IEEE.802.15.7m (OCC) and IEEE 802.15.7-2011 (VLC). OCC is considered an extended version of VLC standard IEEE 802.15.7-2011. The VLC standard led researchers to formulate OCC standard. Therefore, it was essential to develop a task group to develop OCC standard including OCC system architecture, transceivers, media access control (MAC) and physical (PHY) layers specifications. In 2014, a task group named as TG7m was introduced to find technical requirements of OCC [27]. TG7m includes UV (100-400 nm), VL (400-700 nm) and NIR (700-1000 nm) bands. This task group contributed in OWC solutions including LiFi, LED identification and OCC. Later, OCC standardization has been in process by IEEE 802.15.7r1 task group TG7r1 [9, 28].

3.5. Modulation Techniques

There are several modulation techniques for OCC such as on-off keying (OOK), color-shift keying (CSK), pulse width modulation (PWM), spatial 2-phase shift keying (S2-PSK), color intensity modulation (CIM), multilevel intensity-modulation (m-IM) and variable pulse position modulation (VPPM) etc. The main issue in all OCC modulation techniques is flickering. While flicker-free techniques are limited to short distance. The most common modulation technique for OCC is OOK. However, high flickering LED leads to a lower data rate and low transmission distance. To overcome communication distance problem, researchers have investigated undersample OOK modulation such as undersampled frequency-shift OOK (UFSOOK) and undersampled phase-shift OOK (UPSOOK) [26, 29]. UPSOOK can be implemented by using RGB LEDs for long distance communication [26]. Furthermore, to overcome data rate issue, researchers have investigated new mopdulation schemes. Rachim et al. [30] achieved 10 kbps data rate by using m-IM technique. Tian et al. [31] achieved 95 kbps through color intensity modulation by combining CSK and PAM. Goto et al. [32] obtained 55 Mbps through orthogonal frequency division multiplexing (OFDM). Thus, these modulation techniques are adopted according to sevices scenarios. Implementation of these schemes has different requirements. Table 4 summarizes different modulation schemes for OCC and their features.

3.6.Error Detection Coding Schemes

Error correction coding and decoding schemes for OCC have gained focus of research community. In [33], Danakis et al. proposed Manchester coding based encoder and decoder for OCC. In [34], T. Li et al. demonstrated real-time screen-camera communication using an alpha channel based enconding scheme. Furthermore, J. Hu et al. [35] proposed RGB coding technique in order to increase data rate for OCC. Similarly, S. Nishimoto et al. [36] demonstrated an overlay coding scheme to further enhance data rate. The authors in [37] proposed robust dynamic barcode to improve realibility in order to boost throughput of OCC system. Later, Wang et al. [38] propsed Rainbar coding scheme by improving color barcode to enable flexible synchronization for robus localization. In [39], W. Du et al. used an adaptive approach Soft-Light which adapts data rate on the basis of quality of the link. Shi et al. [40] achievd 4.32 kbps data rate by using hybrid OOK and Manchester coding. Zhang et al. [41] proposed reed-Solmon coding to detect ultra long IDs of LEDs

Table 4. Comparison between modulation schemes for OCC

Reference	Modulation scheme	Distance (m)	Data rate
[92]	OOK	0.5	0.3 kbps
[93]	PWM	0.1	9 kbps
[94]	CSK	0.5	0.24 kbps
[82]	CIM	1.4	126.7 kbps
[95]	Hybrid OOK-PWM	1.5–5.5	0.62–1.35 kbps
[96]	UPSOOK	12	0.15 kbps
[97]	UFSOOK	4	15 bps
[30]	m-IM	2	$>$ 10 kbps
[98]	OFDM	10	12 Mbps
[32]	DCO-OFDM	1.5	55 Mbps

Table 5. Comparison between coding schemes for OCC

Reference	Coding scheme	Data rate	Complexity
[35]	RGB coding	450 kbps	Moderate
[36]	Overlay coding	0.25 kbps	Low
[37]	Robust dynamic coding	17 kbps	Moderate
[40]	Manchester coding	4.32 kbps	Low
[41]	Reed-Solomon coding	-	Moderate
[99]	QR codes	31 Mbps	Moderate
[73]	Alpha39 coding	2.46 kbps	Low
[53]	BCH coding	10 Mbps	High

for reducing the complexity and improving the localization. Table 5 summarizes the characteristics of different coding scheme for OCC.

4. PRACTICAL CONSTRAINTS

4.1. Visual Constraints and Solutions

There are pervasive electronic displays such as TVs, electronic advertising boards, computer monitors, tablet screens and smartphones. Due to ubiquity of these electronic displays, a new OCC architecture named as camera-screen communication (CSC) has been becoming popular for quick information acquisition. A commom example of CSC is quick response (QR) code [42] which presents data in 2D barcodes. In recent years, several new QR code like tag forms with enhanced security, reliability and improved communication capabilities have emerged. A colour barcode COBRA based on five colors was propoed to achieve higher capacity [43]. However, additional colors can cause decoding errors. In [38], Wang et al. proposed RainBar color coding for accurate data extraction, flexible frame synchronization and high capacity. However, these proposed techniques are perceptible to human eyes. Generaly, users are inclind to enjoy a normal full-screen. This type of CSC is known as hidden CSC or covert CSC leading to a visual constraint for human eyes. Researchers have made tremendous efforts regarding communication performance and visual contents. T. Li et al. [34] realized a real-time covert CSC system and discussed different aspects of viewing angel, hand motion, ambient light and transmission distance. In [44], authors proposed a dynamic and invisible messaging approach for a visual MIMO optical system. Nguyen et al. [45] demonstrated adaptive encoding approach to achieve unnoticeable flickering and high throughput. These covert CSC systems make a trade-off between visual experience and communication performance including BER and data rate. However, these traditional methods cannot meet the booming demands of imaging and high-definition videos. Thus, researchers should investigate more efficient embedding techniques for better user experience.

4.2. Frame rate constraints and solutions

As we know that a commercially available camera has low frame rate of about 30 fps, it puts restrictions on maximum symbol rate below 15 fps. Low frame rate will cause a serious flickering which is hazardous for human eyes. Moreover, commercially available cameras undergo fluctuaion due to unstable sampling rate. These issues can be overcome by appropriate modulation schemes to enhance data rate, by exploring roller shutter, employing high-speed camera and tracking the frame rate instability [23]. Apart from existing standard modulation schemes, research fraternity has proposed various modulation scheme as given in Table IV to obtain high spectrum efficiency and match the low frame rate camera. Furthermore, high-speed cameras have been introduced for reliable performance of high-frame rate processing to meet requirements of OCC applications. Additionally, effective synchronization methods should be adopted in OCC systems to overcome data rate and perceptible flickering issue.

4.3. Link blockage and non-line of sight solutions

Non-line-of-sight (NLOS) or link blockage is a major issue in OCC as mostly OCC systems rely on line-of-sight (LOS) path. This problem emerges when transmitter is not within field-of-view (FOV) of receiver such as a wall blocks the link between smartphone and lamp in an indoor scenario. In such conditions, it is not possible to establish a direct link. In constrast, a non-line-of-sight (NLOS) OCC link such as indoor surface reflections or outdoor atmospheric scattering are explored. Figure 5 presents typical NLOS OCC scenarios in indoor and outdoor environments.

4.3.1 Indoor reflective non-line of sight

Mostly OCC systems have been studied for indoor LOS communications. However, due to limitation of camera FOV, an LOS link suffers from blockage or shadowing, which limits the performance and mobility [46, 47]. Thus, OCC through an NLOS link appears to be a promising solution to achieve strong robustness to mobility and blockage. It can establish communication links by leveraging the light reflections from ceiling or walls. However, it may suffer from inter symbol interference (ISI) or high path loss. In [48], Wang et al. proposed rolling shutter pattern demodulation algorithm on the basis of light reflections from wall. In [49], Hassan et al. demonstrated 2×N indoor NLOS OCC system to enable a 30 fps data transmission rate at 5m distance. Thus, NLOS OCC can maintain a stable communication link with strong robustness to mobility and blocking in an indoor environment.

4.3.2 Outdoor scattering non-line of sight

Sometimes receiver FOV is unable to receive transmitter beam in outdoor scenarios. For example, communication links undergo shadowing due to high buildings. Vehicles moving in a perpendicular direction cannot find each other. Thus, NLOS scattering in outdoor scenarios is essential. With the ubiquity of smartphones equipped with flash LEDs and cameras, OCC NLOS scattering communication becomes a promising solution for outdoor applications like remote control instructions or steering information for vehicles. Liu et al. [50] predicted and experimently validated distant NLOS image sensor based communication. Authors conducted experiments to check long distance impact and camera noise characteristics.

5. APPLICATIONS

OCC system is not flexible like RF communication due to low speed and LOS restrictions. However, cameras have special features like RF effect, RGB filter and spatial separation ability. It offers unique features in OCC systems such as data detection from static and dynamic images, non-flicker data transfer and supporting MIMO functionalities. Therefore, aforementioned features make OCC suitable for a wide range of applications including eHealth, vehicular communication, indoor positioning, localization, smart cities, intelligent transportation system and IoT based applications.

5.1. OCC-based Intelligent Transportation Systems

LEDs offer both lighting and communication with low heat generation and low power consumption.

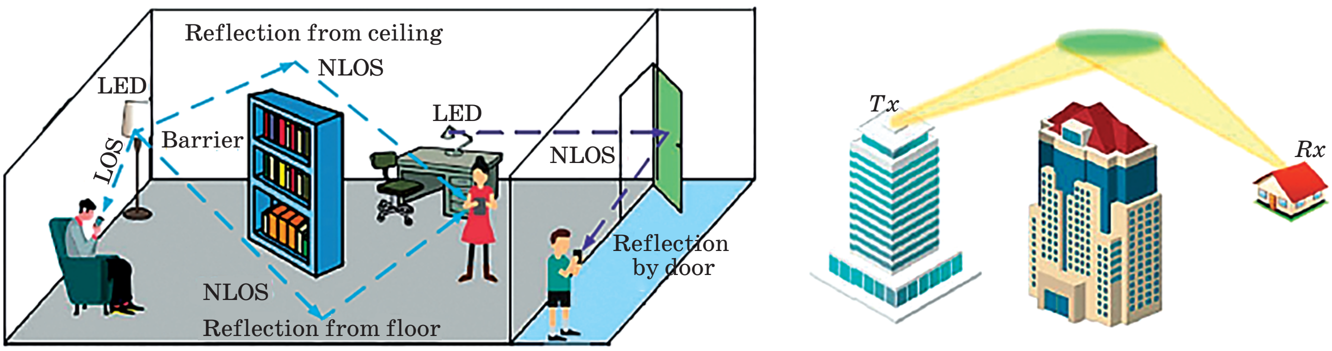

Fig. 5. NLOS OCC indoor and outdoor scenarios [23].

These features make LEDs suitable for intelligent transportation system (ITS). LEDs based ITS is useful in regulating traffic and reducing traffic accidents. ITS offers a great potential to address environmental effects, improve traffic flow and enhance the traffic safety by communication between vehicles or roadside infrastructure and monitoring driving behavior. For example, LED based vehicle brake light can produce warming signal to infrastructure or approaching vehicle (V2I/V2V). In ITS, OCC provides distinctive advantages including (i) low level of interference and high scalability, (ii) high precision pointing depending on LOS path and (iii) low cost and low complexity. Additionaly, OCC based ITS enables both V2I and V2V communication. Furthermore, cameras integrated in vehicles can receive optical signals from signage, brake lights, headlights or traffic lights. The notable requirement of OCC-based ITS is high-speed capturing and extraction of the data to provide flicker-free LEDs. This issue of selective capturing was addressed in [51] and [52] with a realistic camera with 60 fps. In [53], authors achieved 10 Mbps data rate using OCC system for V2V communication. In [54], T. Yamazato et al. provided OCC based ITS for V2X communication.

5.2. OCC-based Localization and Navigation

Positioning systems based on location-based services (LBS) are used to find user location [55]. The most common positioning system used in surveillance, tracking and navigation is global positioning system (GPS). However, GPS suffers from inaccuracy and limited coverage in harsh environment like indoor and urban canyons. Therefore, several indoor positioning systems (IPS) have been designed to overcome limitation of GPS. These IPS are based on different wireless technologies including Zigbee, infrared, acoustic, Bluetooth, WiFi and radio frequency identification (RFID). Recently, researchers have used VLC for indoor positioning systems [56, 57]. Researchers have proposed a number of localization algorithms for VLC and OCC based IPS [58, 59]. S. Yoshizawa et al. [60] demonstrated visible light beacon-based IPS enabling millimeter level of accuracy. In [61], authors have presented an in-depth survey VLC based positioning systems. In [62], authors have demonstrated OCC based 3D indoor localization. M. Hossan et al. [63] proposed a novel indoor mobile localization system based on OCC.

5.3. 5G eHealth architecture based on OCC

OCC can be used as an alternative approach to traditional RF technology for for self-healthcare monitoring systems. G. Sato et al. [64] developed OCC based system and highly precised novel event timeing encoding method with the capability to measure heart rates (HRs) of multiple people with positioning information. VP Rachim et al. [65] demonstrated RGB LED based OCC for healthcare applications. Authors

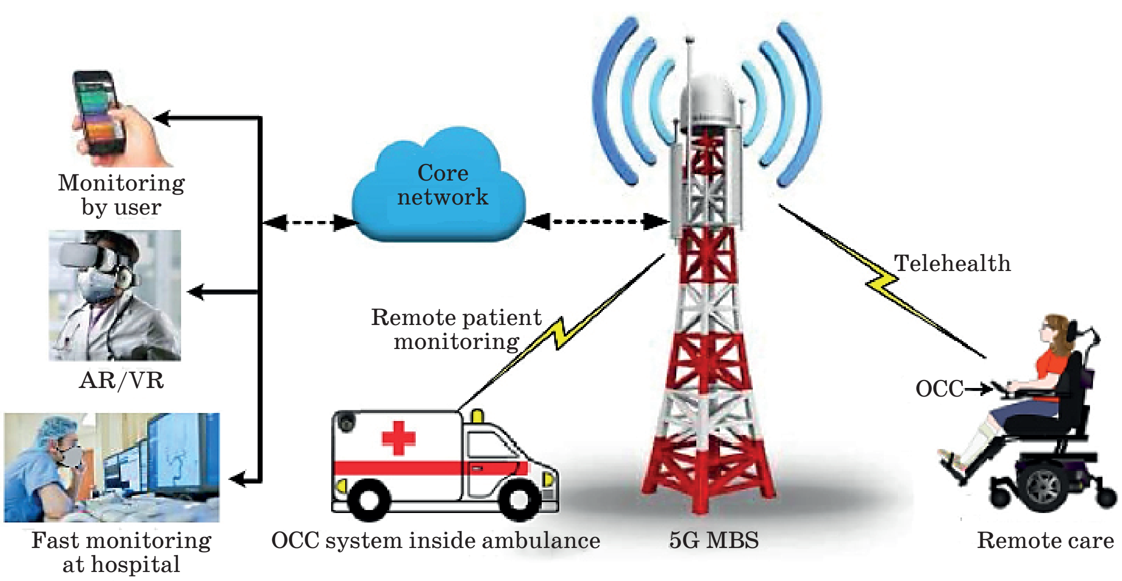

Fig. 6. OCC based remote patient monitoring [66].

have proposed a multilevel variable pulse position modulation scheme for wearable biomedical data monitoring system. In a recent study, researchers have proposed a novel idea of a low latency and reliable 5G based eHealth monitoring system [6, 7]. This OCC based eHealth system has the capability to monitor patients remotely. Proposed system offers highly reliable communication for 5G networks to sensors/patches. In this system, the patients have wearable patches or sensors with LEDs. These wearable patches or sensors measure health data such as blood pressure, pulse rate, electromyography (EMG), photoplethysmogram (PPG), electroencephalogram (EEG) and electrocardiography (ECG), while LEDs are used to transmit this information. The OCC system obtains this health data and forwards it to the desired destination such as smartphones, servers, doctors or hospitals. This OCC system enables remote monitoring of multiple medical parameters of multiple patients for healthcare systems. It is a promising candidate to provide human-free assistance during the outbreak of contagious diseases such as COVID-19. It can remotely monitor patients or provide assistance to robot-assisted OCC systems in hospital to give food or medical supplies to the affected patients. However, remote monitoring systems must meet security, reliability and wearability requirements. This OCC based eHealth system can be employed in different scenarios such as OCC based system installed in an ambulence as shown in Fig 6. The doctors can also remotely monitor patients while transporting by an ambulence.

5.4. OCC based IoT Connectivity

Recently, IoT has proclaimed its potential by supporting communication between billions of devices such as sensors [67]. By enabling seamless connectivity, it offers data exchange between device to device, objects and humans to efficiently use resources and enhance the quality of life. It also opens an era of innovations by providing smart services in smart factory, smart city and smart home applications. OCC is a booming technology which can support the growing requirements of IoT networks. By applying OCC technology, an extensive range of applications can be enabled for IoT networks.

OCC does not use RF waves which makes it suitable for long distance IoT communication. With capability to mitigate interference effectively, OCC offers high security for IoT networks. Figure 7 presents a basic architecture of OCC based IoT connectivity. All the data from various devices, patches, sensors can be collected and monitored by using camera in OCC systems in IoT network. All patches, sensors have integrated LED or LED arrays for transmitting data simultaneously to camera of various smart devices such as intelligent robot, head-mounted display (HMD) and CCTV [68]. After receiving data at camera from multiple devices, OCC system will process data and will pass it to gateway through wired or wireless network. Furthermore, data will be forwarded to backhaul networks such as 5G or satellite networks. In last, data will be stored in server or cloud for IoT based applications.

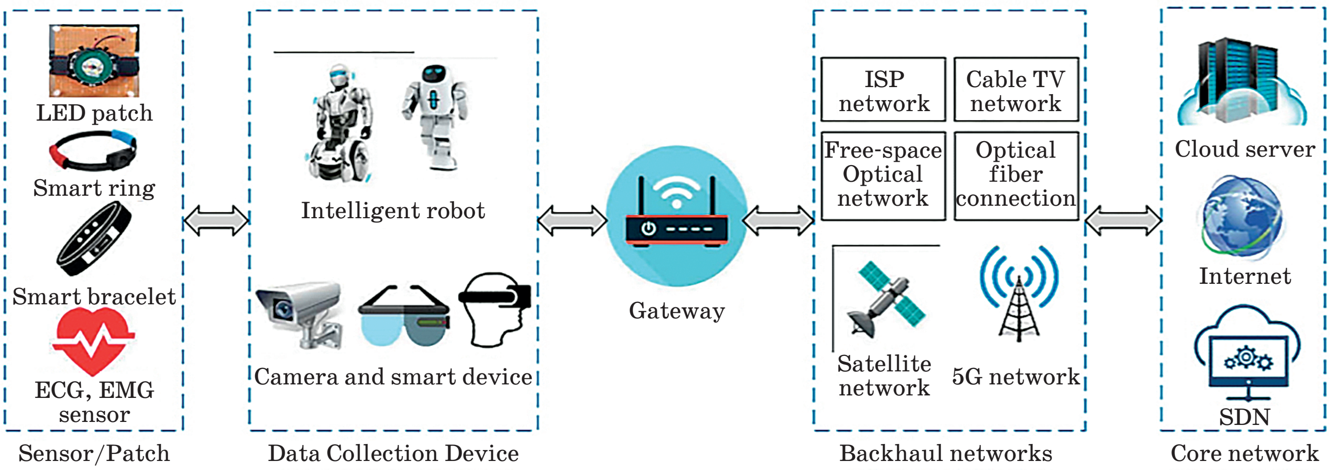

Fig. 7. OCC based IoT connectivity [68].

5.5. Role of OCC in 5G and B5G

It is envisaged that OCC, using both NIR and visible light, will become an integral part of future communication systems envisioned in 5G and B5G [9]. It is due to the fact that frequencies ranging from 100 GHZ to 3 THz, containing both NIR and VL, will be emerging communication bands for the future wireless networks. 6G technology has been envisioned to emphasize on increasing its massive bandwidth and massive interconnectivity among wireless devices. For realization of future 6G, it is essential to ensure various available wireless communication techniques. Being an important component of OWC technologies, OCC has a key role in future wireless communication beyond 5G. Meanwhile, unmanned aerial vehicles (UAVs) have become a major part of 5G and IoT [69]. It is worth noting that multiple cameras are mounted on UAVs to watch, record and communicate effectively. Thus, OCC-assisted UAVs have great potential for significant benefits beyond 5G wireless networks.

5.6. Other Applications

Other interesting applications of OCC include IoT [70], monitoring system for smart factory [71], vehicular communication [72], mobile payments [73], motion capture [74], internet of vehicle (IoV), smart cities [75], underwater environment [76], drone-to-drone communication, digital signage and augmented/virtual reality.

6. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

Despite numerous promising features of OCC technologies, there are several challenges which limit practical implementation. For example, current studies focus on simplex communication while there is a gap in full-duplex communication. Besides, OCC may be operating under harsh ambient radiation from advertising boards, street lamps and solar irradiance. Moreover, LEDs exhibit nonlinear distortion which must be mitigated for real-time implementation. To overcome these limitations and improve the communication data rate, modulation scheme integrating with frequency, phase, spatial and color must be adopted. Furthermore, high quality image sensors must be developed to enable higher sensitivity, wide dynamic range, high resolution and high frame rate. This section summarizes several research challenges and future directions for OCC.

6.1. Modeling of Ambient Light

OCC systems exhibit vulnerability to ambient light sources. Ambient light orignates error in decoding process resulting into original data loss. Ambient light also introduces flicker noise which causes drastic decrease in OCC system performance. Most of the existing studies have neglected the impact of ambient light such as CamComSim [77] and CeilingTalk [78]. One important solution to remove noisy pixels is to consider high speed cameras with 1000-10^6 fps [79].

6.2. Defocusing

Defocusing occurs when transmitter source and receiver camera mismatch. It is an inevitable issue which causes distortion. Furthermore, another challenging issue is blur. Researchers should focus to investigate the combined impact of blur and defocusing in OCC systems.

6.3. Synchronization

The problem of synchronization arises due to mismatch between transmitter and receiver candidate as mostly existing cameras have low and diverse frame rates. For example, frame rate of smartphoen camera is 30 frames per second while LED has 30-60 frames per second. Therefore, mixing the frames or losing frames occurs at the receiver. Thus, researchers should investigate new synchronization techniques for OCC systems.

6.4. Hybrid Systems

The hybrid systems combine two or more different technologies such as acoustic/optical, optical/optical and RF/optical [80]. Hybrid networks can play an essential role in interference reduction, security enhancement, remote wireless connectivity, high energy efficiency, seamless mobility, link-reliability, smart handover, optimum resource allocation and load balancing. In terrestrial perspective, we can use both optical/optical e.g. OCC/FSO and RF/optical e.g. WiFi/LiFi hybrid systems. OCC can be integrated with both optical and RF systems. For example, Nguyen et al. [81] proposed a hybrid VLC/OCC system for versatile indoor applications. Proposed system reduces deployment cost for indoor optical wireless systems and facilitates users to obtain data regardless of their device.

6.5. Robust Image Processing Techniques

The OCC system receives data in the form of images and therefore it needs robust and reliable image processing techniques to extract original data. Recent researchers have introduced deep and neural networks to solve complexity issue of image classification and recognition. As major services of OCC systems such as motion capture, navigation and localization depend on image processing techniques, therefore efficient algorithms are required to enhance the performance for these services.

6.6. Medium Access Control

Existing studies on OCC have focused on physical layer issues while network and MAC layers are yet to be explored. Novel MAC protocols should be developed to overcome different challenges in OCC systems regarding mobility, MIMO, defocusing and low frame rate.

6.7. Higher Order Modulation Formats

As vehicles move at a high-speed in V2V communication, it is envisaged that transmitted packets are captured instantly at receiver, prior to the complete scenario being changed significantly. Thus, given that the data rate is fixed, multi-carrier and higher-order modulation schemes may be utilized to maintain the packet size as short as possible with a low probability of packet loss or error.

6.8. Atmospheric Phenomena

The changes in temperature along with dust, fog, smoke, fog and rainfall can severly impact resulting picture from camera. Depending upon the atmospheric conditions, the light can be reflected, scattered, diffracted and absorbed so that the received optical power can be substantially attenuated resulting in location changes in region of interest (ROI) of camera. Moreover, fluctuations in refractive index of air can also cause distortion in the resulting images.

6.9. Data Rate

OCC based on smartphones face low data rate problems. Multiple LEDs can be used to overcome these problems. Color intensity modulation (CIM) has been proposed for RGB LED to enhance data rate but it suffers from short communication distance. Researchers should find solutions to achieve considerable data rates.

6.10. Communication Distance

OCC based on VLC is limited to short communication distance. Communication distance can be enhanced by using a large transmitter but it offers low data rates. Research fraternity should investigate possible solutions in this regard to achieve considerable communication distance.

6.11. Motion over Camera (MoV)

MoV can face detection issue in mobility scenarios. In order to ensure reliability, deep learning algorithms can be implemented for accurate detection. The detection system can be trained according to the movement of users. By using all possible observations, a database can be constructed. Furthermore, OCC based MoV can be improved by using modified key frame configuration, modulation scheme and advanced cameras for indoor applications.

7. CONCLUSION

This paper presents a comprehensive survey on optical camera communication. It covers different aspects of OCC which includes principles, IEEE standardization activities, modulation schemes and error correction coding schemes. Firstly, this study provides an overview of OCC and research contributions discussed in literature. Furthermore, this paper includes a discourse on the practical constraints including frame rate constraint, visual constraint, link blockage and promising solutions. Finally, this paper discusses several application scenarios, potential challenges and future directions. This survey will help novice readers to understand OCC and current developments of OCC in multiple perspectives. It is envisaged with ongoing research and technical advancements, OCC will offer great potential in next generation of wireless technologies.

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