Novel Hybrid Temporal–Spatial Phase Shift On–Off Keying for Optical Camera Communications

광학 카메라 통신을 위한 혁신적인 시공간 위상변이 온오프 변조 방식

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이 논문을 석사학위 청구논문으로 제출함

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심사위원 장영민
심사위원 주만철

국민대학교 일반대학원
Abstract

Novel Hybrid Temporal-Spatial Phase Shift On-Off Keying for Optical Camera Communications

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This thesis introduces architecture of a hybrid region-of-interest (RoI)-signaling multiple-input-multiple-output (MIMO)-optical camera communication (OCC) system, which can guarantee high-speed transmissions, while reduce the computational workloads. The hybrid waveform using for this kind of systems is the combination of a low-rate and a high-rate data stream. In this thesis, a new hybrid waveform, which is the combination of Camera on-off keying (C-OOK) and dimmable spatial 8-phase shift keying (DS8-PSK), is proposed for hybrid RoI-signaling OCC system. The thesis also presents the development and performance analysis of C-OOK, a potential candidate to modulate low-rate data stream in proposed hybrid RoI-signaling MIMO-OCC system. The main contents of this thesis consist of three chapters organized as follow:

Chapter I introduces briefly the development and the salient features of OCC. The advantages of optical wireless communication/optical camera communication (OWC/OCC) and visible light communications (VLC) compared to radio frequency (RF) technologies are also discussed to point out the huge potential of OCC in the future. In addition, the standardization roadmap of OCC is summarized. In the second section of Chapter I, we discuss the impact of camera parameters in OCC. Four parameters can affect the performance of an OCC system. They are camera shutter speed, camera frame rate, camera rolling rate, and camera focal length. Consequently, they should be considered carefully in specific applications.

Chapter II presents a new approach in developing an OCC system. A hybrid RoI-signaling multiple-input-multiple-output (MIMO)-OCC system that comprises a low-rate and a high-rate data stream, is proposed. This new
hybrid MIMO-OCC system design can gain advantages of high-speed data acquisition and cost-effectiveness compared to traditional approaches. Also, technical consideration for the new proposed hybrid system and proper modulation schemes for the proposed hybrid OCC system are discussed as the references for developers. Finally, signal-to-noise ratio (SNR) measurement experiments are introduced to validate the feasibility of applying OCC at a far distance.

Chapter III addresses the design, encoding and decoding method of a novel encoding scheme called C-OOK, which can deploy as a low-rate data stream in proposed hybrid OCC system. Numerous implementation and simulation results are also provided in this chapter to appraise the performance and the application feasibility of novel proposed scheme.
Chapter III. Implementation and Performance Analysis of C-OOK

3.1. Design of Camera On-Off Keying (C-OOK)

As discussed in the Chapter II, camera on-off keying (C-OOK) is one of undersampled modulation schemes, based on OOK scheme that can be a strong candidate for the low-rate data stream in the proposed hybrid RoI-signaling-OCC system. This chapter mainly focuses on introducing C-OOK waveform and its performance analysis. Numerical of experimental and simulation results are provided to prove the feasibility of C-OOK not only for V2X applications using hybrid waveform but also for standalone applications.

C-OOK is designed to support a wide range of rolling shutter cameras, which have limitation on the shutter speed (e.g. most of smartphone cameras have approximately 8 kHz of shutter speed [25]) in the current market. C-OOK is first introduced in 2016 [25] by Kookmin University. However, due to some limitations of Rx decoder, while testing, the author proposed some solutions to update C-OOK Rx decoder in this chapter. These updates are discussed in some sections below. In addition, C-OOK is also contributed to PHY V mode in IEEE 802.15.7-2018 standard, which was just released in April 2019.

3.1.1. Encoding Method

The Tx encoding process is shown as in Figure 26.

![Figure 26. Reference architecture of C-OOK Tx](image)

At first, data is encoded with optional outer FEC. In IEEE 802.15.7-2018 standard, developer can decide to use outer FEC or not by configuring via the physical layer personal area network information base (PHY PIB) attribute phyCookFEC. After FEC encoding, asynchronous bits are inserted to packet. Asynchronous bits are proposed to support the frame rate variation of rolling shutter camera and to check the sequence of packets. The detail descriptions of asynchronous bits are discussed in the next section of this chapter.
Inner FEC is used to encode the packet once again. As a comprehensive look at the FEC development for decades, the FEC are classified as three generations [26]. Elementary Hamming code, Bose–Chaudhuri–Hocquenghem (BCH), Reed-Solomon (RS), or convolutional code (CC) are considered as the first generation of FEC. The second generation of FEC can be considered as the combination of RS and CC or two RS combined. The third-generation of FEC is seen as the use of advanced decoding technique such as turbo codes and LDPC. In C-OOK system, some well-known codings such as Hamming code and CC are proposed to use due to the length of data packet and the easy-to-use of these channel codings.

In OWC/OCC or VLC, run-length-limited (RLL) coding is used for many modulation schemes to maintain DC balanced in Tx light intensity, provide the error detection capability, and provide clock recovery for Tx signal. Manchester, 4B6B or 8B10B coding are some well-known RLL codings that can be considered to use in this OOK-based modulation scheme. Equation (6) below can be used to estimate the efficiency of when RLL coding are applied.

\[
\eta = \frac{\text{Actual data rate}}{\text{Throughput}} \times 100\% \tag{6}
\]

Undeniably, Manchester coding only has 50% of data rate efficiency while 4B6B coding has 75%. 8B10B has up to 80% of efficient data rate, however, it requires up to 10 bits per packet. Therefore, for cameras that have limitation in shutter speed and frame rate, the selection of RLL coding should be considered to not decrease the bandwidth while keep flicker-free to human eyes. With some reasons above, Manchester and 4B6B coding are chosen to use for this scheme. It is also used in many modulation schemes addressed in IEEE 802.15.7-2018 standard.

### 3.1.2. Data packet structure

The proposed C-OOK data packet structure is as shown in Figure 27 [25] below. This data packet structure is designed to support the frame rate variation problem that existed in almost cameras in the current market by transmitting repetition data sub-packet (DS) per packet. It means that a data packet includes multiple data sub-packets. Packet rate is defined as the number of different packet that is transmitted during a period. The number of repetition DS depends on the configuration of C-OOK Tx and it can be calculated using equation (7) below.
Chapter III. Implementation and Performance Analysis of C-OOK

Where $N_{\text{repetitionDS}}$ is the number of repetition sub-packet per packet, $DS\_rate$ is the C-OOK sub-packet rate, and $packet\_rate$ is the C-OOK packet rate, which is the number of different packet that is transmitted during a period.

Table 4 [7] illustrates the DS structure with RLL coding. Manchester and 4B6B coding are chosen to use in C-OOK packet structure because it is suitable with the length of proposed packet that intended to support almost cheap cameras in the market. Like RLL coding, the preamble (Start-of-frame) of a DS is proposed to maintain the DC balance and flicker-free for Tx.

The payload of DS consists of three sub-parts: two front asynchronous bits (front Ab), data, and a rear Ab. Both front Ab and rear Ab include two asynchronous bits in each. Asynchronous bits are also proposed in DS structure to support the frame rate variation of Rx cameras in recovering packet process. The use of front Ab and rear Ab are discussed in details in Section 3.1.3.3 below.

Table 4. DS detailed packet structure

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Data sub-packet (DS) payload</th>
<th>Front Ab (2 bits)</th>
<th>Data payload</th>
<th>Rear Ab (2 bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>011100</td>
<td>Manchester coding</td>
<td>Ab_1 Ab_1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>011111000</td>
<td>4B6B coding</td>
<td>Ab_1 Ab_1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The number of DS payload depends on which C-OOK mode is used. There are 4 C-OOK modes that were introduced in IEEE 802.15.7-2018 standard. Table 5 [7] below illustrated detailed parameters for each C-OOK working
mode. These 4 modes are intended to support a wide range of camera in current market. Therefore, base on the camera’s specifications and specific use-case, proper C-OOK working mode is chosen for operation.

Table 5. C-OOK suggested working mode

<table>
<thead>
<tr>
<th></th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical clock rate</td>
<td>2200 Hz</td>
<td>2200 Hz</td>
<td>4400 Hz</td>
<td>4400 Hz</td>
</tr>
<tr>
<td>Sub-packet rate</td>
<td>100 DS/s</td>
<td>60 DS/s</td>
<td>60 DS/s</td>
<td>60 DS/s</td>
</tr>
<tr>
<td>RLL code</td>
<td>Manchester</td>
<td>4B6B</td>
<td>Manchester</td>
<td>4B6B</td>
</tr>
<tr>
<td>DS clock</td>
<td>22B</td>
<td>37B</td>
<td>74B</td>
<td>74B</td>
</tr>
<tr>
<td>Preamble</td>
<td>6B</td>
<td>10B</td>
<td>6B</td>
<td>10B</td>
</tr>
<tr>
<td>Payload (Ab, Data, Ab)</td>
<td>8 bits (16B)</td>
<td>18 bits (27B)</td>
<td>33 bits (66B, 2B unused)</td>
<td>40 bits (60B, 4B unused)</td>
</tr>
<tr>
<td>Uncoded bit rate</td>
<td>80 bps</td>
<td>180 bps</td>
<td>330 bps</td>
<td>400 bps</td>
</tr>
<tr>
<td>Bit rate</td>
<td>40 bps</td>
<td>110 bps</td>
<td>220 bps</td>
<td>400 bps</td>
</tr>
</tbody>
</table>

3.1.3. Decoding Guidance

Figure 28 shows the decoding method for C-OOK Rx. The decoding procedure starts by pre-processing and down-sampling to provide input 1D image. Then, the down-sampled 1D image is de-trended. Removing a trend from the data can help Rx decoder to focus on the fluctuations in the data about the trend. The input 1D data is then ready for SF detection process. Matched filter is used for both SF detection and packet demodulator process. For more details, matched filter is discussed in Section 3.1.3.1.
Chapter III. Implementation and Performance Analysis of C-OOK

The packet demodulator procedure includes two parallel decoders, forward and backward decoder, which can be operated based on the detected SF and Ab bits positions. The packet recovery procedure consists of three processes. Received bit sequence from packet demodulator process are merged based on the number of bits in DS payload, which is defined by the C-OOK working modes. RLL decoder and FEC decoder are also operated based on the parameters that was defined in each C-OOK mode.

3.1.3.1. Matched filtering decoder
Matched filter can be applied to sampling process of Rx C-OOK decoder for bit detection. Based on matched filter’s property \cite{27}, it can be applied to helps Rx sample the input signal with less error by increasing the SNR of incoming signal if the impulse response of Tx is matched to Tx pulse shape. The matched filter can also increase the overall SNR of the system by mitigating some amount of noise of the incoming signal. Figure 29(a) and Figure 29(b) presents the input signal and its impulse response respectively while Figure 29(c) shows the results when matched filter is applied to detect input bit sequence. Because the impulse in Figure 29(b) matched with the input Tx signal in Figure 29(a) then the amplitude of output signal is maximized.

Figure 28. C-OOK Rx decoding procedure
3.1.3.2. Data fusion algorithms

As we discussed in the Chapter I, frame rate variation is one of the critical problems of cameras. C-OOK is one of the modulation schemes that can be called undersampled modulation scheme because C-OOK can support Rx to mitigate the frame rate variation effect by proposing data fusion techniques for packet recovery process. When the rolling rate of camera is greater than the Tx optical clock rate, the sampling process can be called as the oversampling scheme. In this oversampling scheme, if the number of pixel rows of an image is much higher than the total number of pixel rows in a DS, it is easy to recover all bits of DS because Rx camera can capture fully this DS. On the other hand, we can say that the DS can be recovered completely if every DS is captured in just one captured image. This condition for recovering a DS correctly is given by equation (8).

\[ N_{DS} < N_{Cam} \times \frac{f_{Tx}}{F_s} \]  

(8)

Where \( N_{DS} \) is number of pixels per DS, \( N_{Cam} \) is the total number of pixel rows per captured image, \( F_s \) is camera rolling rate, and \( f_{Tx} \) is Tx optical clock rate.
However, due to the asynchronization in Tx Rx caused by frame rate variation phenomenon, a DS may not appear fully in a captured image. In this case, two fusion algorithms are proposed to recover all DS. Figure 30 illustrates two data fusion techniques that are introduced to use in C-OOK decoder. They are inter-frame and intra-frame data fusion algorithms. In these techniques, asynchronous bits play an important role for merging two pieces of bit sequence in an image.

- **Inter-frame data fusion**: is used to recover a DS from two-bit sequences in different captured images. In this scenario, Ab bits of each bit sequence are used for comparing to each other. If they are the same, two-bit sequences will be merged into a complete DS.
- **Intra-frame data fusion**: is used to recover a complete DS from two different bit sequences in the same captured image. By comparing the similarities of Ab bits in two-bit sequences, Rx may decide to merge them into a DS or not.

### 3.1.3.3. Asynchronous bits

As mentioned, asynchronous bits are proposed to support frame rate variation when recovering data packet. Asynchronous bits are not only play an important role on recovering DS, but also contributing to detect lost data.
In a DS, each front Ab or rear Ab carries two bits \( Ab_1 \) and \( Ab_2 \). Front Ab and rear Ab of a DS carry the same information. \( Ab_1 \) and \( Ab_2 \) are square pulses. While the \( Ab_1 \) changes from zero/one to one/zero in every period when a single DS is transmitted, the square pulse \( Ab_2 \) only changes in every two transmitted DS. This means that the combination of \( Ab_1 \) and \( Ab_2 \) forms four-bit patterns: 00, 01, 10, and 11. With these combinations, C-OOK Rx can detect a maximum of two continuous missing DS. To detect more missing DS, more bits should be added to front and rear Ab of Tx DS. However, it leads to the increase in DS length that may not support Rx camera with limitation in shutter speed and image sensor resolution.

3.2. C-OOK implementation and performance analysis

3.2.1. Implementation Results

In this section, numerical implementation results are provided to demonstrate the feasibility of C-OOK modulation schemes. Table 6 below shows the parameters of C-OOK prototype system for experiments. Two C-OOK decoders are deployed to support both single link and dual-link communication scenarios.
Table 6. C-OOK experimental system specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tx Specification</strong></td>
<td></td>
</tr>
<tr>
<td>Modulation rate</td>
<td>2.2 kHz; 4.4 kHz</td>
</tr>
<tr>
<td>LED size</td>
<td>12 VDC - 2.4 W; 12 VDC - 30 W</td>
</tr>
<tr>
<td>RLL code rate</td>
<td>1/2 (Manchester); 2/3 (4B6B)</td>
</tr>
<tr>
<td><strong>Rx Specification</strong></td>
<td></td>
</tr>
<tr>
<td>Camera type</td>
<td>FLIR FL3-U3-32S2M</td>
</tr>
<tr>
<td>Camera frame rate</td>
<td>60 fps</td>
</tr>
<tr>
<td>Camera rolling rate</td>
<td>96 kHz</td>
</tr>
<tr>
<td>Image resolution</td>
<td>1280 x 1024</td>
</tr>
<tr>
<td>Focal length</td>
<td>16mm; 35mm</td>
</tr>
</tbody>
</table>

3.2.1.1. C-OOK Decoder with Single Link Support

In single-link communication scenarios, C-OOK is tested in a distance range from 1 to 20m. In these experiments, two LEDs with different sizes and power consumptions are used as shown in Figure 32.

The small LED light source (25 x 25mm flat square LED) is used to prove that C-OOK can be deployed to some applications that required small light sources such as health care applications. In such applications, patient may be equipped with wrist monitor devices that can communicate their body parameters to doctors via monitor camera systems. The experiment setting is also presented in Figure 33 below.
Chapter III. Implementation and Performance Analysis of C-OOK

Figure 32. LED used for C-OOK testing: (a) 12 VDC - 30 W LED; (b) 12 VDC - 2.4 W LED

Figure 33. C-OOK single-link experiment with 12 VDC - 2.4 W LED at 1m distance
Chapter III. Implementation and Performance Analysis of C-OOK

The big light source (12 VDC - 30 W) is also used to test the communication ability of C-OOK system in far distance as in experiment setting in Figure 34. 35mm of focal length is installed for Rx camera in this experiment. Communication in 20m distance can be achieved. Chapter I has discussed the relationship between focal length and the object size in the captured image. Therefore, to transmit data in further distances, proper LED size and focal length should be deployed for Tx and Rx respectively.

Figure 34. C-OOK single-link experiment with 12 VDC - 30 W LED at: (a) 8m, and (b) 12m

Figure 35. C-OOK Rx user interface operated at working mode 4 with 10 kHz of optical clock rate
Four C-OOK modes are tested in these above experiments. Text messages are sent from Tx to Rx during experiments. From these experiments, 716 bps of throughput can be achieved using C-OOK mode 3 with original 4.4 kHz of optical clock rate. To achieve higher throughput, higher optical clock rate should be implemented. In practice, using 10 kHz optical clock rate in C-OOK mode 3 can help to achieve up to 773 bps of throughput while implementing 10 kHz of optical clock rate in C-OOK mode 4, throughput can reach to nearly 1 kbps as presented in Figure 35. FEC has not implemented in these experiments yet. Implementing FEC may decrease the data rate, however, it may help to enhance data reliability by correcting the bit errors in received packets.

3.2.1.2. C-OOK Decoder with Dual-Link Support
Dual-link testing experiments are also conducted to prove the ability of C-OOK Rx in detecting and decoding data signal from multiple light sources. In the first experiment, C-OOK Rx decode the lighting waveform from two 25 x 25mm flat square LEDs at 60cm of distance. In the second experiment, big LED is used. These light sources have the same average power consumption of many vehicles’ headlight/taillight, currently. FLIR rolling shutter camera with 35mm of focal length is also deployed in this experiment. Figure 36(a) and Figure 36(b) below illustrate the testing scenarios with different types of light sources.

Similar to those single-link experiments, texts are sent from C-OOK Tx to Rx. Using Mode 2 with 4400 Hz of optical clock rate. Both links can achieve up to 400 bps of throughput. The experiment also shows that this scheme can work at 6m distance in indoor environment and in daytime.

![Figure 36](a) ![Figure 36](b)

Figure 36. Dual-link testing scenario with (a) two 25 x 25mm LEDs at 60 cm, and (b) two 12 VDC - 30 W LEDs at 6m
3.2.2. C-OOK Performance under AWGN

The transmission quality in optical channel is affected by shot noise due to high-level ambient light intensity. This ambient light causes a steady shot noise in photodetector and it can be considered as AWGN channel [28], [29]. A simulated C-OOK system is designed to analyze the performance of C-OOK under additive white Gaussian noise (AWGN) channel. Equation (9) [28] presents the received noisy signal over AWGN channel:

$$y(t) = h_r(t) \otimes r(t) + n(t)$$

Where $y(t)$ is the received noisy optical signal, $h_r(t)$ is the overall impulse response for optical-electrical converter of image sensor/photodetector, $r(t)$ is the original optical signal from Tx, and $n(t)$ is AWGN.

Figure 38 illustrates a simulated C-OOK waveform with AWGN of our simulated software. In these simulations, AWGN is generated with a given SNR value and added to simulated Tx waveform. Four C-OOK working modes are simulated and appraised in both scenarios when FEC is enable and FEC is disable. Figure 39 to Figure 42 present the simulation results of C-OOK in both scenarios.
Chapter III. Implementation and Performance Analysis of C-OOK

Figure 38. Simulated C-OOK waveform with 5 dB of AWGN level

Figure 39. Simulation of BER versus pixel SNR of C-OOK in four working modes (no FEC) and theoretical OOK

Figure 40. Simulation of BER versus pixel SNR of C-OOK operated in mode 2, S2-PSK, UFSOOK, and UPSOOK
Figure 39 presents the performance of C-OOK compared to theoretical OOK. Although not any FEC decoder has implemented in C-OOK Rx, almost C-OOK modes show that they still can achieved a $10^{-5}$ of BER at less than 12 dB of pixel SNR requirement. While some undersampled modulation schemes such as UFSOOK or S2-PSK as mentioned in Section 2.4 of Chapter II may require up to 10 dB of pixel SNR to guarantee a $10^{-4}$ BER level, C-OOK mode 2 waveform requires only approximately 7 dB to achieve a $10^{-4}$ of BER as illustrated in Figure 40. In addition, from the results of pixel SNR measurement experiments that have been discussed in Figure 24 of Section
2.4, Chapter II, 12 dB of pixel SNR can be guaranteed in 200m of distance using FLIR rolling shutter camera with a proper exposure time configuration. With all above reasons, the author believes in the feasibility of applying C-OOK in RoI-signaling hybrid waveform for V2X communications with a far distance requirement.

Furthermore, Figure 41 and Figure 42 presents the BER versus pixel SNR curves of some C-OOK working modes when FEC decoders are implemented. The requirement of pixel SNR level of C-OOK mode 3 for guaranteeing the same level of $10^{-4}$ BER has decreased slightly (approximately 1 dB) when Hamming (15, 11) is applied in Rx. In contrast, when CC is implemented for C-OOK mode 4, the decrease of pixel SNR requirement is significant due to the advantages of CC compared to Hamming code. Approximately 4 dB of pixel SNR can be improved as shown in Figure 42. However, there is a trade-off in data rate between using FEC and without using FEC. Developers should consider the use of FEC carefully to enhance the data rate while keeping the data reliability in every specific applications.