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The first tests of smartphone camera exposure effect on optical camera communication links

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***Abstract*—In this paper, we study the effect of smartphone camera exposure on the performance of optical camera communications (OCC) link. The exposure parameters of image sensor sensitivity (ISO), aperture and shutter speed are included. A static OCC link with a 8×8 red, green and blue (RGB) LED array employed as the transmitter and a smartphone camera as the receiver is demonstrated to verify the study. Signal-to-noise ratio (SNR) analysis at different ISO values, the effect of aperture and shutter speed on communication link quality is performed. While SNRs of 20.6 dB and 16.9 dB are measured at 1 m and 2 m transmission distance, respectively for a ISO value of 100, they are decreased to 17.4 dB and 13.32 dB for a ISO of 800. The bit error rate (BER) of a 1 m long OCC link with a camera's shutter speed of 1/6000 s is 1.3×10^{-3} (i.e., below the forward error correction BER limit of 3.8×10^{-3}) and is dropped to 0.0125 at a shutter speed of 1/20 s. This study provides insight of the basic smartphone settings and the exposure adjustment for further complex OCC links.**

***Index Terms*—Visible light communications (VLC), optical camera communications (OCC), Smartphone OCC, light emitting diodes (LEDs)**

I. Introduction

Over the past few decades, mobile phones and smart devices have been equipped with a built-in complementary metal-oxide-semiconductor (CMOS) cameras [1]. These CMOS cameras are capable of capturing high-resolution videos with a resolution of at least 1280×720 pixels and a capture rate of 30 fps. Due to the large scale and increasing availability of mobile phones, smartphone camera based visible light communications (VLC) has become an attractive option for data communications, as nearly six billions of smartphones have been sold worldwide [2]. The smartphone camera-based VLC also termed as optical camera communications (OCC) has been studied within the framework of optical wireless communications within IEEE 802.15.7rl standard [3], [4]. Both VLC and OCC using the visible light spectrum (370-780 nm) is being considered as possible wireless technologies within the fifth generation wireless communication networks [5], [6].

The OCC, unlike conventional VLCs employing photodetectors (PDs), utilizes a mobile phone CMOS camera as the receiver and thus has an inherent advantage of capturing data in 2-dimensions (2D) in the form of image sequences [7] and possibly higher dimensional information. Thus, a series of images (i.e., frames) containing information are embedded in intensity, multiple colors and spatial coordinates. However, it suffers from a longer frames processing due to a larger dimension of frames and offers significantly lower data rates compared with PD-based VLC schemes.

In OCC, image processing is essential and critical point for detection and recovery of the transmitted information in the form of captured image frames therefore, the camera's exposure settings for focusing capturing data is important. Various image processing studies have been proposed such as the multi-exposure fusion method, where by considering the exposure level measurement of the local and global luminance components of the input images were investigated [8]. The sensitivity of an image sensor is measured using ISO. In OCC links, high ISO results in amplified image signal as well increased noise levels [9]. The ISO induced noise effect on the luminance and chrominance channels were investigated in [9]. Moreover, a pixel wise coded exposure for high-speed imaging [10] and multiple exposure fusion for high dynamic range image acquisition [11] were also proposed with the effects of camera exposure settings within image processing.

In [12] multiple exposure coding was proposed for short and long distance transmissions in vehicular OCC. High signal quality transmission for long distances and high data rates for short distance communications were achieved using two cameras with different levels of exposure times [12]. Recently, a 160 m long optical link was demonstrated [13] utilizing undersampled phase-frequency shift on-off keying modulation with red, green and blue (RGB) light emitting diodes (LEDs) by exploiting the ISO at the receiver [13], [14]. Moreover, the works [14] and [15]–[17] utilized fast shutter speeds at the receiver, thereby imposing restrictions on the minimum signal-to-noise ratio (SNR) to achieve a specific communications distance. In [18], a comprehensive theoretical model for non-line-of-sight $2\times N$ OCC system was experimentally investigated, showing that higher ISO levels and exposure times led to a reduced transmit power level by 3 dB for every doubling of the exposure time and ISO at a bit error rate of 10^{-3}.

In this work we study the effect of camera exposure settings including ISO, shutter speed and aperture on the OCC links. A 8×8 RGB LED array and a Samsung Galaxy S9 smartphone camera are used as the transmitter and the receiver, restrictively. Experiments are performed by changing the ISO and the shutter speed by setting the resolution to the commonly used full-HD (FHD) (1920×1080 pixels) resolution. The effect of aperture, shutter speed and different ISO values on the link performance are investigated. We show, a SNR of 20.6 dB and a bit error rate (BER) of 1.3×10^{-3} (below the forward error correction BER limit of 3.8×10^{-3}) for a 1 m OCC transmission link span.

The remainder of the paper is organized as the following. Section II describes the smartphone camera based OCC, while Section III shows the experiment setup, followed by Section IV with discussion of results. Conclusions are drawn in Section V.

II. Smartphone camera based OCC

A. Exposure triangle for camera capturing

The exposure time sets the amount of light that reaches the image sensor, which determines how light or dark an image will appear. Note, too much light captured will overexpose (too bright/no details) images thus resulting in blooming effect, while less light results in underexposed (dark/grainy/less details) images. The blooming effect means that the number of photons reaching the detector exceeds its maximum capacity, and the excess photons will either spill and merge to adjacent pixels or are not counted, thus leading to non-precise intensities [19]. The camera's exposure is based mainly on three camera settings: aperture, ISO and shutter speed as shown in Fig. 1 [20], [21].

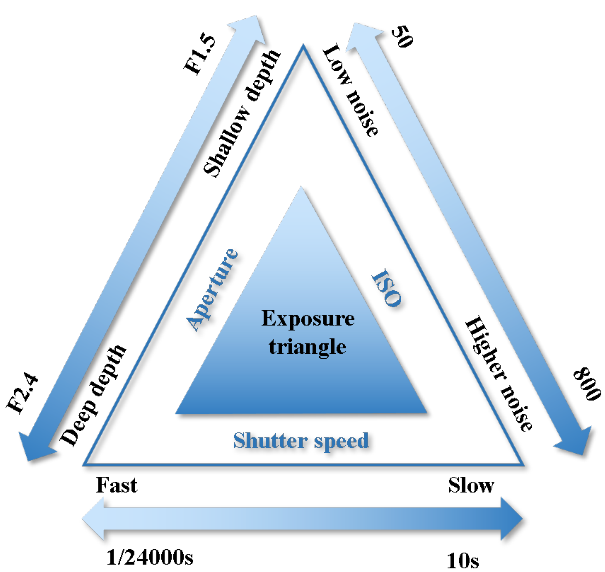

Fig. 1. Camera exposure triangle.

A cameras shutter speed is typically measured in fractions of a second. Slow shutter speeds allow more light incident and are used for low-light and night photography, while fast shutter speeds help to freeze motion [20], [21].

Aperture or also called as f-stop controls the amount of light being captured through the lens as well as controls the depth of field, which is the portion of a scene that appears to be sharp. For very small aperture the depth of field is large, while for large aperture, the depth of field is small. In photography, the aperture is expressed by F number (focal ratio) that represents the ratio of the diameter of the lens aperture to the length of the lens [20], [21].

Higher ISO (i.e., sensitivity of camera) means faster light absorbed by the sensor, but at the cost of increased noise level [20], [21].

B. Smartphone camera based OCC

A Samsung Galaxy S9 smartphone camera is utilized in proposed smartphone camera based OCC. The camera has shutter speed in the range of 1/24000 s to 10 s, aperture setting of F1.5 and F2.4 and ISO of 50 (low ISO) to 800 (high ISO). The resolutions supported by S9 front and rear camera are listed in Table 1. The rear and front camera support up to Ultra-HD (UHD) (3840×2160 pixels) and Quad-HD (QHD) (2560×1440 pixels) resolutions, respectively. These resolutions can also be expressed in terms of the image size (in megapixels) and the aspect ratio as:

$$Size\ of\ image = W \times H \tag{1}$$

$$Aspect\ ratio = \frac{W}{H} \tag{2}$$

TABLE I
Smartphone camera video resolution, size of image and aspect ratio.

Resolution (pixels)	Size of image (Megapixels)	Aspect ratio
3840×2160 (UHD)	8.3 (8294400)	16:9
2560×1440 (QHD)	3.69 (3686400)	16:9
1920×1080 (FHD)	2.074 (2073600)	16:9
2224×1080 (R1)	2.4 (2401920)	18:5:9
1440×1440 (R2)	2.074 (2073600)	1:1
1280×720 (HD)	0.92 (921600)	16:9

The pixel density of the S9 camera was also calculated as:

$$Pixel\ density = \frac{\sqrt{(W)^2 + (H)^2}}{Screen\ size} \tag{3}$$

where, W and H are the pixel width and height, respectively. Note the diagonal screen size of Samsung Galaxy S9 smartphone is 5.8".

Pixel density is usually referred to as pixels per inch (PPI). The calculated PPI with respect to the resolutions (as listed in Table 1) is shown in Fig. 2. The higher the PPI, the more details can be found within the image. It can be seen from Fig. 2 that, the maximum PPI of 759.6 is achieved using UHD resolution. Note that, not all cameras support UHD resolution, therefore the PPI of 300 is the limit set for high

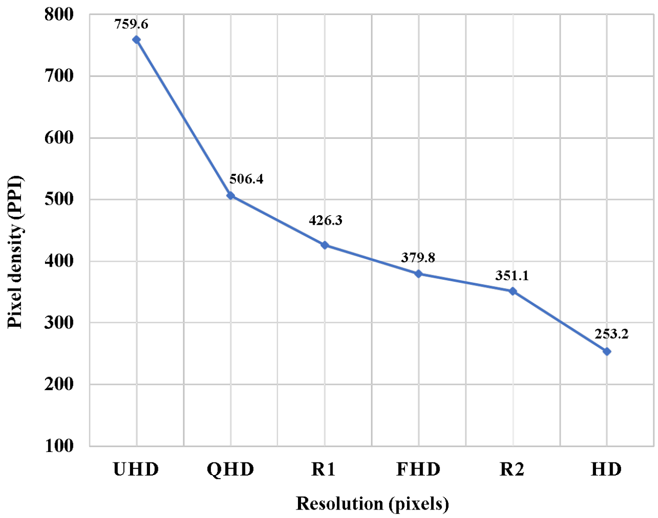

Fig. 2. Pixel density with respect to camera resolution.

quality image [22]. Thus, for further analysis, we use full-high definition (FHD) (i.e., 1920 × 1080 pixels) resolution with a PPI of 379.8 PPI.

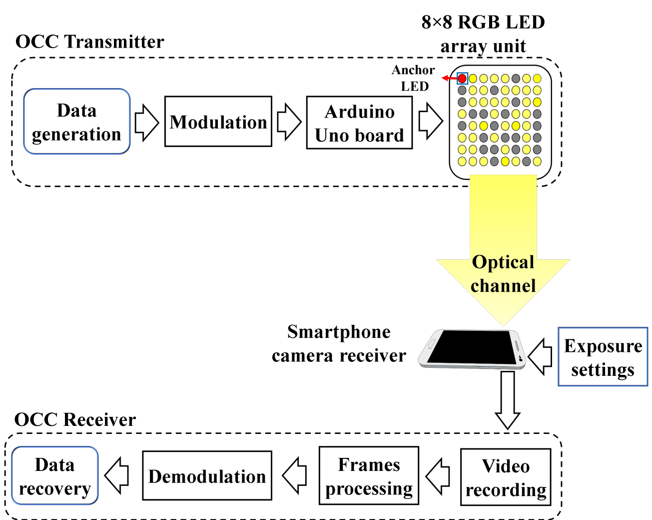

Fig. 3. Block diagram of smartphone camera based OCC.

Block diagram of smartphone camera based OCC with 8×8 RGB LED array is shown in Fig. 3. For data modulation, we have employed on-off keying (OOK), which is the most commonly used in OCC. The proposed OCC link is static, therefore, we include only one anchor LED in the first frame of data transmission for evaluating the transmitted data at the receiver.

Following image capturing using the camera at the receiver, frame processing and demodulation the estimated version of the transmitted data is regenerated. Note, time and spatial synchronization are carried out in the demodulator [24]. For the precise LED detection in the array on the OCC link, an efficient detection scheme known as differential detection threshold (DDT) is employed [25].

III. Experiment Setup

Figure 4 shows the experiment setup, which was used to investigate the effect of camera exposure settings on the performance of the OCC link. The LED array was controlled using a Arduino Uno board, which is an open-source microcontroller board based on the ATmega328 [23]. A random binary data stream of 1279 bits (20 Hz transmitter flicker rate) and 1919 bits (30 Hz transmitter flicker rate) and a anchor bit was generated in the software domain (processing PC) and was mapped to each LED (i.e., address) using a Arduino Uno board. Table 2 shows the system parameters used to perform the experiments.

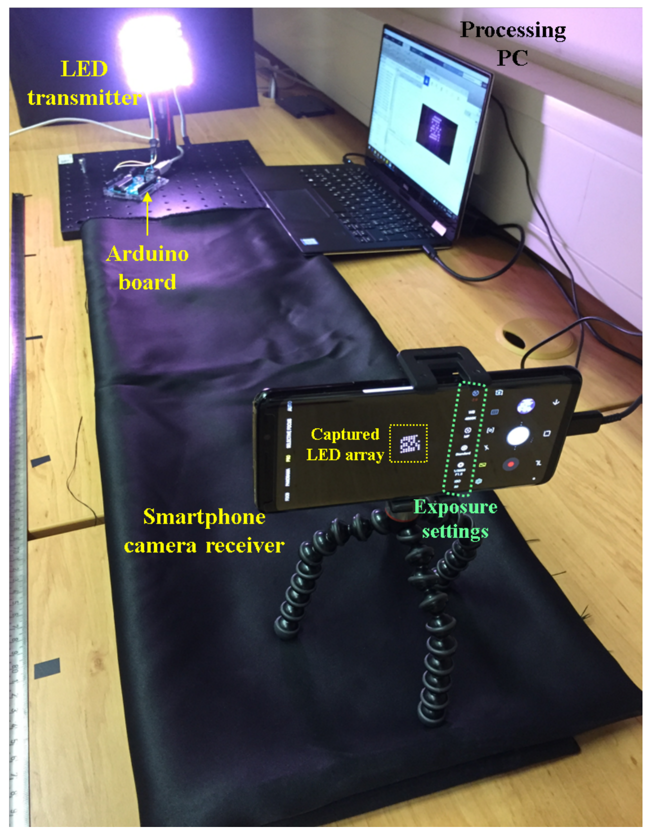

Fig. 4. Smartphone camera based OCC experiment setup.

As previously mentioned, both the front and rear cameras of Samsung Galaxy S9 smartphone support FHD resolution with a PPI of 379.8. For the purpose of demonstration of the proposed study, experiments were performed at two different transmission distances of 1 m and 2 m by changing the smartphone camera exposure settings under a static condition (see exposure settings of the rear camera used as the receiver in Fig. 4). Figure 4 also shows the captured LED array over the smartphone screen using the exposure settings.

TABLE II
System parameters.

Parameters	Description
Number of LED chips in an LED array	8×8 Neo pixel RGB LED array
LED array Dimensions	71.17mm / 2.8" x 71.17mm / 2.8"
Supply voltage and power	4.95 V, 95 mW
Transmitter flicker rate	20 Hz, 30 Hz
Transmission distance	20 - 200 cm
Receiver	Samsung Galaxy S9 smart-phone
Camera resolution used for capturing	1920 × 1080 pixels
Front camera specifications	8MP AF sensor Sensor size: 1/3.6" Pixel size: 1.22μ Sensor ratio: 4:3 FOV: 80°
Rear camera specifications	12MP AF sensor Sensor size: 1/2.55" Pixel size: 1.4μ Sensor ratio: 4:3 FOV: 77° ISO: 50-800 Aperture: F1.5, F2.4 Shutter speed: 10 - 1/24000 s
Frame period	50 ms, 33.34 ms

IV. Results

Due to the small LED array transmitter, the opening of camera lens, i.e., aperture, was set to F1.5 so as to capture shallow depth of the LED array. Videos were recorded by changing the ISO values from 100 to 800 with FHD resolution for 1 m and 2 m long OCC links. The recorded video streams were divided into image frames for further processing. Figure 5 illustrates the SNR performance as a function of ISO for two transmission distances. It can be seen from Fig. 5 that, the SNR degrades with increased ISO and transmission distance. For instance, at transmission distances of 1 m and 2 m the SNR values are 20.6 dB and 16.9 dB, respectively for a ISO of 100, which are reduced by 3.2 dB and 3.6 dB for a ISO of 800.

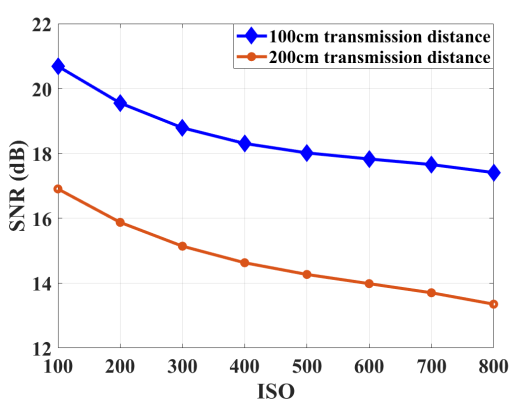

Fig. 5. Performance analysis: SNR with respect to ISO.

Figures 6 and 7 illustrates the captured LED with shutter speeds of 1/6000 s and 1/20 s for a 1 m OCC link and there image intensity profiles. Figures 6(a) and 7(a) were cropped to a 160 × 60 pixel size to plot the respective image intensity profile of the captured LED array. It can be seen from Fig. 6(b) that, the pixel intensities (measured from 0 to 255) for each LED peak is well distinguishable and the intensity at each peak is 252, which is close to the maximum intensity.

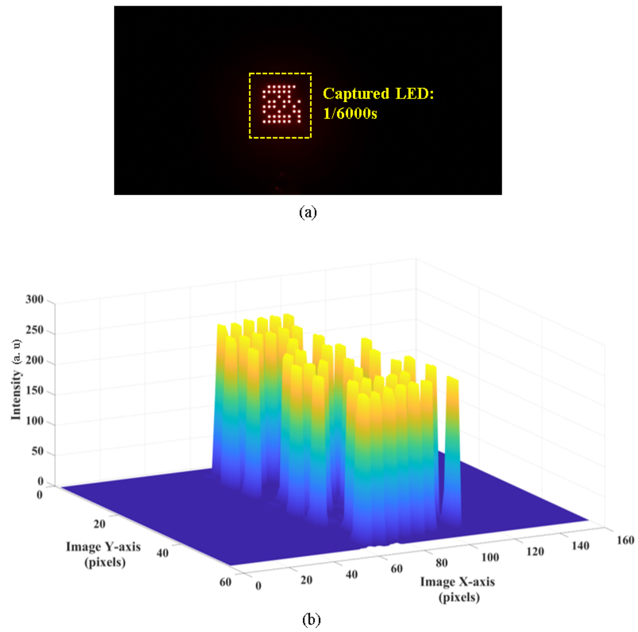

Fig. 6. LED array captured at a 1 m transmission distance: (a) shutter speed - 1/6000 s, and (b) image intensity profile.

As the shutter speed increases from 1/6000 s to 1/20 s, blooming of the LED array can be seen in Fig. 7(a). This is due to the fact that increasing in the shutter speed a higher time of light passing through the camera lens, thus increasing the number of incoming photons. Due to this, the photons start to spread and merge with the photons on the adjacent pixels causing blooming effect as seen in Fig. 7(b). The pixel intensity in this case is 254, which is higher compared to intensity shown in Fig. 6(b) due to the blooming effect. Table 3 shows the results for the BER at the shutter speeds of 1/6000 s and 1/20 s for 1 m and 2 m of transmission distances. For example, the BER for the shutter speed of 1/6000 s is 1.3×10^{-3} (below the forward error correction BER limit of 3.8×10^{-3}) at 1 m, which degrades to 0.0125 at a shutter speed of 1/20 s.

TABLE III
BER with respect to shutter speed and transmission distance.

Transmission distance (cm)	Shutter speed (s)	BER
100cm	1/6000 1/20	1.3×10^{-3} 0.0125
200cm	1/6000 1/20	0.1045 0.3756

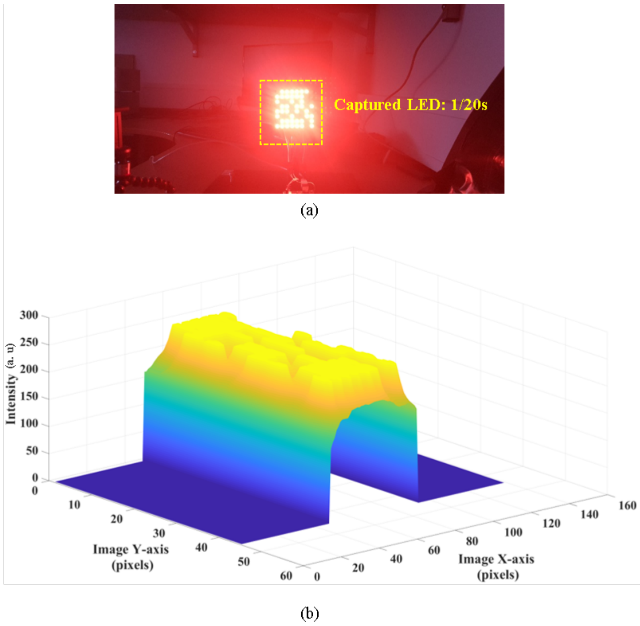

Fig. 7. LED array captured at a 1 m transmission distance: (a) shutter speed - 1/20 s, and (b) image intensity profile.

The S9 smartphone provides 30 fps and 60 fps at FHD and UHD resolutions, respectively. Therefore, the maximum data transmission rates of 1.279 kbps and 1.919 kbps were achieved when the camera was set to capture a 8×8 RGB LED array with one anchor LED at transmitter flicker rates of 20 Hz and 30 Hz for 30 fps and 60 fps, respectively.

V. Conclusion

A study on effect of smartphone camera exposure settings on OCC links was performed using a Samsung Galaxy S9. The experimental results demonstrated that, the higher ISOs and the shutter speeds increased the sensitivity of camera to absorb light faster and therefore experienced more noise. The SNRs of 20.6 dB and 16.9 dB SNR were achieved at ISO value of 100 while 17.4 dB and 13.3 dB SNR were achieved at ISO value of 800 at 1 m and 2 m transmission range. The BER for the shutter speed of 1/6000 s was 1.3×10^{-3} (below the forward error correction limit of 3.8×10^{-3}) at 1 m transmission which degraded to 0.0125 at the shutter speed of 1/20 s. The study can be further extended to complex analysis of exposure settings and increasing the communication link span using large LED array transmitter.

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