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Survey on optical camera communications: challenges and opportunities

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Abstract: Wireless technologies based on radio frequencies (RFs) have always dominated other types of wireless technologies up until now. However, the recent proliferation of media-rich smart devices has pushed the RF spectrum usage to its limit. Therefore RF band expansion towards the optical spectrum is imminent in commercial scale. Indeed, the research on wireless communications using the optical spectrum has gained tremendous ground during the past couple of decades and standardised, respectively, by infrared data association for infrared communication and IEEE 802.15.7 for visible light communication. However, only few shortcomings of the IEEE 802.15.7 standard have led to the development of a revised version, called IEEE 802.15.7r1. This article provides an insight on the activity of the proposed revision of IEEE 802.15.7r1. The proposed revision version targets communication systems that mainly use either image sensors or cameras, known as the optical camera communications (OCC). Leveraging the existing infrastructure, OCC systems will be able to provide ubiquitous coverage in both indoors and outdoors. The authors present their survey focusing on the key technology consideration in IEEE 802.15.7r1, current research status, impairments, enhancements and futuristic application scenarios of the OCC systems.

1 Introduction

In recent times, we have witnessed an unprecedented growth in the wireless device technology along with numerous groundbreaking wireless innovations. These innovations have significantly improved wireless communications. Along with cellular services, modern wireless devices accommodate a range of multimedia services, such as internet protocol television, videoconferencing, gaming and social-networking. These services require a tremendous amount of bandwidth and ubiquitous network coverage for apposite functionality. With radio frequency (RF) spectrum crisis looming large, several techniques, such as spectrum aggregation, multiple-input–multiple-output (MIMO), coordinated multi point and last but not the least small cell technology have been introduced in order to bridge the gap between traffic demand and achievable network capacity. However, in addition to their advantages, aforementioned technologies have disadvantages that ultimately lead to limitations in the achievable network capacity. For example, small cell technology aims to increase spectral efficiency gain by attempting to densely reuse frequencies. However, dense small cell deployment requires complex coordination among small cell antennae, introduces interference in practical cases, thereby tending to reduce the achievable network capacity. Therefore expansion of the RF band towards the optical frequency (OF) is the best possible solution. Optical wireless communication (OWC) system is likely to be a part of the future heterogeneous network as a complementary option to RF, and in contention to be featured in fifth generation (5G) network [1]. The unregulated and unused spectrum in the optical domain, that includes the spectrum of infrared (IR), visible light (VL) and ultraviolet (UV) regions, can provide new spectrum opportunities for wireless communication.

OWC was first employed by Alexander Graham Bell in 1880 [2] to transmit voice over a wireless link using light waves. A device named photophone was used for transmitting data by modulating sunlight beam. In spite of the early inception of OWC, RF communications excelled in terms of research and applications, simply because of the lack of advanced optical components. However, the improvement of optical device manufacturing and semiconductor technology led to an OWC resurgence in the early 1970s [3], where signal transmission using OF was achieved using glass fibre. In [4], a novel OWC system was proposed using IR radiation at 950 nm wavelength. Subsequently, OWC using IR was subjected to extensive research during the 1980s and 1990s [5]. Indeed OWC using IR became popular, and was standardised by infrared data association (IrDA) [6], and implemented for short-range communications spanning a number of applications.

OWC using VL spectrum, also known as VLC was gained popularity only a decade ago. The potential of using VL for wireless communication was first demonstrated in [7], where audio signal was transmitted using VL. The VL emission of LED was modulated and encoded with an audio signal and received by maintaining direct line-of-sight (LOS). A typical VLC system uses LED as the transmitter. The light intensity of the LED is modulated according to the data to be transmitted. The intensity modulated light is then detected by the photodiode (PD). Inspired by the availability and the possibility of gaining access to bandwidths of hundreds of terahertz, communication protocols for VLC has been proposed in the IEEE standard 802.15.7 [8]. However, standardisation of VLC was fist initiated by Japan-based VL communication consortium (VLCC) to standardise ubiquitous VL indication, illumination light, intelligent transport systems (ITSs) VL communications and so on. The IEEE 802.15.7 standard describes the use of VLC for wireless personal area network, merging data communications and lighting application together. Certainly, VLC is becoming a feasible option for wireless communication and subjected to A tremendous amount of research worldwide.

Recently, a new optical communication technique called optical camera communications (OCC) has been proposed [9]. OCC allows the use of huge unregulated 10 000 nm bandwidth in the optical domain, spectrally located between microwave and X-ray wavelengths, as shown in Fig. 1. In this system, an image sensor and/or a camera has been proposed to be used as potential receivers to demodulate the transmitted signal modulated according to on–off keying (OOK). OCC is the pragmatic version of VLC, implementable using smart device camera [10], which allows easier implementation of various services into smart

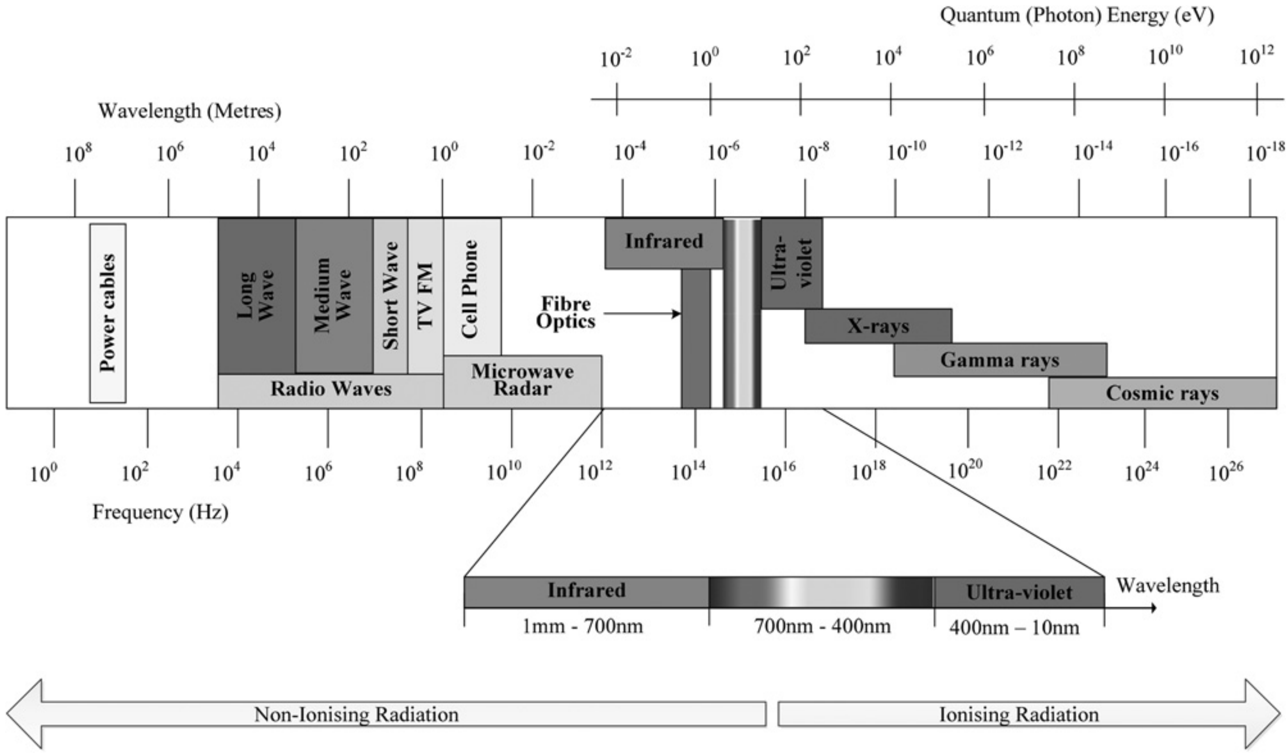

Fig. 1 *Electromagnetic spectrum range*

devices. The OCC revision effort based on IEEE P802.15.7 project authorisation request (PAR), proposes a physical layer to support OCC functionalities and MAC modifications in order to accommodate the OWC link.

The rest of the paper is structured as follows. In Section 2, a synopsis over OCC is presented, where we discussed about spectrum opportunities in the OCC system, transmitters and proposed receiver. In Section 3, we discuss about several deployment challenges of OCC systems. In Section 4, various OCC research challenges, such as modulation schemes, optical MIMO, medium access control (MAC), the logical link control (LLC) problem, multiple access techniques, different positioning techniques along with a comparison table summarising their features, and uplink are covered and discussed. Section 5 briefly describes future application scenarios. Section 6 provides an insight on current standardisation status of OCC and its commercialisation. Finally, the paper concludes in Section 7.

2 Optical communications for camera overview

The possibility achieving high data rate in the order of several Gbps, using low cost commercial VL LEDs and PDs created excitement in both academia and industry. To date, achieving such data rate has only been accomplished in laboratory prototype and it has not yet been deployed commercially. Several standards are available for VLC system with 100 Mbps data rate, for example, IEEE 802.15.7 which permits data rate up to 96 Mbps. IEEE 802.15.7 however, does not allow the use of image sensor as receiver. Today, there exist millions of smart devices. Because of the phenomenal improvement in smart devices technology in the past few years, the majority of these devices are equipped with LED flash and front and/or rear cameras. This opens a possibility of pragmatic form of VLC implementation for these devices that use a flash and a camera as the transceiver pair, without a need to enforce additional hardware modifications. Surely, there is a growing interest for VLC implementation using LEDs and displays for wireless data transmission, and with the use of the camera as the receiving module. Considering this fact, draft PAR has been submitted to revise the IEEE 802.15.7 standard. The revision version will address the necessary changes required for OCC physical layer and MAC layer, aiming to trigger commercialisation in massive scale. Also listed below, are the features of the revision version IEEE 802.15.7r1 that support functionalities for the system referred to as the OCC system.

2.1 Wider spectrum

OCC spans a much wider spectrum compared to the spectral regions of the VLC, defined in accordance to IEEE 802.15.7, and RF systems. The proposed revision version IEEE 802.15.7r1 defines a physical layer supporting OCC functionalities using light frequencies over the spectral range of 10 000 nm, spanning wavelength values from IR to 190 nm. Fig. 1 shows the electromagnetic spectrum range specifying the IR, VLC and UV spectrum regions. Therefore OCC deployment using such a broad spectral region will not only allow usage of this unregulated and unused spectrum regions, but also alleviate the currently congested mobile communication traffic. However, only some of these spectrum regions are suitable for wireless communications. For example, wavelength values within the range of 780–950 nm are currently the best choices for IR-based OWC systems [11]. The UV-C band is suitable for wide field of view (FOV) application [12]. In case of VLC, performance variation is observed for different wavelength channels. In addition, the modulation bandwidth of the commercial LEDs is in the region of 20 MHz, thereby representing a major obstacle for achieving high data rates. On the other hand, OCC uses a camera-based receiver. As a result, the data rate of the OCC system is limited by the camera frame rate. Nevertheless, the broad OCC spectrum availability is undoubtedly preferred to support high-speed applications compared to the RF spectrum.

2.2 Transmitters

The OCC system aims to use commercial LED lighting sources that include, LED-based infrastructure lighting, LED flashes, LED tags, displays, laser diodes, image patterns, some current generation

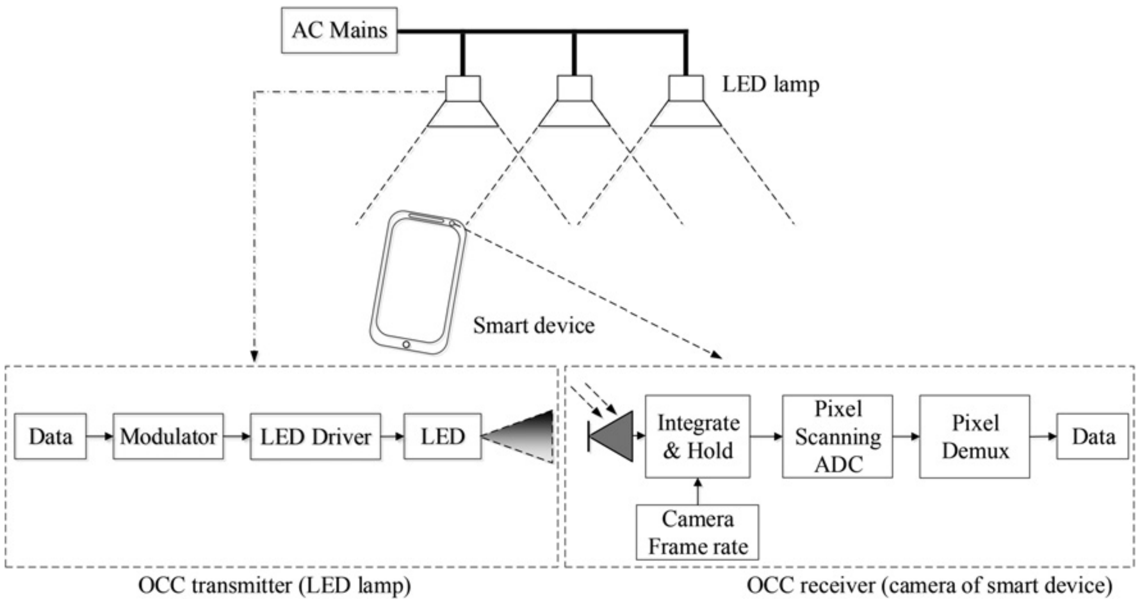

Fig. 2 *Schematic of OCC system [15, 16]*

projectors, as well as the other targeted light wavelengths for transmission. The major driving forces of OCC deployment are the widespread availability of VL LEDs, including uses for indoor lighting, traffic lights, rear and front lights of vehicles, road side luminaire, outdoor LED signage and the possibility of utilising the camera in the smart devices to decode LED modulated data. The emerging LED lighting systems are already equipped a with pulse-width modulation (PWM) dimming circuit. Therefore these LED infrastructures can be used for data transmissions using OOK with little modifications to their existing circuitry and in such a way that LED flickering effects will be imperceptible to the human eye. Some of the state-of-the-art smart devices have built-in IR support which can be used to provide uplink. For wider FOV and non-line-of-sight (NLOS) applications, UV is a viable option [12]. Displays are also capable of transmitting information and therefore can act as a transmitter. In order to transmit information using the display, specific colour of several areas of the display is changed in a manner that human eye is unable to recognise it. Casio and Fujitsu developed such display – camera-based OCC system [13, 14], capable of transmitting at a rate of 5 and 16 bps, respectively.

2.3 Receivers

A typical OCC system is shown in Fig. 2, where camera is used as a receiver. The OCC system based on IEEE 802.15.7r1 aims to use image sensor and/or camera as a receiver. A camera consists of imaging lens, image sensor and readout circuit. The imaging lens projects light onto image sensor. The image sensor comprises of multiple PDs and detects the incident optical (photon) radiation. The received signal by this process can be viewed as individual pixels across image sensor. Each activated pixel generates a voltage proportional to the number of photons that impinge on it. At the same time, each pixel is connected to an external circuit. In its turn, the circuit converts the pixel voltage into binary data. On the basis of the pixel exposure, cameras can be classified into two categories, namely, the global shutter and the rolling shutter categories. Global shutter typically employs charge coupled device (CCD) image sensor, exposes all pixels per frame simultaneously. On the other hand, the cameras with rolling shutters generally employ CMOS image sensors and scan pixels sequentially. Unlike the case of the global shutter, this is achieved using either the row-by-row or column-by-column methods, and with exposure of one row/column at a time. Note that CMOS imagers with global shutter have already been developed and available commercially. However, they have not been used yet in smart devices. Rolling and global shutter methods have their advantages and disadvantages. A comparison between these two methods is presented in Table 1.

3 OCC implementation challenges

There are several factors that make OCC deployment challenging. The data rate of OCC system is inherently limited by camera's frame rate. Off-the-shelf smart device cameras typically operate at 30 fps that ultimately limits the achievable data rate. Exposure time and film speed have a tread-off in case of data decoding by camera-based receiver [17]. Exposure time has a direct relationship with frequency of the transmitted signal. This relationship can be understood based on the rolling shutter camera principle, that is, the mechanism with which the accumulated photon is collected

Table 1 Comparison between rolling shutter and global shutter

Attributes		Rolling shutter with CMOS imagers	Global shutter with CCD imagers
pixel exposure		exposed sequentially	all pixels are exposed at the same time
pixel-level memory		not required	required
transistor count per pixel		low	high
ambient noise		low	high
dark current		low dark current results low pixel noise	high dark current results high pixel noise
SNR		high	comparatively low
image distortion types	smear	yes	yes, smear like effect occurs by parasitic light contamination
	skew	appears upon horizontal motion within the camera FOV	no
	wobble	appears upon vertical motion within the camera FOV	no
	PWM banding	occurs when imaging in conditions of fast and changing illumination	generally not affected by partial exposure
featuring in smart devices		yes	extremely rare, an example, Sharp Aquos 922SH

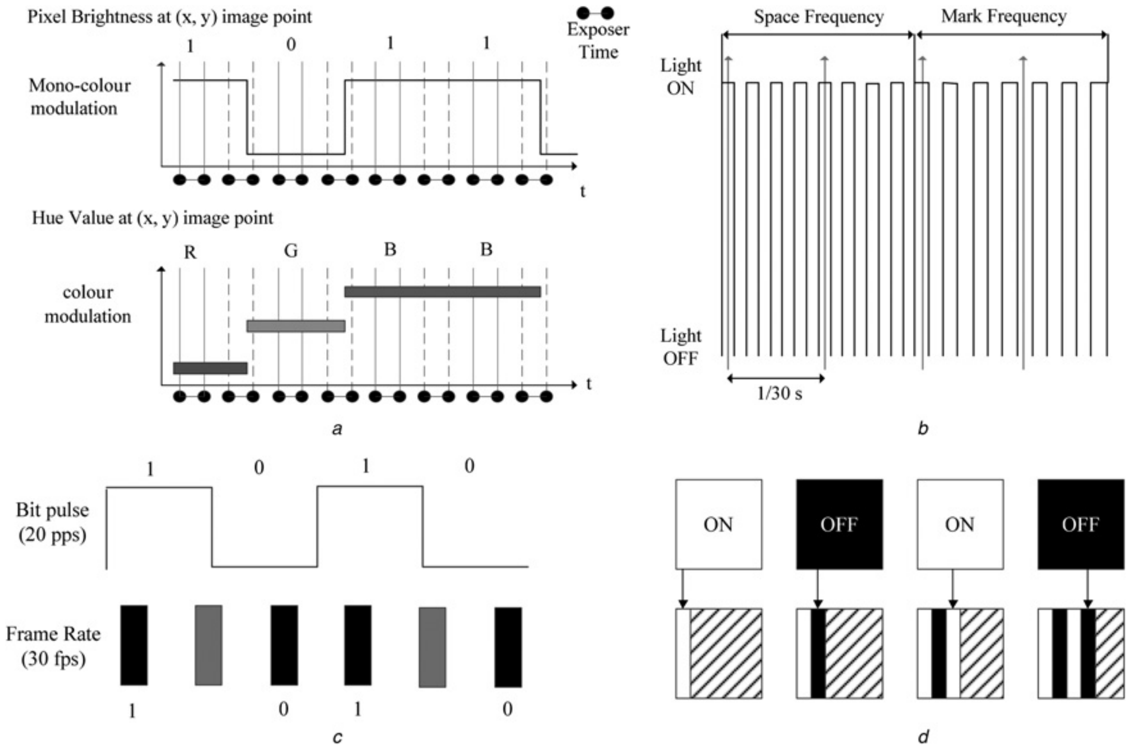

Fig. 3 *Schematic of several modulation schemes considered for OCC*

a Data decoding using Nyquist sampling [13]
b Data decoding using USFOOK [15]
c Data decoding using scheme in [21]
d Data decoding using rolling shutter scheme in [10]

and read out. In order to decode data efficiently, exposure time should be significantly smaller than the on and off periods of the transmitted signal. Long exposure time results in a partial exposure problem in cameras with a rolling shutter camera. Therefore received image will have reduced contrast between bright and dark bands that may lead to bit error. In order to decode data bits with short exposure time, a smaller film speed is preferred (in accordance to the recommended value defined by ISO) [17].

Owing to the frame rate mismatch between display and camera [18], synchronisation problem arises when camera is used for decoding signal transmission from display. LCD and AMOLED display have frame rate 30 or 60 fps, compared to a maximum frame rate of 30 for typical smart device cameras. Moreover, this frame rate is not constant during capturing signal. This is because of a variable exposure time and software issues, such as those relevant to firmware and API. During exposure time image sensor pixels get bombarded by light signal, and eventually become saturated. Saturation of a pixel requires sufficient light exposure, a phenomenon that depends on the quantum efficiency and fill factor of the CMOS image sensor, and the illumination intensity. From the illumination perspective, the synchronisation of the transmitter whose function is based on the use of LEDs differs from the transmitter whose function is based on the use of the display. Therefore exposure time setting in camera will be different in both types of transmitters, can be controlled manually. However, the exposure time also depends on the frequency of the OCC signal transmission. Both firmware and API constraints contributes on variable camera frame rate. The frame rate mismatch ultimately results mixed frame and missed frame, as explained in [18, 19]. On the other hand, OCC signal can also be detected by PD but will not subject to frame rate constraint, thereby can achieve higher data rate. Furthermore, synchronisation is much easier. The proposed OCC system in [16], can simultaneously communicate with camera-based receiver and PD-based receiver at two different data rates. In the cases where OCC transmission is executed via the display, the screen colour changes should be unrecognisable to human eyes.

4 Research challenges

4.1 Modulation schemes

In this section, we discuss about several modulation techniques, which have already been employed for OCC. In OCC, light form LEDs collected by image sensor is similar way like photo diode, as image sensor is the array of photo diodes. Hence modulation technique for VLC can also be applicable for OCC. However, some adjustments are needed since bit decoding technique for camera is different from photo diode as the final output of a camera is an image rather than voltage. Some recently developed image sensor [20] has the ability to decode data bits similar like photo diode but most of the cases, we need image processing technique where data bits are decoded by pixel brightness or hue value. Received data bit sampling is directly related to pixel readout method and frame rate in OCC. In addition, achieving synchronisation in OCC system is challenging because of the camera frame rate, display frame rate and LED pulse rate. Hence raises the necessity to modify the modulation techniques compared to technics mentioned in the IEEE 802.15.7 standard.

Nyquist sampling method is proposed in [13] for OCC system using OOK modulation scheme, where received data bits are sampled using Nyquist method (frame rate = pulse rate × 2). Pixel (x, y) received the transmitted signal, therefore data bit can be decoded from pixel (x, y) brightness or hue value as shown in Fig. 3*a*. In case of OOK modulation, pixel high brightness indicates the data bit is ‘1’ and low brightness indicates as ‘0’. As frame rate is twice than pulse rate consecutive two fame will indicates the same data bit. However, because of the transition of LED (on and off), one frame may be indicates unclear state of LED (not fully on or fully off), so data bit can be decided by the pixel brightness of other frame. The achievable data rate is in the region of 150 bps–1.1 kbps for high speed camera (600 fps–4.6 kfps) with mono colour OOK modulation using pulse rate of 300 Hz–2.3 kHz. Another implementation with low frame rate camera like ‘Picapicamera’ (11 fps) they achieve data rate 5 bps for colour modulation.

Undersampled frequency shift OOK (UFSOOK) is proposed in [15], where mark (logic 1) and space (logic 0) frequencies are higher than 100 Hz in order to avoid flickering. The mark and space frequencies are chosen as harmonics of camera frame rates. Both mark and space frequencies are sent for two frame rate durations and space frequency is harmonics with camera frame rate without any offset frequency but mark frequency is harmonics with camera frame rate plus frequency offset (frequency offset = ±camera frame rate/2). Mark and space frequencies are selected as 105 and 120 Hz, respectively, and sub-sampled by camera typically with 30 fps as shown in Fig. 3*b*. Space frequency is four times than camera frame rates, can complete four cycles within 1/30 s, hence same LED state is observed between consecutive two frames. On the other hand, mark frequency is 3.5 times than camera frame rate, can complete three and half cycle within 1/30 s. As a result, toggling is observed between two frames. In this modulation scheme, it is necessary to select two consecutive camera frames that sample same data bit, otherwise mislead the decoded data. Synchronisation is performed using start frame delimiter technique. The advantage of this scheme is its applicability in both rolling shutter and global shutter cameras. However, maximum achievable data rate is only half of the camera frame rate, that is, 15 bps for a camera with frame rates 30 fps. In order to decode two OOK modulated data bits, scheme proposed in [21] samples three times as shown in Fig. 3*c*, that is, it proposes to sample in three frames to decode 2 bits. The data rate achieved in this process is 20 bps for a camera with 30 fps. In spite of achieving higher data rate than UFSOOK, this scheme cannot mitigate flickering problem.

Understanding rolling shutter method is very important in the context of OCC because almost all the smart devices’ cameras employ rolling shutter-based CMOS imager. Generally, CMOS image sensors with the rolling shutter mechanism are preferred in such devices because of their smaller size and lower cost compared with CCD image sensors. Rolling shutter-based camera is subjected to PWM banding effect while capturing LED light sources, can be used constructively in the case of OOK signal decoding in OCC systems. By rapidly switching the LEDs on and off and by varying the on-interval of light emission with respect to the off-interval in such a way that our eyes cannot perceive LEDs’ flickering. LED pulsating frequency is kept lower than the rolling shutter’s scanning frequency but higher than the camera frame rates. Thus, the camera output of OOK modulated LED is the distinct bright and dark bands as shown in Fig. 3*d*. The bright and dark bands represent ‘on’ and ‘off’ intervals, respectively. The ‘on’ interval is represented as bit ‘1’ and ‘off’ interval is represented as bit ‘0’. Rolling shutter sampling is used in [10], to decode data. However, because of the lack of considerations for synchronisation and long processing time of the decoder application per frame, this approach suffers from high packet drop rate [19]. Along with OOK, binary frequency shift keying (BFSK) is also used to modulate LED signal where, bit ‘1’ and bit ‘0’ is represented by two distinct frequencies f_1 and f_0, respectively. Camera is also able detect this BFSK signal as a form of banded image the frequency of which is proportional to the frequency of the LED [16]. Data decoding in OCC system directly depends on camera frame rate. In addition, frame rate of a camera depends received light intensity, camera hardware design, firmware setting and API constraints, therefore frame rate may not be constant. Thus different cameras may show different frame rates, depending on the manufacturing company [18]. As a result, variable camera frame rate may lead to poor synchronisation and bit error. Therefore extensive research is required to tackle camera frame rate variation. LED flash of the smart devices can also be utilised to transmit data. Like camera, LED flash’s frequency also varies because of operating system and can reach up to 50 Hz [22]. Variation of LED flash’s blinking frequency may also result synchronisation problem. Therefore main challenges in designing a modulation scheme for OCC system are to overcome low data rate, synchronisation problem and flickering problem.

4.2 Optical MIMO

Achieving high data rate in the OWC system is hampered by inherent hardware limitations. The low modulation bandwidth of LED reduces achievable data rate. The camera frame rate is another constraint in the way of achieving high data rate in case of OCC system, especially for smart devices rather than the custom-made camera receiver. However, availability of multiple high SNR channel in OCC system facilitates the adoption of the MIMO technique. Fig. 4 portrays an OCC-MIMO system, uses $N_T \geq 1$ transmit LEDs and $N_R \geq 1$ receive detectors. In OCC-MIMO system, receiver is either camera or image sensor, belongs to the imaging receiver category. All the LEDs transmitted signal simultaneously, which propagate through optical channel, pass through imaging lens of the camera and projected on to different places of the image sensor. In this way, the signal corresponding to every transmit element is separated spatially and has different power spectral densities. Each of the N_T LEDs is being received in the form of image by N_R receiving elements. Afterwards, each pixelated image is collected and fed into processing circuit to extract data.

MIMO technology for OCC system seems to be feasible to overcome data rate impairment but many research challenges are needed to solve for successful adoption of the technology. OCC-MIMO performance mainly depends on the receiver characteristics. There exist two types of receiver construction considering the receiver front-end design. The non-imaging receiver consists of non-imaging lens that concentrates optical radiation on the surface of PD-based receiver. Non-imaging MIMO systems is not considered to be practical because the optical power distribution is evenly among the PDs. The rank of the channel matrix is compromised and may reduce to unit rank because of this evenly optical power distribution resulting very little or no diversity at all. On the other hand, image sensor and/or camera, falls into the category of imaging receiver. A performance comparison is presented in [23], shows that imaging-MIMO

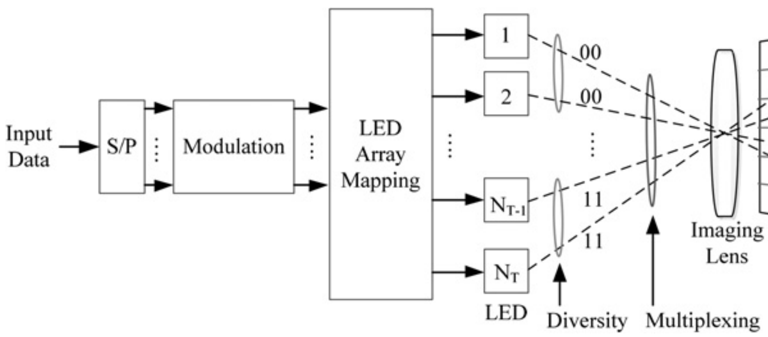

Fig. 4 *Visualisation of OCC-MIMO system*

system has superior performance over non-imaging MIMO system in terms of diversity and misalignment. Indeed the geometries of transmitter and receiver are very important for imaging-MIMO system. In order to receive all the channels, transmitters and receiver should be aligned in a manner that receiver must keep the transmitters in focus. For example, if a receiver is moved horizontally to the corner of the room, it will be unable to capture all the LED transmitters at a time because of its FOV limitation, also known as defocusing problem. As a result diversity order will be reduced [24, 25]. In order to solve transmitter–receiver misalignment problem, receivers need to have tilt feature and transmitter tracking capability to receive all channels. Such technical complexities and their implementations require extensive research. Another problem arises in the OCC-MIMO system when the image of transmitter is rotated at the receiver. Hierarchical transmission scheme using two-dimensional (2D) Hadamard coding, as proposed in [26], reduce the computation complexity at the camera-based receiver for rotation detection in RGB-LED array-based MIMO transmission.

There are three important reasons for using MIMO for OCC: to increase the data rate considerably by spatial multiplexing, to achieve a high SNR gain with the use of spatial diversity combining techniques, and for multiple access. In addition, utilising high spatial diversity gain, distance between transmitter and receiver can be increased [27]. An imaging diversity receiver is either a custom-made receiver with image sensor and imaging lens or camera. One of the advantages of imaging receiver is that optical transmissions are received as pixels in imaging diversity receiver. Thus pixelated reception in both receivers offers selection and combining of pixels with high SNR, resulting high gain at the receiver. Imaging diversity is proposed for IR in [28, 29]. Two ways are considered in [28] to process the resulting electrical signals, namely, select-best and maximal-ratio combining. Angle diversity reception is considered in [29] for non-directed links. Imaging diversity for OCC system explained in [23, 24, 27]. Diversity performance of imaging receiver depends on the spatial signal separation capability of the receiver, that is, on the uncorrelated channel paths that depend on the imaging lens characteristics. Hemispherical lens is used in [24], can separate channel spatially and achieve significant diversity. Thin convex lens is considered in [25] shows that transmitter image size formed at the receiver depends on FOV of the lens. This lens type can increase the channel correlation when the image size of the transmitter is increased. Imaging-MIMO system described in [30], uses fish eye lens to achieve high spatial diversity and high spectral efficiency. Fish eye lens provides better spatial resolvability of optical channels, since it projects planner and small-sized images. Surely, lens characteristics that affect the diversity performance of the OCC system need further investigation. In addition, suitable diversity combining techniques to choose best channels for the sake of minimising signal processing complexity in OCC-MIMO system remain an open problem. Pixelated MIMO approach in [31] achieves spatial multiplexing gains, by exploiting the large number of optical transmitters and receivers through the use of spatio-temporal coding. In [27], both multiplexing and diversity are analysed with the help of classical ray tracing techniques and computer vision theory. It is shown that pixel resolvability issue is much more serious in case of multiplexing than diversity, since images of the LEDs moves closer to each other, cause an effect analogous to blur effect when the distance between transmitter and camera receiver is increased. In OCC-MIMO system, the MIMO gain is perspective dependent. There is a performance tread-off between MIMO gain and distance. Analytical result in [27] shows that OCC-MIMO system can achieve data rate in the order of Mbps at distance about 90 m. On the other hand, the OCC-MIMO demonstration in [32] reports 1 Gbps data rate. For short-range communications, OCC-MIMO system can be benefitted from multiplexing mode and switch to diversity mode for long-range communications. However, determining appropriate time for autonomous mode selection is particularly challenging, and requires further research. The large number of transmitter and receiver elements in OCC-MIMO also raises the possibility of employing multifunctional MIMO [33].

4.3 Medium access control

MAC provides addressing and channel access control functionalities which enable several users to communicate within a multiple access network. A novel lightweight MAC protocol is necessary in order to address several challenges in OCC system, including, low data rate, link blockage, mobility and MIMO support in smart devices. OCC system relies mainly on the LOS link. However, momentary blockage or shadowing may degrade link quality. Seamless connectivity may not be achievable because of the user mobility in OCC system, resulting volatile links. Also, new vision is required for designing MAC protocol to support optical MIMO in the OCC system. Achievable data rate in smart devices is limited due to camera frame rate. Therefore the main challenge for designing new MAC protocol is to minimise overhead, given the low data rate in smart devices.

4.4 LLC problem

The LLC sublayer provides multiplexing mechanisms so that several network protocols can coexist within a multipoint network, and to be transported over the same network medium. It has been decided that OCC needs to interface with LLC [34]. However, it is very challenging because of low data rate. Moreover, to support LLC for OCC system, bi-directional communication is mandatory [34]. Generally, several applications of OCC can actually execute with low data rate, for example, e-coupon transfer, optical quick response (OQR) code transfer, positioning information downloading and so on. Therefore low overhead is necessary. Fig. 5 provides an insight on probable protocol stack for OCC system. In Fig. 5*a*, the transmitter does not have any network connection, therefore cannot support link layer, transmits URL message in a broadcasting manner. The URL message is pre-stored in a server. Camera decode message and utilise WiFi for URL browsing. In Fig. 5*b*, the transmitter networked with optical fibre or power line communication and able to support link layer in the transmitter. Finally, Fig. 5*c* bi-directional mode is provided between transmitter and receiver through an optical link and able to support link layer. However, providing reverse link via RF is challenging. IEEE 802.15.7 does not allow RF to provide reverse link, however, it can be considered revision version of IEEE 802.15.7.

4.5 Multiple access techniques

Multiple access techniques are crucial for any wireless communication systems to accommodate multiple users simultaneously. There are broad ranges of multiple access technique than can be implemented in OCC, such as space division multiple access (SDMA), wavelength division multiple access (WDMA), frequency division multiple access (FDMA), time division multiple access (TDMA) and optical code division multiple access (CDMA). In the OCC system, generally LED-based optical access points (OAPs) are used. Camera-based receiver has the ability to provide better spatial separation of optical channels, facilitates (SDMA) to be employed in the OCC system. In WDMA, each user is assigned with a unique wavelength channel in case of single cell topology. Such a system is demonstrated in [35]. However, this technique requires complex, expensive structure [11]. Each user is allocated with non-overlapping frequency bands in single cell FDMA system. For multiple cell scenarios each OAP is assigned with different frequency bands. However, this system suffers from low power efficiency. In TDMA, different users are allocated with different time slots, a technique associated with very good power efficiency. Direct sequence spreading-based optical CDMA is another option for OCC system. Implementation complexities arises of such system since transmit power control is needed to deal with near-far

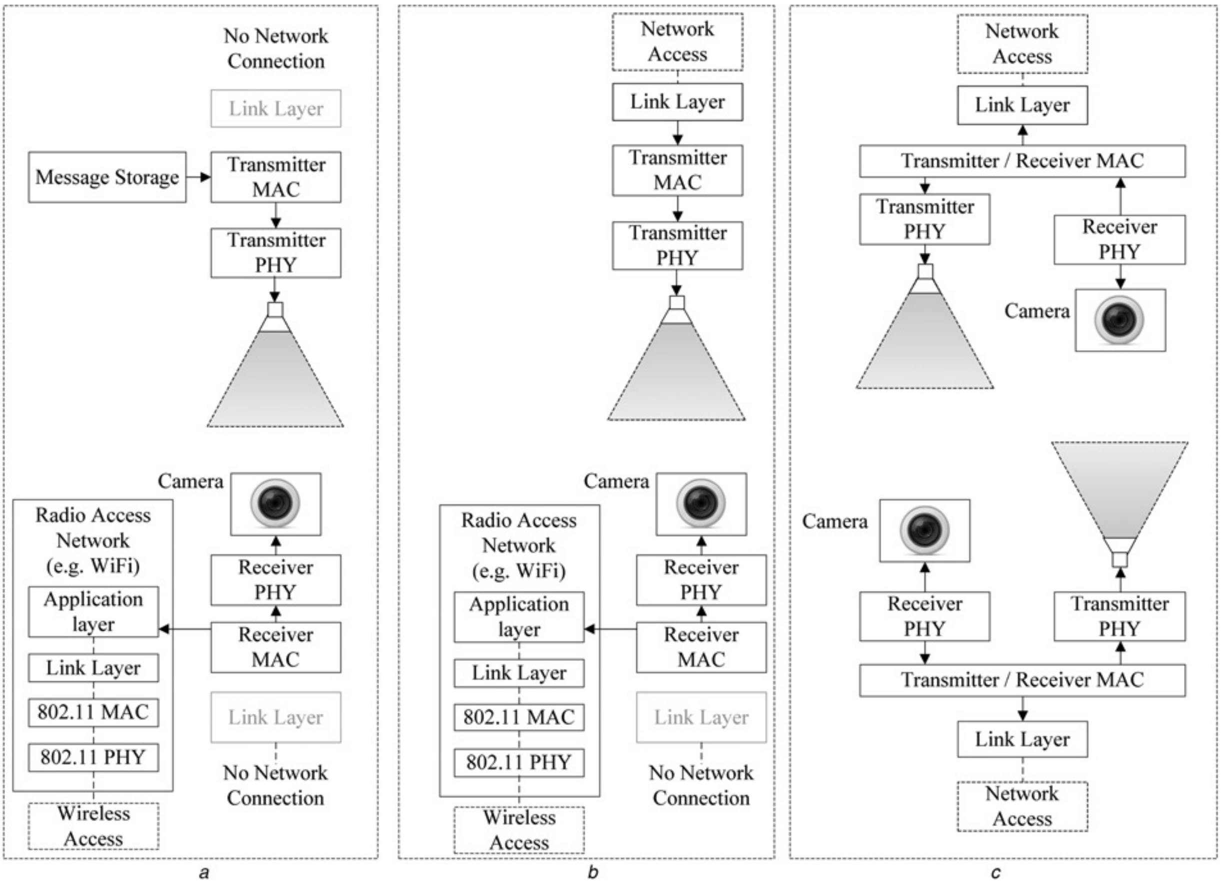

Fig. 5 *Exemplary protocol stack for OCC system [34]*

a No network connection
b Partial network connection
c Full network connection

problem. However, the choice of appropriate multiple access technique for OCC system requires further research and needs to comply with smart device camera-based reception.

4.6 OCC-based positioning

Positioning, especially indoor positioning is a very attractive research topic of growing interest. The need for high accuracy indoor positioning arises from the fact that revenue can be increased greatly by selling 'unfound products' in the shopping malls by notifying users about precise location of products to their smart devices. In OCC-based positioning system, multiple LEDs transmit their identifiers or coordinate information. At the receiver side, camera is used to decode that information and determine its position and orientation relative to the LEDs as shown in Fig. 6*a*. Therefore whole process can be divided into two parts – distance measurement from reference points (LEDs) to receiver (camera), calculate unknown position of camera using that distances and LED coordinates or ID information transmitted by LED itself. However, OCC-based positioning techniques can also be applied in outdoor for high accuracy positioning, for example, vehicle's position and range estimation, as shown in Fig. 6*b*.

• *Legacy positioning methods in OCC.* In order to determine distance from reference points (LEDs) to camera, time of arrival (TOA), time difference of arrival (TDOA), received signal strength (RSS) or angle of arrival (AOA) can be used. In TOA-based technique, multiple LEDs (at least three) transmit signals at exactly same known time and receiver calculate the distances from time difference between transmit and receive signal. On the other hand, TDOA measures distance using time differences at which signal arrived from multiple LEDs rather than absolute arrived time. Optical signal-based TOA and TDOA have been simulated for PD-based receiver in [36, 37], respectively. However, it is difficult to measure time difference both for TOA and TDOA-based techniques as transmitted signal propagates at speed of light. Also in OCC, TOA and TDOA techniques are not feasible for real-world implementation because of the low frame rate at camera and synchronisation problem. On the other hand, RSS-based technique measures signal attenuation to calculate relative distances from LEDs hence no synchronisation is needed [38]. However, several factors, such as received signal strength depends upon the particular LEDs dimming level, LOS requirement and ambient light condition affect the accuracy of RSS-based technique in the OCC system. One of the most promising positioning technologies in OCC is AOA as camera is intrinsically an angle or arrival sensor. Thus possible to calculate 3D position and orientation of camera [17, 39], while PD-based receiver can only be used to calculate position because photo diode cannot detect angle or arrival of the incoming light [39]. Moreover, camera can spatially separate all LED light source as well as ambient noise because of the property of AOA. Hence computer vision technique along with OCC can be used to solve unknown camera position and orientation, discussed in brief in the following subsection.

• Computer vision-based positioning techniques. Computer vision is the study of analysing projective geometry where 3D real world projected onto 2D image of a camera. It can be used for camera pose estimation, 3D object reconstruction, object recognition, object tracking, motion estimation and so on. It can be classified as single-view geometry and multiple-view geometry. OCC and computer vision technique can be used jointly to estimate camera unknown pose (position and orientation).

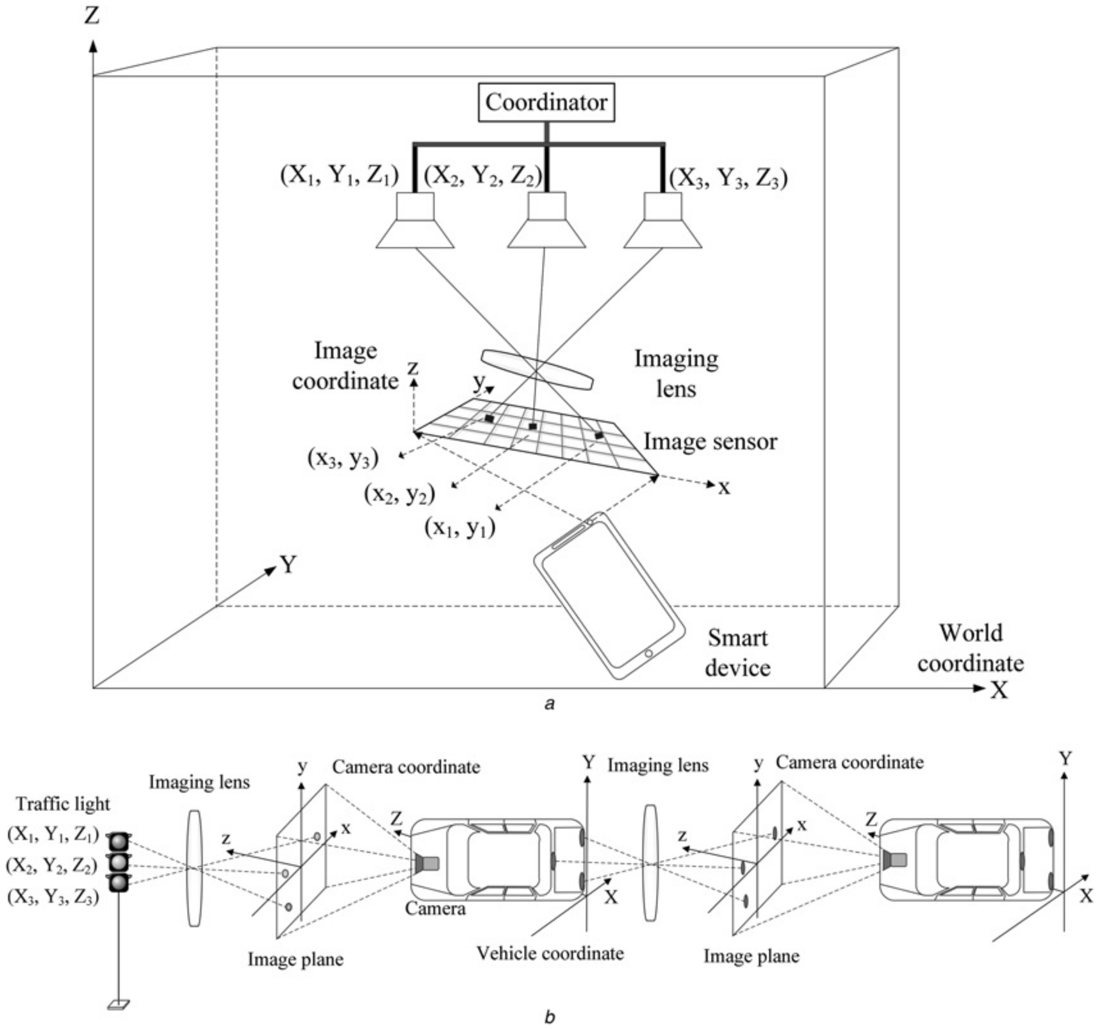

Fig. 6 *Positioning technique using OCC*

a Indoor positioning
b Outdoor positioning

(a) Single-view geometry. In single-view geometry necessary information is extracted from single image. When camera takes picture it actually maps every 3D coordinate points onto 2D image points. Thus the projection of the 3D world coordinate point and 2D image point is described as [40]

$$\tilde{x} = K[R|t]\tilde{X}_w \tag{1}$$

where $\tilde{x} = (x, y, 1)^{\mathrm{T}}$ is a homogeneous image coordinate (LED image point), $\tilde{X}_w = (X_w, Y_w, Z_w, 1)^{\mathrm{T}}$ is the homogeneous world coordinate system (LED coordinate). $\boldsymbol{K}$ is the intrinsic camera calibration matrix, describes camera focal length, skew factor and principle point. The value of $\boldsymbol{K}$ can be determined using camera calibration technique [41]. $\boldsymbol{R}$ is the camera orientation and $\boldsymbol{t}$ is the camera position. LEDs themselves transmit their 3D world coordinates and their image coordinates can be determined from their images, thus camera unknown position and orientation can be solved using (1). At least three LED coordinates and their corresponding image points are required to estimate camera

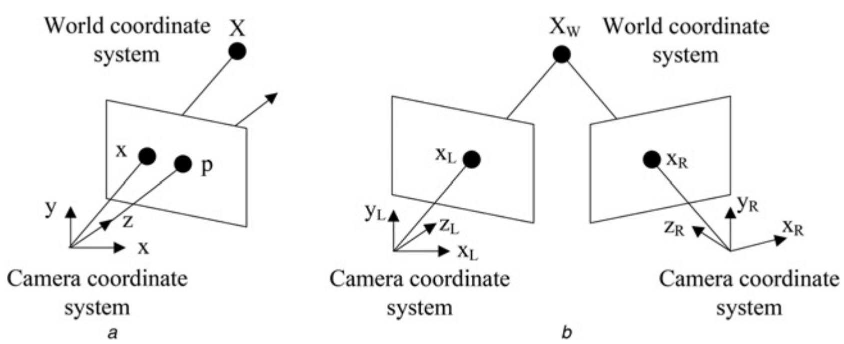

Fig. 7 *Application of computer vision for OCC-based positioning*

a Single-view geometry
b Multiple-view geometry

position and orientation [42, 43]. Fig. 7*a* shows camera position estimation scenario in OCC using single-view geometry. Each LED transmits coordinate information, camera receive that information and use computer vision technique to solve its position and orientation.

(b) Multiple-view geometry. Multiple-view geometry can be applied for several images from multiple cameras or alternatively form multiple views of a single camera. When any 3D world coordinates are projected onto two different views, position of this unknown 3D world coordinates can be estimated by knowing internal projective geometry between two views also known as epipolar geometry, as shown in Fig. 7*b*. Thus it can be used for moving object tracking purpose [44]. OCC can leverage complex image processing as LED can transmit their unique ID, then each object can easily be identified form multiple views.

Multiple view geometry can be applied for ITS application, for car tracking and safe navigation. If multiple cars transmit their unique IDs along with their coordinate information through OCC, cameras can be used to decode that information and position estimation.

- Artificial intelligence (AI)-based positioning. Although there are many mathematical models to represent the relationship between 3D world coordinate point and 2D camera image point, however, complexity arises while solving those equation. The complexity can be understood from (1), where three-axes rotation and three-axes translation, focal length, skew factor, principle point coordinates of camera all are required for representing 3D world coordinates onto 2D camera coordinates. Hence many researchers are interested about using AI for camera-based positioning technique [45, 46]. Neural network can be used for OCC-based positioning [45] to learn the relationship between 3D world coordinate and 2D image coordinate hence possible to estimate camera position without solving any complicated mathematical equation. The performance of neural network-based positioning in OCC system [45] is shown in Fig. 8, where two types of back propagation (BP) neural networks are used for training and testing purposes. Neural network combined with OCC positioning (network 1) can be used for estimating camera position in case of trained and untrained environment (different LED positions are used to train and test purposes) as shown in Figs. 8*a* and *b*. However, only neural network-based positioning (network 2) cannot be used for untrained environment as shown in Figs. 8*a* and *b*. A comparison of different OCC positioning techniques is given in Table 2.

4.7 Uplink

There has been extensive debate on the suitable uplink for an OWC system. RF, VLC and IR have all been considered as options for uplink while using VLC as downlink. RF, VLC and IR can also be used to provide uplink for OCC system, since smart devices are generally incorporated with WiFi, flash and IR. Uplink or reverse link is necessary in order to send data download request and acknowledgement. IEEE 802.15.7 allows bi-directional communication by allowing time slots for both uplink and downlink in the contention free period of MAC superframe. However, it is very difficult achieve full duplex communication mode by using VLF for uplink and downlink without inter symbol interference (ISI). A high speed bi-directional VLC system is demonstrated in [35], which employs two-stage frequency allocation. This is achieved by jointly employing wavelength division multiplexing (WDM) for coarse frequency allocation using different colours (wavelengths) and orthogonal frequency division multiplexing (OFDM) for precise frequency allocation. The data rate reported for downlink and uplink are 1.15 Gbps and 300 Mbps, respectively. Both IR and VLC are combined together to provide bi-directional communication [48]. Full duplex multi-access VLC system based on optical carrier sense multiple access with collision detection method is presented in [48], where, uplink and downlink are provided by IR and VLC, respectively. ISI in full duplex mode was mitigated by choosing IR as uplink, operating at 850 nm and VLC for downlink. The experimental demonstration in [49] reports uplink data rate of 250 Mbps, compared to 100 Mbps, achieved in [48]. The system demonstrated in [48], supports 1-to-n high speed interconnection, however, providing uplink using IR to the distributed transmitter structure without causing ISI still possess problem. In addition, receivers with optical uplink require point and tracking functionalities and location information of the desired transceiver for synchronisation. These shortcomings can be overcome using RF uplink, as proposed in [50]. In [50], VLC is only used for downlink and RF for uplink. In order to maintain seamless connectivity, the proposed hybrid network switches to RF downlink mode when receivers move out of the VLC coverage zone. Traditional VLC system requires additional hardware in order to implement uplink based on IR and RF. On the other hand, implementing OCC functionalities in to smart devices, both IR and RF, can be used as uplink, for example, IR or WiFi can be used for uplink. Therefore additional hardware requirement can be avoided using smart devices as receiver. Using WiFi as uplink is challenging, since WiFi uplink will reduce throughput of both OCC link and collocated WiFi devices [51]. Therefore careful management of WiFi spectrum will be necessary.

5 OCC deployment opportunities

OCC presents several deployment opportunities, such as ITS, location-based services (LBS) and augmented reality (AR). In fact, ITS is currently being revisited within the framework of OCC systems [52]. In [53], VLC is proposed for road safety signalling and vehicular positioning to replace dedicated short-range communications unit. The proposed scheme is implemented using scooter LED tail lights, PD and software defined radio. Successful reception of the overtaking scooter's broadcasting signal is confirmed by the overtaken scooter through a series of experiments that emulated real-world environment. Considering the camera's spatial signal separation capability, using low cost camera instead of PDs will certainly provide improved performance in the presence of ambient light. In addition, a lot more neighbouring vehicles can be detected using cameras than PDs, since camera allows longer distance optical signal reception [27]. Indeed, OCC presents a unique and cost-effective solution, that merges communication and high accuracy positioning [54] for vehicle safety in ITS. The combination of communication and positioning using OCC systems enable cooperative vehicle positioning, by which a vehicle can decode messages and determine front, rear and side vehicles' position and orientation. Another promising application of OCC system is the LBS [55]. Various LBS opportunities can be developed, combining OCC positioning and communication. In fact, the use of camera allows simple positioning techniques to be implemented in camera-based receivers. Utilising the high accuracy positioning, various types of LBS can be provided. Certainly, there is a growing need for indoor LBS, especially in shopping mall and supermarkets in order to increase revenue by informing users about precise location of products. 'Smart product search' application can be developed for future smart shopping. Consumers can download location information for a particular product by using preinstalled application in their smart devices via light wave. Furthermore, guided navigation can be provided for customers. Note that, positioning using OCC is not restricted only indoors but will also be possible outdoors. Parking vehicles can be made easy by utilising OCC beacon transmission. Location of free parking spot can be transmitted by LEDs, and received and decoded by vehicle cameras. Using simple OCC navigation application, car can reach the vacant paring spot. Advertising can be revolutionised by the introduction of smart OCC tag-reader technology and OQR. Information about new products or sale on certain products can be send as a broadcast message by using readily available signage

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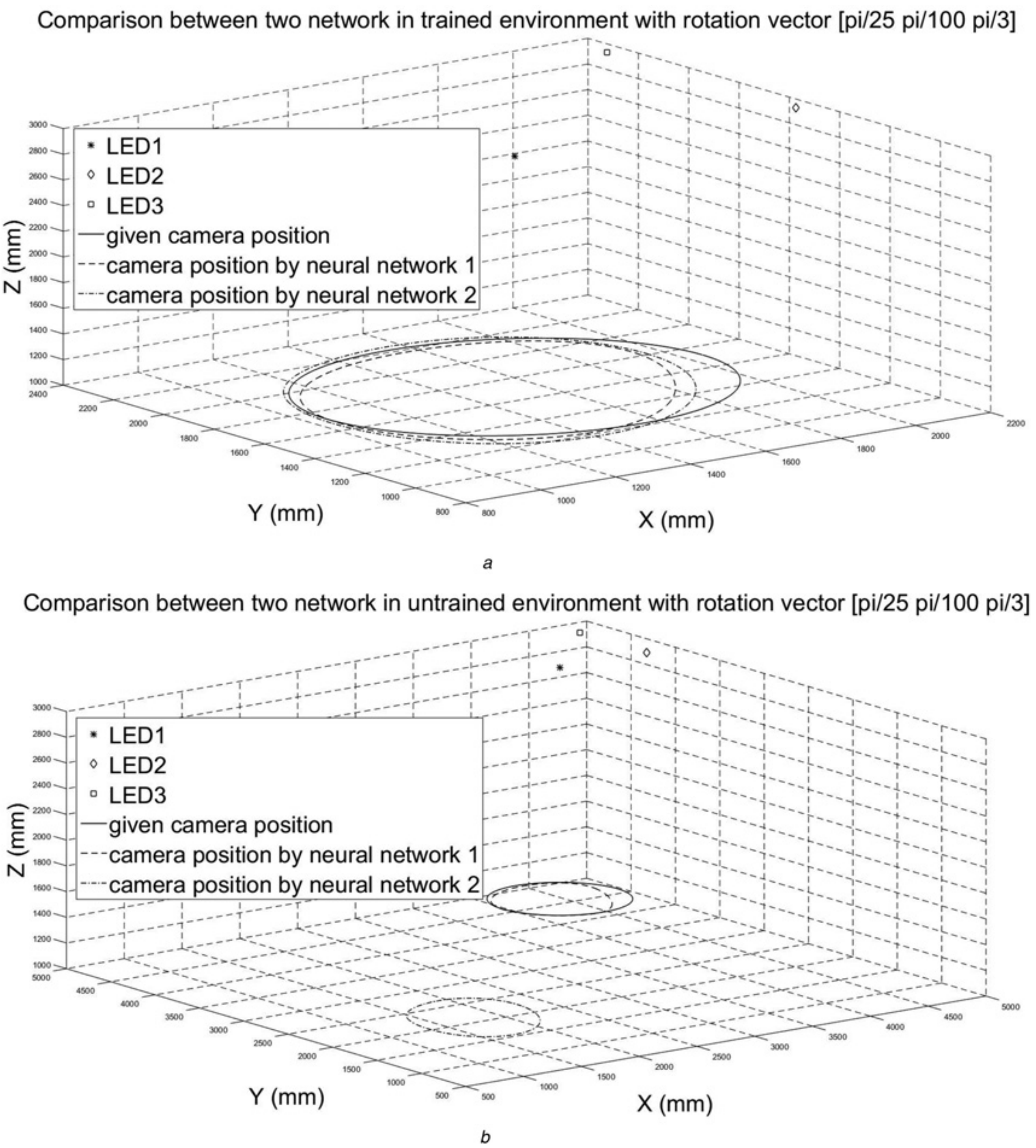

Fig. 8 *Simulation of OCC-based indoor positioning system using neural network*

a Neural network-based positioning for trained environment (same LED coordinates are used for trained and test purpose)
b Neural network-based positioning for untrained environment (different LED coordinates are used)

and other optical broadcasting system to the smart devices. Using these devices, buyers can download necessary information or even perform e-shopping. This process is termed as line of sight marketing [55]. Arguably, OCC is more suitable than other technologies to provide AR experience by simple applications. OCC transmission that includes data, 3D positioning information and orientation can be received by the camera. In addition, the camera can also provide visual information. Casio has already developed an AR application for smart devices called 'Picapicamera' uses OCC technology to receive data from display, and then translate into codes relating to specific information content [56].

6 Standardisation and commercialisation trends

OCC is the pragmatic approach to attain the potential of VLC. In addition OCC, is not restricted to VLC spectrum rather allows the use of IR and near UV spectrum. However, currently, there is not any standard at present that defines physical layer and MAC layer for data transmission using LEDs and image sensor and/or camera. Moreover, VLC has a complex ecosystem, hindering its commercial deployment. Acknowledging these facts and the broad marketing potential has led to the initiation of the revision version IEEE 802.15.7r1 of the existing IEEE 802.15.7 standard. This effort aims to provide a basis for VLC deployment in the smart devices, aiming to bridge the gap between two different ecosystems. An interest group is formed in 2012, namely IEEE 802.15 IG-LED in order to modify or enhance the VLC technology that has been proposed in IEEE 802.15.7, followed by study group in the 2013. A task group, TG7r1 has formed as of the writing of this paper to provide the revision standard named IEEE 802.15.7r1.

There are only few companies actively working on OCC commercialisation. General electric (GE) and a startup company ByteLight have joined their forces to bring commercial OCC product into market. They have indeed showcased their product in lightfair industry conference 2014. ByteLight's chip combines both VLC and Bluetooth low energy, aims to provide indoor LBS and an enhanced retail experience [57]. Using the ByteLight's

Table 2 Comparison of different OCC positioning techniques

Attribute	TOA	TDOA	RSS	AOA	Computer Vision	AI based positioning
description	absolute travel time of a signal from transmitter to receiver	time difference of arrived signals from synchronised transmitters	signal attenuation to calculate relative distances from multiple transmitters	location finding using triangulation	measurement of 2D image coordinates which is exclusively based on AOA technique	neural network is used to estimate camera position by learning the relationship between 2D image and 3D object point
reference point	3	3	3	2	3 [43]	3 [45, 47]
resolution	cm	cm	cm	cm	cm	cm [45, 47]
dimension	2D	2D	2D/3D	3D positioning and orientation	3D positioning and orientation	3D positioning and orientation
synchronisation	yes (precisely)	yes (precisely)	no	no	for single camera: no for multiple camera: yes	no
one way positioning	yes	yes	yes	yes	yes	yes
complexity	high/medium	high/medium	low/medium	high/medium	high/medium	high/medium

chip, GE made overhead lighting accessories that can transmit data using unique light patterns and Bluetooth signal emitted by overhead LED infrastructures and receive using smart phone camera. According to opus research, the predicted market for indoor location and place-based marketing and advertising will surpass $10 billion by 2018 [58]. Certainly, OCC-based LBS technology can share a modest portion of annual indoor LBS business. ByteLight's second invention is the light field communication, a software-as-a-service that is analogous to the purpose of its RF counterpart, the near field communication [59]. LVX systems offer a commercial overhead LED lighting system that works in a plug-and-play manner, able to support data rates up to 3 Mbps [60]. Klipsch, a US audio device manufacturer implements speaker able to receive music embedded in the LED transmission [60]. Reasonable optical near joint access (Ronja) is a user-controlled optoelectronics device that provides a long-range optical point-to-point data link, developed by Twibright Labs in the Czech Republic. Their implementation using red light and IR can transmit data up to 1.4 and 1.25 km, respectively, and a communication speed of 10 Mbps can be achieved with full duplex mode [60]. The German company Siemens is working on developing high speed wireless links using commercial LEDs. The referred corporate efforts justify the intense amount of interest on VLC implementation and commercialisation. However, the lack of a support camera receiver, the complexity of the VLC standard and the VLC ecosystem, all restrict at present worldwide VLC commercialisation. Therefore standardisation will be necessary to ease the VLC implementation and commercialisation, as well as to ensure compatibility between multiple vendors, while maintaining consistent performance.

7 Conclusion

In this paper, we have introduced OCC technology, a novel paradigm that combines illumination, wireless communication and imaging into single platform. Typically, OCC system uses smart phone camera to decode data bits, which are embedded into LEDs optical illumination. The camera captures a picture of the surroundings. Only the portions of the picture associated with the LEDs are extracted using image processing techniques since only those parts convey useful information. We have briefly explained data reception in camera-based receivers and discussed challenges regarding the data decoding schemes. Recent work on OCC-MIMO has been presented and issues associated with the MIMO deployment in the OCC system have been discussed. We have also discussed that new MAC and LCC protocols are necessary for the OCC system that will lead to low overheads. Moreover, a summary of several positioning techniques in the OCC system has been presented. In addition, positioning techniques based on computer vision have been introduced that exploit the camera geometry to extract the LED coordinates. With smart devices at our disposal for the OCC receiver, systems including IR, VLC or WiFi can be considered for the uplink. Correspondingly, there are several promising applications using the OCC system, both indoors and outdoors. Smart automotive communication, indoor positioning, AR, LBS and LOS marketing, are possibly the selected applications of the OCC system with the greatest commercial potential. Thankfully, all of these applications require low data rates and can be implemented in smart devices without any hardware modification. However, a software application will be necessary. In this work, we have also discussed about current status of IEEE 802.15.7r1 along with commercialisation trends. In the case of high data rate services, the frame rate of the camera in the smart device presents a constraint. Fortunately, the OCC receiver can also be realised using the imaging lens and the image sensor, that is, a customised receiver can provide high data rates. In addition, the OCC system provides high security since transmission and reception typically occurs within short distances. We envisage that the OCC technology will complement RF communications in near future. However, in order to realise the full OCC potential and ensure faster commercialisation, a standard is necessary. Indeed, standardisation of OCC technology through IEEE 802.15.7r1 may well provide the platform for OCC deployment and faster commercialisation.

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