Chapter 25
Optical Camera Communications

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Abstract Visible light communications (VLC) has been evolving at a much faster rate because of the development of high energy efficient white light emitting diodes (LED). For the first time, we see a unique device which offers triple functionalities of illumination, data communications and indoor localization, thus opening up the opportunities for applications at homes, offices, planes, trains, etc. In modern vehicles with LED-based head and tail lights, VLC can be used for car-to-car communications to convey regular traffic information to other vehicles as well as the road side infrastructure. Cameras are also being widely used in vehicles for monitoring speed, collision detection avoidance, traffic sign and object recognition. The VLC technology employing the camera as a receiver opens up new possibilities offering multiple functionalities including data communications. This chapter gives an overview of the optical camera communications and outlines the technological concept behind it.

25.1 Introduction

As the number of wireless users has been rapidly increasing and their individual demands on bandwidth have been growing dramatically, we are witnessing an ever-crowding spectrum usage. In order to relieve the spectrum congestion...
associated with the existing radio frequency bands and to release of new frequency bands, alternative wireless communication technologies are urgently needed. One alternative technology that has emerged in the past decade is visible light communication (VLC), which is a subset of optical wireless communication (OWC) technology. High-intensity solid-state white light emitting diodes (LED) are being widely used to replace conventional lamps in many applications. LEDs can be switched on and off at a high-speed (few nanoseconds or less) higher than the critical flicker frequency (CFF) \( f_{\text{max, eye}} \) [1], which allows data transmission not visible by human eye. Therefore, these energy efficient devices can be used for illumination, data communication and indoor localization [2], a unique feature not seen in any other devices. This newly developed optical wireless communication technology offers several unique advantages compared to the radio frequency (RF)-based technologies such as: (i) abundance of unregulated bandwidth [3] compared to the limited and expensive RF spectrum [4]; (ii) inherent security, unlike RF signal which passes through walls, light is confined into a well-defined coverage zone; (iii) lower power consumption and therefore a green technology; and (iv) safe for human use since there is no RF electromagnetic radiation during transmission [5], and (v) longer life span. However, there is a number issues associated with VLC including a short transmission span to ensure high data rates \( R_b \) since the received signal strength drops dramatically particularly for non-line-of-sight (NLOS) configurations, and interference [6] due to the artificial and natural light sources if high enough can saturate the receiver increasing shot noise [7], compatibility with the existing lighting and data communications infrastructure.

VLC can be used in many applications including homes, offices, planes, trains, etc. In vehicles VLC can be used for car-to-car communications considering that more and more vehicles are being fitted with LED-based headlamps that can be used to transmit information to other vehicles for to regulate traffic and avoid accidents. The VLC technology can also be used as a vehicle-to-road side infrastructure communication network by utilizing traffic light and street networks to transmit traffic and safety information to drivers. In vehicles we are seeing the introduction of cameras for monitoring driver’s drowsiness, adaptive cruise control and collision detection avoidance, traffic sign and object recognition and intelligent speed adaptation. Combining the VLC technology with camera will lead to optical camera communication (OCC) systems, which provide both multiple functionality including data communications. This chapter gives an overview of the OCC. The rest of the chapter is organized as follows. Section 25.2 outlines the concept of OCC together with the transmitter (Tx), and the receiver (Rx). The imaging multiple-input and multiple-output (MIMO) concept is introduced in Sect. 25.3, whereas the modulation scheme adopted in OCC is covered in Sect. 25.4. Finally Sect. 25.5 outlines OCC applications in particular for indoor positioning and vehicular communications, followed by the summary in Sect. 25.6.
25.2 OCC Concept

In traditional optical communication systems, which include optical fibre communications and optical wireless communications, the receiver is normally a non-imaging device, e.g., PIN photodiode (PD) or avalanche photodiode (APD). The role of the PD is to absorb incident photons and convert them into electrons. If the detector is not saturated, the output current of a PD changes linearly with the incident light power. Generally speaking, a PD with a smaller active area will lead to a faster response. However, compared to the transmission distance (≈ m) the small area (≈ mm²) PDs will result in reduced optical power detection, thus limiting the transmission range. Therefore, there is a trade-off between the communication range and the achievable $R_b$. To increase the received optical power level, a concentrator is usually employed in front of PD. Although VLC employing a concentrator and a small area PD can provide high $R_b$—in the order of several Gbps [8], the drawbacks are shorter range, lack of mobility and difficulty to separate each of the optical signals, thus limiting VLC’s practical application at the present time. However, with introduction of new materials and devices and utilizing advanced signal processing these limitations can be addressed in the near future.

Modern cars do come with a number of optical devices. Infrared (IR) LEDs and PDs have been used for rain detection and the automatic activation of wipers. PDs are used to automatically switch-on headlamps when the luminosity level drops. Cameras are being used both within and outside cars. Inside the car, cameras are used for driver attention monitoring, whereas outside the car cameras in the near-IR/visible range are used for a number of applications including road signs reading, blind spot, back-up cameras, lane departure monitoring, detection of other vehicles, monitoring distance to other vehicles or objects etc.

In VLC an image sensor (IS) (or a camera), composed of a PD array and a built-in readout circuit, can also be used as a receiver. Using an image lens light from different directions within the field of view (FOV) of a camera can be projected onto different locations in an IS. Each pixel of IS generates electrons, which are proportional to the integration of the received optical spectral density $S_r(\lambda)$ and the responsivity of pixel $R(\lambda)$. Finally, the readout circuit regularly reads out the accumulated charge of each cell in the image. Consider that a camera can be modelled as a two-dimensional PD array, which normally contains more than 10 million pixels and each of the size is ≈ 10 µm [9] to ≈ 1 µm [10]. Therefore, a camera has a very high spatial resolution, which means that light coming from slightly different directions will be projected on the different positions of a sensor using a lens, and be sampled by different pixels. This spatial separation ability enables the camera to separate light from different directions, and is ideal for spatial-division multiplexing (SDM) and imaging MIMO systems in VLC as illustrated in Fig. 25.1.

Generally, there are two main problems in camera communications: (i) Light flickering due to the typical frame rate of a commercial camera, which is low (i.e., 25–50 fps), thus only suitable for video recording. If the signal is transmitted at a
low frequency using visible light sources, human eye will detect light flickering, which is not acceptable for light illumination [11]. (ii) Lower data rate compared to PD-based systems widely used in VLCs. One partial solution to this problem is to utilize the rolling shutter (RS) effect of a complementary metal–oxide–semiconductor (CMOS) camera [12], which exposes an image line by line. By emitting light signals at a high frequency (e.g. few kHz), flickering is no longer observable to human eye. However, dark and bright strips can be captured by RS cameras. One of the drawbacks of this approach is the need for the entire or a large part of the CMOS sensor being exposed to illumination, which of course will restrict the transmission distance and it is not easy to utilize the spatial multiplexing capabilities of ISs. An alternative solution would be to adopt undersampled modulation schemes, such as undersampled frequency shift on-off keying modulation (UFSOOK) [13]. This approach requires a line-of-sight (LOS) path between the transmitter and the receiver and can also support a degenerated case of the classic MIMO scheme with little or no cross coupling between light sources [14] to increase the data rate but at the cost of increased complexity.

### 25.2.1 Transmitters

Among the many light sources such as fluorescent lamp, incandescent light bulb, halogen lamp and LED that are currently used for illumination, only LEDs are suitable as the transmitter in VLC systems. With the ability to be switched on and off at fast rates [15], LEDs are considered the perfect light source for VLC as well as localization [16]. Compared to the traditional lighting fixtures, LEDs have higher energy efficiency, smaller size, longer lifespan, and offer a much wider range of colour that can precisely be controlled. As a result, we are seeing a rapid installation of high luminance LED lighting fixtures at a global level in places such as homes, offices, shopping malls, transportations, traffic and street lights and mobile phone
(flash light). Generally speaking, there are three methods to produced white LEDs [17] as shown in Fig. 25.2:

- Blue LED + yellow phosphor—where the white light is due to blue electroluminescence (EL) emission and yellow photoluminescence (PL) emission.
- Ultraviolet (UV) LED + red green blue (RGB) phosphors—where white PL emission is because of RGB phosphors excited by UV LED.
- RGB LEDs—white EL emission from individual red green and blue LEDs.

Unlike the first two, the latter LED type uses 3 LED chips, which can be controlled independently, thus enabling parallel transmission of three independent
signals. However, VLC based on this approach will require a receiver with three PDs. Each PD should have an optical bandpass filter with a centre wavelength matching the RGB LEDs’ wavelength, thus making parallel transmission (i.e., wavelength-division multiplexing (WDM)) is complex and bulky.

Since almost every IS has a built-in colour filter, which will be discussed later, the camera-based receiver has a natural ability to separate the RGB channels. This unique feature will make the optical camera communication more interesting.

25.2.2 Receivers

As outlined above a camera is composed of an imaging lens, an IS and other supporting components. Imaging lens is a precision optics, which is used to focus an image of an object onto a camera sensor. A digital IS is a two-dimensional array of photodetectors, which detects and conveys the information that constitutes an image. CMOS technology-based active pixel sensors IS are used in most smartphone cameras, which often used to capture 2D barcodes [18]. They are also used in VLC for low $R_b$ due to their relatively low frame rates by exploiting their rolling shutters [19] as well as being adopted in high-speed cameras for tracking or receiving VLC signals for car-to-car communications [20]. Note that high-speed optical receiver (PD + transimpedance amplifiers) is generally used for high bandwidth VLC. However, because of the larger size and higher power requirements PDTIA-based IS tends to have fewer pixels compared to CMOS IS, thus trading off image resolution for speed.

Provided the sampling rate is high enough to avoid aliasing, the impulse response and the corresponding Fourier transform of the CMOS active pixel are given, respectively as

$$h(t) = A(u(t) - u(t - T_{shutter}))$$

$$H(f) = A \exp(-j\pi f T_{shutter}) \cdot 2 \sin(\pi f T_{shutter}) / 2\pi f$$

where $u(t)$ is the unit step function, $A$ represents the responsivity of PD and electrical signal amplification, and $T_{shutter}$ is the exposure time. Note that the $\sin(x)/x$ factor represents the frequency response of integrating the input signal over $T_{shutter}$.

In order to obtain the colour information, IS is normally covered with a red, a green or a blue filter in a repeating pattern. This pattern (or sequence) of filters can vary, but one could use the widely adopted Bayer colour filter array, which is a repeating $2 \times 2$ pattern as illustrated in Fig. 25.3, for digital acquisition of colour images [21].

Note that the array shown in Fig. 25.3 contains twice as many green as red or blue filters. This is because human eye is more sensitive to the green light than both red and blue lights. With green pixels redundancy produces a finer detail and less noisy image than could be achieved if each colour was treated equally. Therefore,
we are able to separate the RGB signal with a colour camera. This characteristic provides us the opportunity to employ the WDM technique in OCC systems directly, which might increase the total throughput many times without increasing the number of receivers. There are two methods used to capture a still picture or each frame of a video signal. The first is called the global shutter (GS), where all pixels of the image sensor are exposed starting and stopping at the same time. Therefore, the GS camera captures the entire picture or the video frame simultaneously. In the contrast, the another method is known as the rolling shutter, the exposure is initiated and stopped one row at a time with each row of the sensor being exposed for the same duration of time. Not by physically moving a shutter across each row of pixel vertically or horizontally, the digital rolling shutter camera tells different row of its sensor to become light-sensitive at different moments in time. This process continues until the entire IS is exposed to the light [22].

Figure 25.4 demonstrates a frame capturing process of the GS and RS cameras [23]. As we can observe, due to the special row-by-row exposure process there is a need for a very fast clocking frequency in order to reduce the time delay between each row. RS will result in effects such as wobble, skew, smear and partial exposure when it is used to take a photo or record a video. However, this drawback could be exploited as an opportunity to record changes in the light intensity within a frame exposure time, we will explain this in detail later. Note that this operation is quite different to the PD-based receiver where an electric current is generated continuously with magnitude directly proportional to the received optical power. The camera captures $f_{\text{camera}}$ frames per second, where $f_{\text{camera}}$ is the frame rate of the camera, and each captured frame has exposure duration of $t_{\text{shutter}}$. Therefore the camera can be considered as integrate-and-dump receiver, where each pixel collects photons within $t_{\text{shutter}}$ and produces a RGB value which changes according the colour of the received light and the light intensity. The pixel is reset and the process is repeated $f_{\text{camera}}$ times per second.
Because of using an imaging lens and an IS to capture image, a camera has the ability to separate lights coming from different directions. Since each pixel is an independent PD, and the sampling frequency (i.e. $f_{\text{camera}}$) is limited to <100 Hz for standard cameras and the built-in camera in smart devices. The camera can be used to achieve a high $R_b$ by employing the imaging MIMO technique [24]. Figure 25.5 presents an illustration of an OCC system using an imaging MIMO, which is composed of multiple LEDs and a camera. As we can see LEDs transmit parallel signals simultaneously, therefore a PD-based receiver cannot be used to separate the mixed signal. This is because a PD capture the sum of all light (i.e. intensity) and it cannot distinguish lights coming from different directions. However, employing a
lens and an IS lights coming from different directions can be projected to different
locations on the IS. Therefore, lights can be separated spatially and their intensity
can be acquired by obtaining the pixel value for each LED image of the received
frame. Finally, the parallel data can be extracted from these pixelated images by
means of image processing.

There are two types of MIMO techniques in VLC systems depending on what
type of receiver being used. The imaging MIMO VLC system (see Fig. 25.5) as
detailed above employs a camera, which has an imaging lens and an IS, to separate
different light signals. The second type—non-imaging MIMO VLC system as
shown in Fig. 25.6—uses multiple PD-based receiver (with a non-imaging lens)
where each PD receives light signals from all LEDs [25]. A channel matrix $H$ must
be obtained in order to de-multiplex the mixed signal. To reduce the correlation of
each channel DC gain, there should be a certain distance between LEDs and
between PDs. Although it is apparent that the imaging MIMO offers an improved
performance compared to the non-imaging MIMO, the lenses used normally have a
small FOV. For instance, for a camera with a 35 mm full-frame sensor and a
50 mm lens the FOV is about 46° [26], which is similar to the popular iOS devices
with a FOVs of ~50° [27] compared to PDs with a FOV of 120° or wider [28].
Therefore, the imaging MIMO system offers limited mobility than the non-imaging
MIMO system.

Imaging MIMO can be used to increase $R_b$, and to offer multiple access, as well
as reducing the bit error rate (BER) by way of all LEDs transmitting the same signal
(i.e. spatial redundancy) [29]. In order to facilitate different functions in imaging
MIMIO, a communication protocol has been developed [14]. Additional advantage
of using the imaging MIMO is the improved received signal-to-noise ratio (SNR),
where lights from signal and noise are received by different pixels, compared to the traditional PD-based receiver, where the sum of all lights (i.e., information, interference and ambient) is captured. Therefore, it is possible to achieve a very high SNR by extracting the received RGB value from the useful portion of the frame.

25.4 Modulation Schemes

In this section, we outline details of the most popular modulation schemes adopted in OCC systems. Compared with the traditional PD-based VLC system, the OCC system employs a camera as the receiver. So that the light emitted from LED will be captured by a camera in the form of pictures or video frames. Hence, the traditional modulation schemes for PD-based VLC system may not be suitable for OCC systems. Thus, there is a need for new modulation schemes to support the lighting as well as OCC systems. Additionally, OCC is a typical asynchronous communication system, and in order to achieve synchronization, a special technique must be used. There are four main modulation schemes in OCC system, which are on-off keying (OOK), undersampled-based modulation, rolling shutter effect-based modulation and liquid-crystal display (LCD)-based modulation.

25.4.1 OOK

In OOK-based OCC systems, the baseband signal intensity modulates the LED. To ensure no light flickering, the frequency of the baseband signal must be higher than CFF, which is normally 100 Hz. As a result the camera’s frame rate (sampling rate) must be at least twice the baseband signal frequency, i.e. >200 fps. Figure 25.7 shows an OCC sampling diagram with the OOK data format, each baseband bit of duration $t_{\text{OOK}}$ is sampled twice with a sampling duration of $t_{\text{shutter}}$ (i.e. the exposure time for IS). Since OCC is an asynchronous communication system, the frequencies of the transmitter and receiver must be the same. Any difference in the frequency will result in errors.

In [30] a series of experimental works on OOK-based OCC using the imaging MIMO technique were carried out. A high-speed camera (1000 fps) and a transmitter with 256 LEDs was used. The modulation frequencies adopted were 250 Hz and 500 Hz. The measured BER results showed that for the transmission span shorter than 35 m no error was recorded. However, for a longer distance within the range of 35–40 m a BER of $10^{-3}$ was observed. Apart from the mono colour OOK scheme, RGB OOK modulation can be also employed to increase the total $R_b$. In [31] a technology known as Picalico was developed, which used blinking RGB colours to transmit information, and a camera-equipped device to extract the information.
25.4.2 Undersampled-Based Modulation

Using OOK modulation, a high-speed camera with a frame rate higher than 200 fps is required. However, regarding most of the commercial cameras or camera-equipped smart devices, the frame rate is limited to about 30 fps. This means that $R_b$ has to be lower than 15 bps, which can be detected by human eye, in OOK-based OCC systems. Therefore, to use a low frame rate camera as a receiver, the low data rate baseband signal must be modulated to a higher frequency. Undersampled frequency shift OOK (UFSOOK) modulation was proposed in [13], which employs two special designed square wave patterns with different frequencies to represent mark (bit “1”) and space (bit “0”). According to [13], UFSOOK transmits a square wave subcarrier frequency shift keying modulated signal with a carrier frequency $f_s^1$ and $f_s^2$. Therefore, UPSOOK signal $s(t)$ can be mathematically expressed as

$$s(t) = \begin{cases} \cos(2\pi f_{s1} t) & \text{if } a_n = 1 \\ \cos(2\pi f_{s2} t) & \text{if } a_n = 0 \end{cases} \quad 0 < t \leq T_c \quad (25.3)$$

where $[\cdot]$ denotes a square wave, $f_{s1} = (m \pm 0.5) \times f_{\text{camera}}$ and $f_{s2} = m \times f_{\text{camera}}$, and $m$ is an integer.

At the receiver side, a camera is employed to continuously undersample the light signal, and it produces steady states (either ON or OFF) or blink states (OFF-ON or ON-OFF) of LED—if the sampled data are the same then bit “0” is received, otherwise bit “1” is detected.

Figure 25.8a depicts an example of the UFSOOK pattern composed of a frame header (FH), 7-cycle of bit “1” and 8-cycle of bit “0” (note the camera frame rate is 30 Hz). As we can see that the time interval between two captured video frames is $t_{\text{camera}}$, and the frame header signal is a square wave with a frequency $f_{\text{FH}} > f_{\text{max,camera}}$, where $f_{\text{max,camera}}$ is the CFF of a camera. $f_{\text{max,camera}}$ depends on the type of camera and varies with the inverse of the shutter speed. At the receiver side, a camera was used to record a continuous series of images of the LED, with each image taken at the position of the grey sampling strobes. It can be observed from Fig. 25.8a that the camera captures two successive images within each UFSOOK symbol. Therefore, from the view of the camera, LED appears as two half ON (average) states when the FH signal is captured, while LED appears two different states for bit “1” and two same states for bit “0” as given in Fig. 25.8.
A unique frame structure to support the asynchronous communication was designed to send the FH symbol prior to each data frame.

In order to increase the video frame samples’ efficiency, especially when a low frame rate camera is used an undersampled phase shift OOK (UPSOOK) modulation was proposed in [32], which is similar to the phase shift keying (PSK). UPSOOK transmits a square wave subcarrier phase shift keying modulated signal with a carrier frequency $f_s = m/C_2 f_{camera}$ ($f_{max_eye} < f_s < f_{max_camera}$), where $m$ is an integer. The UPSOOK signal $s(t)$ can be mathematically expressed as

$$s(t) = \left[ \cos \left( 2\pi f_s t + \theta_n \right) \right] \quad 0 < t \leq T_c$$

where $\left[ \cdot \right]$ denotes a square wave with the phase $\theta_n$ modulated with the input data $\{a_n\}$ as given by:

$$\theta_n = \begin{cases} 0^\circ & a_n = 1 \\ 180^\circ & a_n = 0 \end{cases}$$

Note that the carrier frequency must be an integer multiple of the camera frame rate. Although both the transmitter and camera operated at the same frequency, there might be a random phase difference between them.

Figure 25.8a shows an original baseband signal with duration of $t_{camera}$, and the waveforms in Fig. 25.8b, c demonstrate the modulated UPSOOK signals. It can be seen from Figs. 25.8b, c that because of the phase uncertainty, there will be two possible sampled data with the same received signal. Thus, the uncertainty determines whether the received “ON” or “OFF” symbols represent bit “1” or “0” at the receiver side.

In order to prevent this uncertainty, a framing strategy is needed as described in the following. Each frame is composed of a start frame delimiter (SFD) and a payload of $q$-UPSOOK symbols. SFD enables asynchronous communication as shown in Fig. 25.9a. It is composed of 2-symbol, with the first symbol being the
Fig. 25.9 An example of UPSOOK patterns
\( f_{\text{camera}} = 30 \) fps, 
\( f_{\text{FH}} = 25 \text{ kHz}, \)
\( f_{\text{space}} = f_{\text{mark}} = 120 \text{ Hz}, \)
\( \theta_{\text{mark}} = 0^\circ, \theta_{\text{space}} = 180^\circ; \) a is the original baseband signal, b and c are two possible sampled results for the same received signal.

Fig. 25.10 Data frame structure

frame header, which is a square wave with a frequency of \( f_{\text{FH}} \) and with a time duration of \( 1/f_{\text{camera}} \). The second symbol is the mark symbol, which is also a square wave with a frequency of \( f_{\text{mark}} \) and a time duration of \( 1/f_{\text{camera}} \).

As we have already known that the phase uncertainty between the frequencies at the transmitter and receiver may lead to bit error, but it has no effect on the frame header signal. Therefore, if all data are sent according to the proposed frame strategy, then the error caused by phase uncertainty can be detected by examining the second received symbol of a frame. Figure 25.11 shows two possible received data frames. It is apparent that if the second symbol in a frame is ON then no error

Fig. 25.11 Two possible received data frames, a no need to do error correction, b need to do error correction
is introduced due to phase uncertainty. However, if the second symbol is OFF all the ON symbols in the frame would be OFF, and all the OFF symbols would be ON. Therefore, this procedure can successfully correct the error introduced by the phase uncertainty, and can also be considered as a special forward error correction (FEC) scheme. For the idle state, we send space and mark alternately. By receiving the idle signal the RGB value of ON and OFF are kept up to date.

### 25.4.3 Rolling Shutter Effect-Based Modulation

Apart from the above mentioned modulation schemes, which rely on extracting information from a portion of pixels that contain the image of LED lamps. There is another type of scheme to extract information from all pixels of each video frame by exploiting the RS effect of the CMOS camera. As demonstrated in Fig. 25.4 the RS-based camera capture lights from an image sensor in form of a row-by-row process. Provided light is flickering at a frequency lower than the RS’s scanning frequency but higher than CFF of human eye, the sensor would be able to record the dark and bright stripes as shown in Fig. 25.12a.

When the LED (the left column of Fig. 25.12a) is on, the whole image sensor (the middle column of Fig. 25.12a) is illuminated by the light emitted from LED, and the CMOS sensor exposes the first row of the image (the right column of Fig. 25.12a). The LED is then switched off and the second scan line is enabled, which results in the second black row. The process continuous until all the scan lines are exposed, and finally a video frame is generated. The width of these bands is proportional to the transmitted symbol duration and the scanning rate of CMOS sensor. Therefore, we are able to obtain a waveform, which is sampled at the frequency of the scanning rate of CMOS sensor from a video frame. Figure 25.12b presents a captured video frame of a white wall, which is illuminated by a green light.
LED with a flicker frequency of 1.5 kHz. It is clear that bright and dark bands are uniformly distributed in the frame. The white waveform, which is the sum of pixel values per row, on the right side of this figure shows the LED’s flicker pattern. As we have seen more than one bit per video frame information can be obtained, which leads to an increased data rate compared to the undersampled-based modulation. However, due to the lack of synchronization between LED lamps and the camera, the CMOS sensor might not be able to capture a complete data package/block in a given video frame. Therefore, protocols are required to ensure that the camera is able to extract complete information from a series of successive video frames.

In [12] Manchester coding/decoding together with a block detection scheme to indicate and detect a block of information was demonstrated. The experiment results showed that the RS effect can be exploited to achieve data rates much faster than the frame rate using a camera with a CMOS sensor over transmission distance of <50 cm. Similar to [12], in [33] the RS effect was explored to establish a data transformation link. However, in order to avoid signal collision when multiple LED are used, in [33] binary frequency shift keying (BFSK) modulation and frequency division multiple access (FDMA) were used to support multiple transmitters. According to the experimental work reported, smartphones are able to accurately detect frequencies as high as 8 kHz with 0.2 kHz of channel separation. A prototype was developed to evaluate the proposed system, which is able to transmit signal at a data rate of 10 bps on 29 channels concurrently using an iPad 3.

25.4.4 LCD-Based Modulation

In LCD-based OCC systems, LED lamps are not used to send information, instead the information is transmitted via a 2 dimensional particular square image, e.g. quick response (QR) code. Since LCD screen can display any image dynamically, then using a camera to record these dynamic images the data can be transferred to the receiver (smart device) wirelessly via the camera. Commercial smart device (smartphone or a tablet) with a built-in camera has an image sensor of ~10 megapixels. Although the frame rate of the smart devices is very low (20–50 fps), however, by sending information using the dynamic QR code image, e.g. version 40 [34], a maximum of 7089 numeric characters or 23,624 binary bits data can be transmitted in each frame. What is more, by incorporating RGB coding with this scheme, the data rate can be increased by three folds [35], thus facilitating the potential of high-speed communications.

Figure 25.13 shows an example of a V40 QR code for the first 500-digit of Pi. This QR code has 57 × 57 modules and an error correction level of M, which means that up to 15 % of code words can be restored with a damaged pattern. If we use a QR code reader to scan this pattern, the smart device will immediately display the first 500-digit of PI. Therefore, if we send the QR code at the frequency of the camera’s frame rate (e.g. 24 fps), then we are expected to establish a communications link with a data rate of 12,000 numeric characters per second using the
V40 QR code LCD-based OCC system. Although this LCD-based modulation scheme has the potential to transmit data using the LCD display and a smart device with a built-in camera at a high-speed, the smart device must not move to avoid getting a blur QR code pattern, which may not be suitable for decoding.

25.5 Application of OCC

Due to LOS and low speed restrictions, the OCC system is not as flexible as the traditional RF communication. However, cameras have some unique features such as spatial separation ability, built-in Bayer RGB filter and RS effect. Resulting in some special features of camera-based OCC systems, for example supporting imaging MIMO and WDM, non-flicker data transmission using a low frame rate camera, and data detection from still images or dynamic images. Therefore, the combined features outlined above could be effectively explored to demonstrate the potential of OCC system for data transmission in multitude of applications.

25.5.1 Indoor Positioning

One of the potential applications for OCC is the emerging area of indoor positioning, which uses the LED-based lighting infrastructures. Provided LED lamps are given a unique identification (ID) code, a smart device with a built-in camera can be effectively used to locate people and object within a room. Figure 25.14a depicts the layout of LED lamps in an arrayed rectangular grid shapes within a room, whereas Fig. 25.14b shows the corresponding basic positioning unit with four LEDs and one receiver. When a smart phone is facing vertically upward towards LEDs, its camera may capture light from one or more than one LEDs or none at all. When only one LED is captured, a coarse position can be obtained by querying the received ID from the pre-stored position database. However, when
more than one LED is recorded, e.g. Figure 25.14c, then more accurate position detection schemes such as the angle of arrival (AOA) should be used [11].

Several tests for people shadowing were performed in [36]. Another important issue is to determine FOV statistics. As can be seen in Fig. 25.15a in several cases user shadows contributes to considerable portion of the FOV. In [37] several tests with both panoramic 3D camera and user mobile camera were performed. The single user shadowing statistics of FOV followed almost normal distribution. For more users the derived distribution was Rayleigh (see example of cumulative

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**Fig. 25.14** a Indoor LED lamp arrangement, b the basic unit, and c an example of a captured video frame of 4 LED lamps

**Fig. 25.15** a FOV shadowing by the user, b cumulative distribution function of shadowing camera FOV in case of people moving in the office room
distribution function of FOV shadowing in case of horizontal placed detector of camera in the office room with 2–4 moving people).

25.5.2 Vehicle-to-Vehicle and Vehicle-to-Infrastructure Communication

Intelligent transport systems (ITS) offer a great potential to enhance the road safety, improve traffic flow, and address environmental concerns by monitoring driving behaviour, communicating between vehicles and the roadside infrastructure, thus giving warnings to drivers and providing information for safe driving [38]. Dedicated short range communication (DSRC) systems are considered to be the promising technology for enabling bidirectional communications between vehicles and the roadside infrastructures [39]. Apart from RF-based system alternative technology based on OCC can be used to establish vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Nowadays many vehicles already have LED headlights and even data recorders or front view/rear view camera, which can be used as Tx and Rx in OCC systems as shown in Fig. 25.16.

In ITS, the OCC technology can offer distinctive advantages compared to the RF-based DSRC technologies, such as (i) low complexity and low cost particularly in places where LED lamps are widely used such as vehicles, traffic lights and street lights [40]; (ii) high precision positioning, owing to the directional line-of-sight propagation characteristics of light. VLC based positioning technologies are able to reduce the positioning error to tens of centimetres [41], which are more accurate compared to the RF-based positioning technology [11]; and (iii) high scalability and low level of interference [42], as vehicle density increases (e.g. during the rush hours), the RF technology will typically experience undesirable packet collisions and longer delays as well as poor packet reception rate [43]. Whereas using the OCC technology vehicles only receive signals from neighbouring vehicles, thus leading to much reduced signal congestion and interference.

Although the data rate of OCC system is quite low compared to DSRC systems, it is still believed that this low data rate capability of a few hundreds of bits per second is more than adequate for transmitting emergency messages between cars and V2I [44]. In [20] a high-speed VLC system using the CMOS IS was

Fig. 25.16 A scenario of V2V communication system using OCC
demonstrated in V2V field trial at a data rate of 10 Mbps with correct and real-time LED detection as in [45].

25.5.3 Other Applications

Other applications of OCC include dynamic advertising where background LEDs send advertisement information to users through a smartphone camera [46]. Augment reality is also an interesting application of OCC, for example we might use a Google Glass to receive data from LED lamps and the additional information will appear near the LED lamps.

25.6 Conclusions

This chapter gave an overview of optical camera communications. First, the principle of OCC was introduced, including three types of LED chips and the basic operation of camera as well as the RGB filter of an image sensor. Second, the imaging MIMO using a camera was outlined taking advantage of the spatial separation capability increase the total throughput and improve the BER performance or to establish a multiuser access network. Next, four types of modulation schemes namely OOK modulation, undersampled-based modulation, rolling shutter effect-based modulation and LCD-based modulation were introduced. We showed that using modulation scheme a range of data rates and transmission communication spans can be achieved for a range of applications. Finally, OCC applications were discussed mainly focusing on the indoor positioning and V2V/V2I communications were discussed.

References


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