A Study of Optical Tag Detection Using Rolling Shutter Based Visible Light Communications

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Abstract— **In this paper, we present an in-depth study of light emitting diode (LED) based indoor visible light communication positioning system using a smart phone camera with rolling shutter effect, aiming for smart and connected hospital applications. The LED transmits periodical signals with different frequencies as its optical tags. The camera exploits the rolling shutter effect to detect the fundamental frequency of optical signals. The roles of camera parameters determining the rolling effect are studied and a technique to measure the camera readout time per column is presented. Factors limiting the detectable optical frequency range is explained based on the discussion of rolling shutter mechanism. The Fourier spectrum based frequency resolution, which determines the tracking capacity, is analyzed.**

Keywords—LED, visible light communication, rolling shutter

I. Introduction

In recent years, indoor positioning utilizing LED-based Visible Light Communication (VLC) technology has become an attractive technique as a promising solution to indoor positioning and tracking. LED lighting is greener. The unique property of fast on/off switching of solid-state LEDs enables visible light communications and positioning. Particularly, LED visible light positioning is attractive to indoor navigation where GPS signal is typically missing. Further, where radio-frequency (RF) technology is potentially harmful, such as in critical areas of hospitals, LED VLC technology is a potential solution for both wireless steaming, e.g., for telemedicine, and positioning, such as tracking. The VLC receiver can use photo detectors (PD) or cameras. The latter is widely available due to the proliferation of smartphones that use Complementary Metal-Oxide-Semiconductor (CMOS) imager sensors as the light receivers, opening a door for many applications. Recently, the rolling shutter effect of CMOS imager s has been studied to allow higher data rates than the camera frame rate. Unlike global shutter, which exposes imager array to the entire scene at the same time, each row of imager pixel within a rolling shutter of a CMOS imager array starts integrating sequentially [1]. [2] patents a concept of detecting optical authentication code using a rolling shutter camera, however, missing details about rolling shutter receiving method. [3] explores the possibility of using rolling shutter effect to decode OOK modulated data from LEDs for short distance and uniform reflecting surface. [4] presents an approach to distinguish IDs from different LEDs operating at different frequencies simultaneously in the same collision domain. [5] studies the channel characteristics of the line-of-sight (LOS) light-to-camera link.

When the rolling shutter based VLC link is used to transmit the optical tags, either a unique sequence of bits or a unique frequency can be assigned to LED tags. When a sequence of bits is used as LED IDs, a threshold is usually required to decode the modulated light. Polynomial fitting could be used in a non-homogeneous image to normalize the received optical signals [3]. Image processing techniques are used to enhance the VLC signals and decrease the impact of unbalanced illumination [6, 7]. For frequency based identification, fast Fourier transform (FFT) is usually applied to analyze the frequency spectrum [4, 8] and detect the appearance of certain frequency components. Furthermore, the width and the number of the bright and dark bands captured can be used to measure the modulation frequency [9, 10]. Alternatively, the phase variance can be analyzed to detect modulation frequency [8]. In this paper, we present a detailed exploration of fundamental characteristics of rolling shutter mechanism for LED light based tracking and its impacts on the received optical light tags. The paper is organized as follows. Section II depicts the new concept of LED VLC based live tracking network for smart hospital operations. The rolling shutter mechanism and the related camera parameters are discussed in Section III. In Section IV, CMOS imager parameters limitation on the range of detectable frequency are explained based on the study of rolling shutter mechanism. The frequency resolution is also discussed in this section. Conclusions are given in Section V.

II. Smart Hospitals by Led Vlc Tracking

Energy-efficient LED lighting saves energy up to 70%. LED-based visible light communications and positioning functions can be built into existing LED lighting infrastructure for many applications. VLC technology is an ideal replacement for RF technology in hospitals, eliminating the potential life-threatening RF interferences to medical equipment and radiation harm to human. Due to the ultrawide bandwidth, VLC allows very high data rates desired by telemedicine, typically beyond the capability of RF technologies. On the other hand, the VLC-based tracking can be integrated into the existing LED lighting infrastructure in a hospital for real-time monitoring of personnel and equipment. The live data collected by the LED tracking network can be used to enable smart and connected hospitals, which will not only provide high-throughput wireless streaming in a hospital, such as heavy video streaming for telemedicine, but also allow more efficient personnel and asset management, hence making smart and connected healthcare a reality. Unfortunately, today's hospitals operate as a system where each actor/user (doctor, nurse, patient, visitor) performs his/her own tasks within the same space, using shared but uncoordinated resources, leading to inefficiency and chaos in hospitals. The main barrier to smart and coordinated hospital operations is the lack of robust tracking technology in healthcare settings. Our current project of LED VLC tracking network for smart and connected hospitals aims to develop a revolutionary energy-efficient LED-based VLC platform technology, embedded into the existing LED lighting infrastructure in a hospital, to provide a radiation and interference free wireless network for real-time visible light tracking and communications without using RF signals [11-13]. Fig. 1 shows a prototype LED VLC communication and

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tracking system built in our Lab, which uses LED lights on walls and PD/CMOS imagers in a robot vehicle for simultaneous optical communication and positioning. Fig. 2 shows a prototype LED visible light communication and tracking system demonstrated in a hospital using ceiling LED light and PD/CMOS imager built in a tablet to wireless streaming medical materials by light.

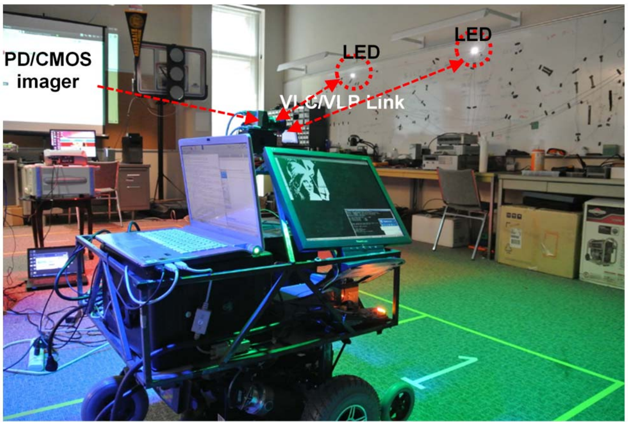

Fig. 1 Vehicle demo for VLC communication and tracking in our Lab uses LED lighting and PD/CMOS imager.

Fig. 2 Demo for VLC communication and tracking at the Loma Linda Medical Center using LED lighting and tablet/CMOS imager/PD devices.

III. Rolling Shutter Characteristics

Fig. 3 depicts the main structure of the indoor VLC tracking network built into the LED lighting infrastructure where each LEDs serve as optical ID tags assigned with unique modulation frequencies. The receiving end uses both PDs and CMOS imager arrays. The CMOS cameras can use either global shutter or rolling shutter modes. In global shutter mode, the exposure process of each row of pixels begins and ends at the same time. The global shutter is especially beneficial when capturing a fast moving scene, but at the cost of sacrificing frame rate. The rolling shutter has the advantage of higher frame rates, because, instead of exposing all pixel simultaneously and waiting for a completely pixel readout, each individual row will begin next exposure as soon as the current row has been read out. The disadvantage for rolling shutter is that the previous row readout passes a delay to next row at the beginning of exposure as depicted in Fig. 4, which results in a time shift at the beginning of each row with respect to the previous row, hence a sequential architecture. The unique character of rolling shutter makes the CMOS imager act like a high speed sample-and-hold ADC. Consequently, bright and dark bands on the image will be captured under the modulated illumination as shown in Figs. 3 and 4. The width of the bright and dark bands is proportional to the LED on-time and off-time, respectively. The rolling shutter mechanism allows a much higher data rate. However, the exposure overlap brings distortion to the original signals.

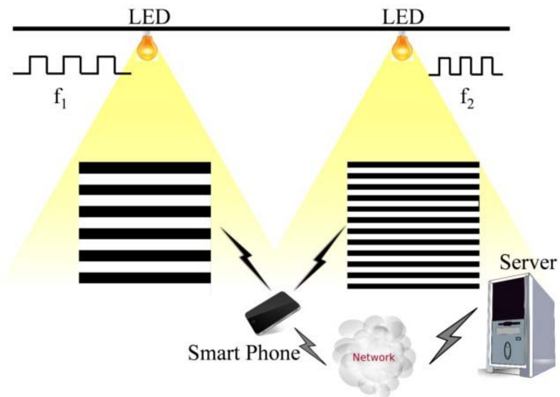

Fig. 3 A conceptual LED/CMOS imager VLC tracking system architecture.

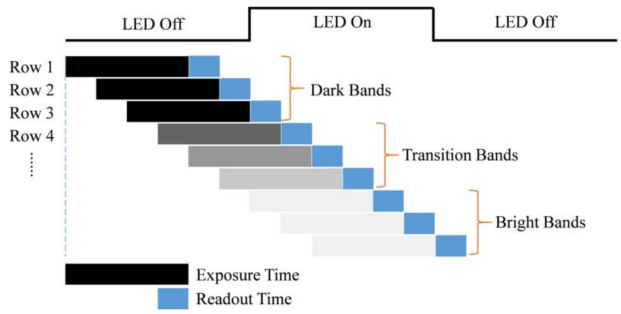

Fig. 4 Rolling shutter VLC receiving mechanism: the bright and dark rows of the CMOS imager indicate the LED on-off states. Transition bands appear due to the long exposure time overlap with both LED on-time and off time.

The readout time of each row $\tau_{readout}$ is a key factor affecting the rolling shutter based VLC system performance. From Fig. 4, the $\tau_{readout}$ acts as the sampling interval. For a CMOS sensor, the readout time is determined by the ADC clock speed and the number of column of the imager. The $\tau_{readout}$ is given as $\tau_{readout} \approx 1/f_{ADC} \times N_{col}$, where f_{ADC} is the ADC speed and N_{col} is the number of pixels in each row to be processed by ADC. $\tau_{readout}$ is estimated at the design stage to correctly detect the received signal frequency. To measure the readout time, transmitted frequency is varied from 200Hz to 2000Hz, and the peak point is located in received digital frequency spectrum. The relation between transmitted analog frequency and the peak digital frequency is given in Fig. 5. The estimated readout time is $\tau_{readout}$ = 12.65µs in our experiment, corresponding to a sampling frequency f_s = 79kHz. The shutter speed is another important parameter for system performance. A simple approach to decide whether an image will experience rolling shutter effect is to check whether the exposure time is longer than frame time τ_{frame}. The frame time is determined by $\tau_{frame} = \tau_{readout} \times N_{row}$, where N_{row} is the total number of pixel rows of the CMOS sensors. If exposure is shorter than τ_{frame}, rolling shutter effect is

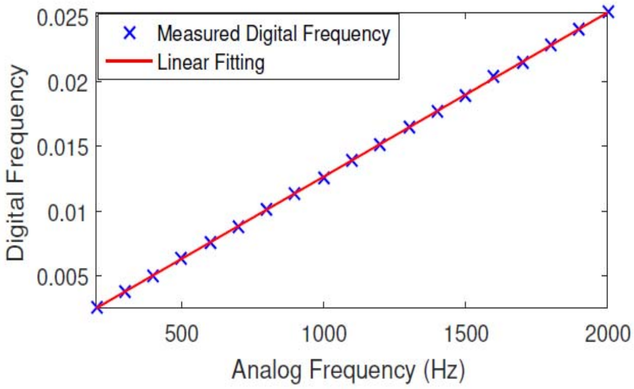

Fig. 5 Transmitted analog frequency *vs.* peak digital frequency: $\tau_{readout}$=12.65µs was measured using iPhone6 at 1/1000 second exposure time and 3264X2448 picture resolution. The red line is a linear fitting of measurement.

expected to occur. From Fig. 4, the exposure time also brings in transition bands between bright bands and dark bands. For those rows whose exposure times overlap with both LED on-time and off-time, they will accumulate less optical energy than those totally covered by the LED on-time, but more than those exposed during the LED off-time. Short exposure time not only reduces the width of transition bands, but also better reflects the true duty cycle of the received signals; hence, fast shutter speed is preferred. However, short exposure decreases the optical energy reaching to the sensor, resulting in an under exposed image. The camera exposure time and ISO value should be optimized based on the application scenarios. Fig. 6 illustrates how different shutter speed affects the received signals. We can see that the interval between two adjacent bright bands is the same regardless of the shutter speed.

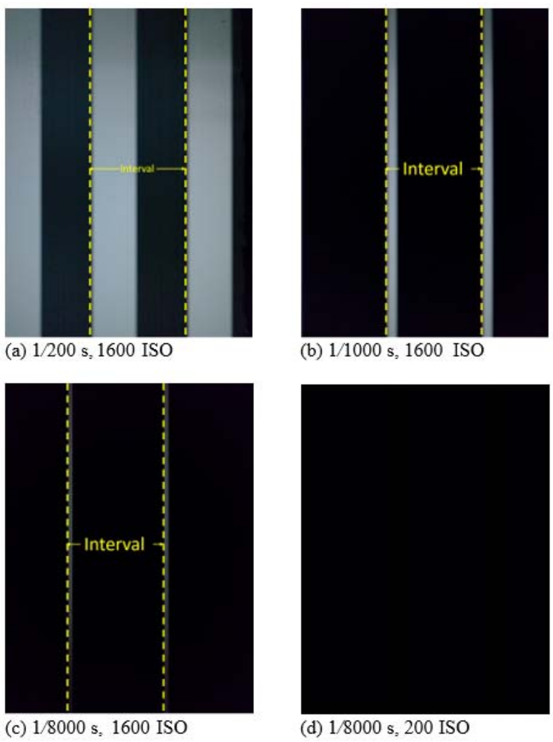

Fig. 6 Photos taken at different shutter speeds and ISO: the band positions shift in different frames because the modulation frequency is not an exact multiple of the video frame rate.

However, the band width changes with the shutter speed. This indicates that the exposure time will not change the pattern of received signals, but the proportion of bright and dark bands. Short exposure time produces images with sharp bands, but it could lead to an under exposed dark image. Increasing ISO can compensate the signal contrast at the cost of increasing the noise.

IV. Frequency Limitation

A. Frequency Lower Bound of Optical Tags

The lower bound of the detectable frequency (f_{min}) is first examined. To successfully observe at least one period of signal, the signal period should be at most one frame time τ_{frame}. Therefore, the lower bound f_{min} should be at least in the order of $1/\tau_{frame}$. Another factor to be considered is the flicker effect when examining the frequency lower bound. Normally, the light flicker effect is considered to be negligible once the modulation frequency exceeds 60Hz. But in rare instances, the flicker can still be sensed at 100−110Hz. So the LED vendors recommend a flicker frequency of >200 Hz. Another factor that limits f_{min} is the background interferences. The main energy of an image is on the low frequency range close to DC frequency. The sharp details in the image contribute to high frequency components. The transmitted signal can be polluted by the background scene when the background is nonuniform or under strong ambient light. Fig. 7 illustrates how background scene interferes with the received signals. In this example, a nonuniform wallpaper (Fig. 7a) is used as the background interference and an 800Hz signal is transmitted. f_{min} should be chosen to avoid conflicting with background scene, otherwise, background removal operation is required to suppress the interferences.

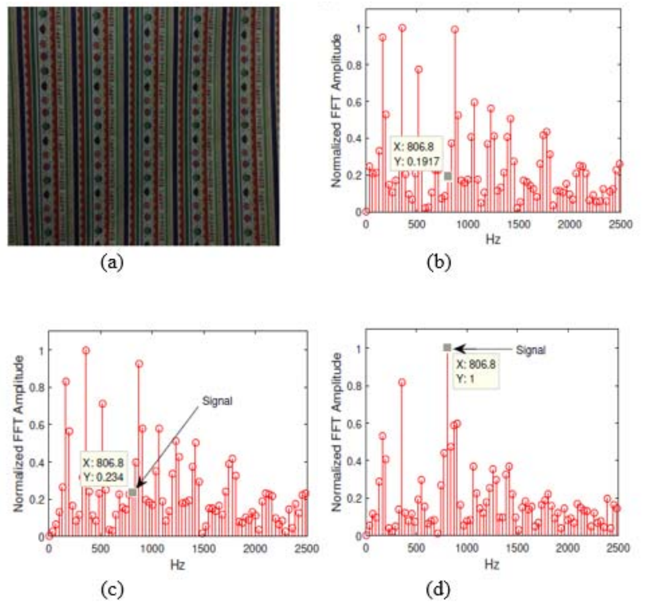

Fig. 7 (a) Received 800Hz signal with nonuniform background and ambient. (b) The FFT amplitude of pure background scene. (c) The FFT amplitude of modulated signal combined with background scene. (d) The FFT amplitude of received signal after background removal operation.

B. Frequency Upper Bound of Optical Tags

Next, we study the upper bound of the detectable frequency (f_{max}). According to Nyquist theorem, in order to recover the signal from its sampled version, the sampling frequency f_s should be at least double the signal bandwidth. In our case, the measured f_s is 79KHz, indicating a maximal 39.5KHz detectable signal frequency. However, as shown in Fig. 8, the frequency response of the camera suffers a significant drop after 1KHz. This is because the impact of exposure time on the received signal was yet considered. To investigate the exposure time effect, we analyzed three different cases depicted in Fig. 9. We define the contrast as the optical intensity difference between the brightest row and the darkest row, and assume the LED power is p_{LED} when LED is on. In Fig. 9a, the transmitted signal period is longer than the exposure time and the contrast is p_{LED} x $\tau_{exposure}$. In comparison, the contrast is zero in Fig. 9b, where the exposure time $\tau_{exposure}$ is exact multiple times of signal period. This is the worst case since the accumulated optical energy of each row is the same and the signal is averaged out. When the signal period is less than $\tau_{exposure}$ (Fig. 9c), the contrast is p_{LED} x $\tau_{readout}$. In this case, the contrast is mainly affected by the ISO and transmitted optical power, which decides how much of the voltage is amplified after the optical energy is converted to current. Since $\tau_{exposure}$ is usually much

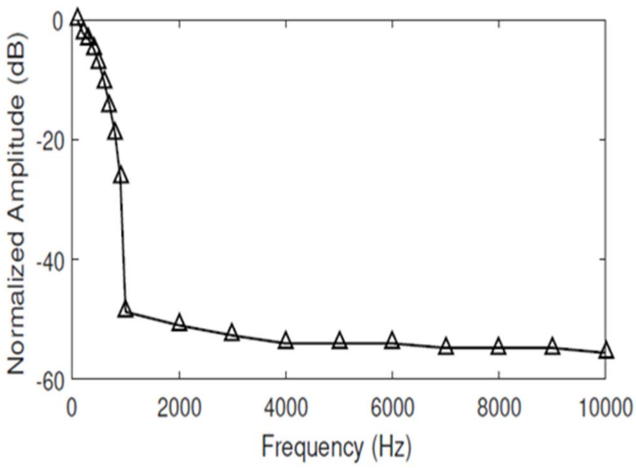

Fig. 8 Measured frequency response of the CMOS imager.

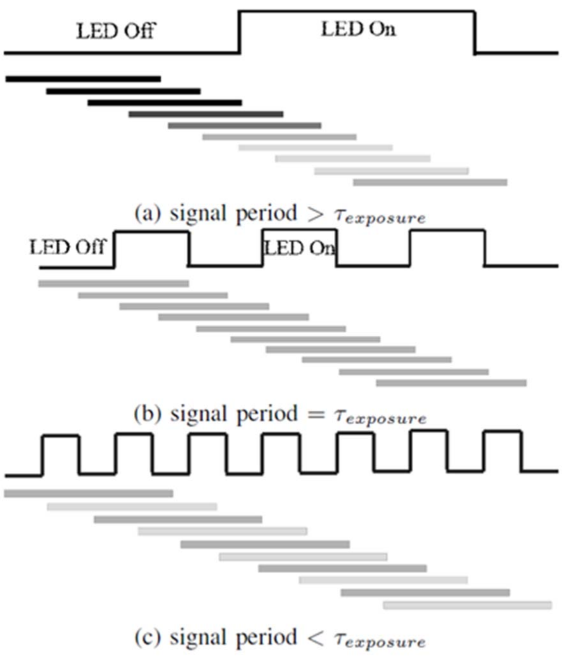

Fig. 9 Effect of exposure time on the received signals by the CMOS imager.

larger than $\tau_{readout}$, Fig. 9a has a much higher contrast than Fig. 9c. This explains the frequency response curve in Fig. 8. In our measurement, the fastest adjustable shutter speed is 1/1000s. When the transmitted signal exceeds 1KHz or its frequency is multiple of 1KHz, the received signal suffers a significant attenuation. Therefore, the upper bound f_{max} is limited by shutter speed of CMOS imager and the transmitted optical power.

C. Frequency Resolution

Frequency resolution is another critical parameter. It determines the minimum frequency spacing between two neighboring frequencies, which is related to the system capacity. The frequency resolution is defined as the ability to distinguish the two different frequencies close to each other when multiple LED IDs are captured at the same time. Due to the limited number of sampling points (N) for calculating the Fourier spectrum, unwanted lobes and ripples appear when using DTFT to analyze the spectrum. The existence of lobes in spectrum will smear the peak points and affect the frequency detection reliability. Assuming there are two neighboring frequencies, f_i and f_{i+1}, which are so close to each other that it is difficult to separate them in spectrum because of lobes, it will be hard to decide whether f_{i+1} occurs without additional information, because the DTFT peak at f_{i+1} could result from the lobes of f_i. This is especially true when the amplitudes of these two frequencies differ significantly. Since the lobes are caused by the limited length of window applied to the signal, the frequency resolution also depends on the window length and window type. We define the frequency resolution f_{res} as the main lobe width of window. With this separation, the lobe's magnitude attenuates deep enough to distinguish the two different frequencies. The interval between neighboring f_i should be at least the main lobe width of the window in order to successfully separate them from the received image.

V. CONCLUSIONS

This paper reports a comprehensive analysis of rolling shutter mechanism used in an LED VLC based indoor tracking network developed for smart hospitals. The shutter speed of the CMOS imager is a key parameter that affects both the observability of rolling shutter effect and the quality of received signals. Fast shutter speed is preferred, but the noise from the increased ISO must be considered carefully. The lower bound of detectable frequency depends on the frame rate, flicker effect and the background scene. The upper bound frequency is determined by the exposure time and is usually in the order of $1/\tau_{exposure}$ for reliable detection with good contrast. Higher frequency detection is possible in a low-noise environment. When Fourier spectrum is used to analyze the received signals, DTFT should be used, instead of FFT, to find a more accurate peak. The frequency resolution is limited by the length and the type of the window used in DTFT analysis. The outcomes of this study help to optimize design of the LED VLC-based tracking network that is embedded in the existing LED lighting infrastructure in a hospital, which may eventually enable next-generation smart and connected healthcare ecosystems, leading to efficient and cost-effective hospital operations in near future.

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