Design and Implementation of Deep Learning-Based MIMO C-OOK Scheme for Optical Camera Communication Considering Mobility Environment

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***Abstract*—Currently, wireless communication systems using radio frequency are widely utilized across various applications for example: mobile communication, satellite networks, and Industrial Internet of Things (IIoT). Wireless communication, owing to its convenient installation, offers advantages over wired counterparts. Nevertheless, utilizing high frequencies for wireless data transfer raises substantial concerns for human health. To address this issue, researchers have explored alternatives deploying visible light in communication systems, leading to three relevant approaches: visible light communication, light fidelity, and optical camera communication. The role of artificial intelligence (AI) in industries and society is pivotal, as it addresses intricate problems, devises intelligent resolutions, and gradually replaces human intelligence in driving emerging technologies like smart home, data analysis, and IIoT. In this study, we introduce MIMO C-OOK architecture, leveraging a convolutional neural network for light sources tracking and a deep learning algorithm for decoding. The proposed method is designed to enhance the performance of the traditional C-OOK such as improving data rate , higher distance, and reducing BER. This approach aims to attain a 8 meters distance with good bit error rate in 3 m/s mobility environment. This is achieved through meticulous control of shuttle speed of camera, camera focal length, and the implementation of suitable FEC.**

Keywords*—*MIMO-COOK, Deep Learning, Optical Camera Communication, IEEE 802.15.7a TG.

I. Introduction

When contrasting wireless communication with wired systems, the former presents distinct advantages. Its installation is simpler, allowing data transmission without the need for physical wires. Consequently, wireless communication systems find widespread deployment in various domains such as smart factories, vehicular systems, and indoor communication networks. Notably, radio frequency (RF) bands are commonly employed in wireless communication, principally in mobile communication and IoT networks. Globally, research groups are actively working on advancing the fifth generation (5G) [1] for mobile communication within the millimeter-wave wave band, promising enhanced data rates exceeding 10 Gbps. However, the continuous use of radio frequencies depletes resources, necessitating an expansion of the frequency band to achieve higher data rates, a practice that poses potential harm to human health. As an alternative, the Visible Light band has garnered attention as a replacement for the Radiofrequency band, with applications such as Visible Light Communication (VLC), Optical Camera Communication (OCC), and Light Fidelity (LiFi). The advantages of light bands over RF bands are enumerated as follows:

• The Light band has no adverse effects on humans [2], unlike RF waves which have been associated with various human impacts.

• The bandwidth of light bands surpasses that of RF by over 1000 times.

• Light bands are less harmful and more efficient when compared to RF waves.

Therefore, numerous companies are allocating a substantial share of their finances to explore this innovative technology. The Optical Wireless Communication (OWC) system was introduced based on the IEEE 802.15.7-2018 standards [3], initially featuring a low rate and short range. In 2020, the IEEE 802.15.7a Task Group [4] proposed novel techniques, as well as Multiple-Input Multiple-Output (MIMO), Artificial Intelligence (AI)-based Physical (PHY) and hybrid modulation, to achieve high data rates and high-speed systems.

In contrast to VLC/Li-Fi technologies, that utilize photodiodes for data reception, OCC technology employs a camera as the data reception. In [5-7] demonstrates that the data rate of OCC systems is contingent on camera types, with Global Shutter and Rolling-Shutter cameras being common in the market. Compared with VLC/LiFi, OCC can easily deploy the MIMO approach, which operates efficiently, facilitating multiple LEDs and multiple image sensors. Though, the MIMO is not possible for multi-links if we applied photodiodes in VLC/LiFi. The Region of Interest (RoI) algorithms, a popular choice for detecting multiple light sources in OCC technologies, can be applied. In a study [8-9], C-OOK was proposed for Rolling Shutter camera considering high data rate, but the conventional C-OOK scheme reveals some disadvantages: short distance and high bit error rate. Another proposal [10-11] considering the orthogonal frequency-division multiplexing technologies and the rolling shutter camera to generate RS-OFDM scheme for a high speed architecture for OCC system. The MIMO technique for OCC systems, aiming to growth the data rate, was introduced in [12], but it suffers from drawbacks for mobility environment.

Region of Interest (RoI) signaling was considered for LED detection, which is proposed long time ago in IEEE 802.15.7-2018 standard considering low processing time with low computation computer. Currently, we have many devices to increase image processing performance such as NDIVIA GPU devices. It also is applied for AI model. The term "Deep learning" refers to a subset of artificial neural networks, which aids in addressing OCC difficulties, supporting object detection for high accuracy, increasing decoder performance, and low latency processing for high velocity. In [13], You Only Look Once version 8 (YOLOv8) algorithm also was considered for real-time detection and recognized Region of Interest of objects. Authors in [14] proposed Optical fringe codes for OCC system using convolutional neural network (CNN) achieving accuracy of 95%. Though, this study employed multiple RGB cameras positioned in parallel. To improve C-OOK scheme performance, we propose a transmiiter tracking algorithm deploying the YOLOv8 process to get high precision tracking of light sources considering mobility environment . Moreover, we introduce a AI decoder to reduce BER of MIMO-COOK scheme in this study.

The remaining portions of this research consist of three segments. In Section 2, we elucidate the MIMO C-OOK scheme reference architecture utilizing AI. The implemental results also have outlined in Section 3. Section 4 is conclusion of this study.

II. SYSTEM ARCHITECTURE

The most basic form of amplitude-shift keying modulation, known as on-off keying, signifies information by indicating ON and OFF levels. Bit '1' signifies the ON level, while a Bit '0' indicates the OFF level for similar duration. This study presents MIMO C-OOK scheme, which incorporates MIMO, deep learning for LED detection, and Deep learning decoder approaches to enhance the existing C-OOK scheme.

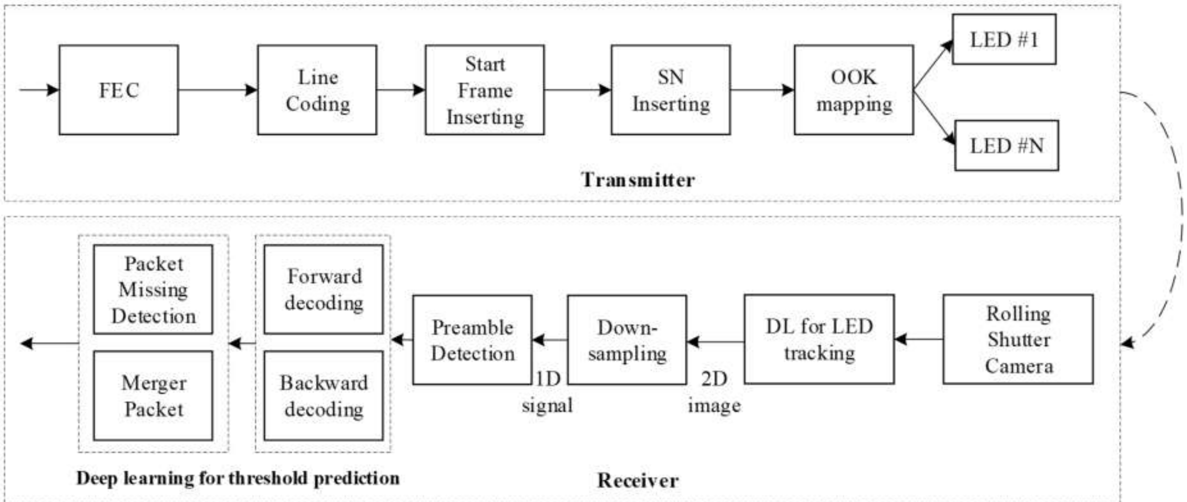

Fig. 1. MIMO C-OOK architecture using Deep learning for mobiliry environment.

A. Detecting and tracking LEDs using Deep learning

In Optical Camera Communication (OCC) systems, algorithms are firmly recognized. Almost RoI methods, geared towards real-time processing for object detection, employ both object and feature-based tracking approaches. As previously mentioned, when we use rolling shuter camera, LEDs appear in images as black/white strips matching to bit "0" or "1". The presence of numerous strips in each image poses challenges for RoI detection, especially in the context of mobility effects.

Deep learning algorithms have become well-setting tools for various computer vision applications such as object tracking, object classification, and picture reconstruction. Convolutional Neural Networks (CNNs) have particularly proven to be effective for deep learning-based computer vision tasks. The CNN-based You Only Look Once (YOLO) [15-17] algorithm stands out as a state-of-the-art for real-time tracking architecture. In this study, authors propose the customizable architecture and training models specifically for LED detection and tracking using YOLOv8 algorithms, taking into account the rolling-shutter and mobility effects.

To assess the performance of our LED detection and recognition method, we collected an experimental dataset from real traffic scenes. Daytime and nighttime video footage, incorporating the mobility effect, was recorded, and we generated 1,000 blurry and clear images with varying shutter speed. By trainning the collected dataset, authors labeled and trained dataset with YOLOv8 model, that is adapted with 7/9 convolution layers. The model focused on a single detection class, and the final number of filters in the convolution layers amounted to 40.

B. Deep learning decoder

The zero-crossing filter, settled in the same work [17], distinguishes ON/OFF levels in images by zero value as the threshold level. This approach performs well when the SNR value of OCC system is high. However, under low SNR conditions, discerning between ON/OFF statuses becomes challenging. The matched filter, a technique comparing the real signal to a template signal [18], maximizes SNR in the presence of additional random noise, making it advantageous for low SNR scenarios. Howevers, with mobility environment, the matched filter reveals drawbacks. Mobility-induced blur occurs when the transmitter and receiver undergo relative movement, leading to inter-symbol interference in the Optical Camera Communication (OCC) system and a consequent decline in system performance.

To address these challenges, a deep learning decoder as well is employed to decode data [19], taking the mobility environment. This paper utilizes Root Mean Square Error (RMSE) as an evaluation metric for error assessment. By training within 500 epochs, the system achieves high precision in predicting value errors considering low values (<0.09).

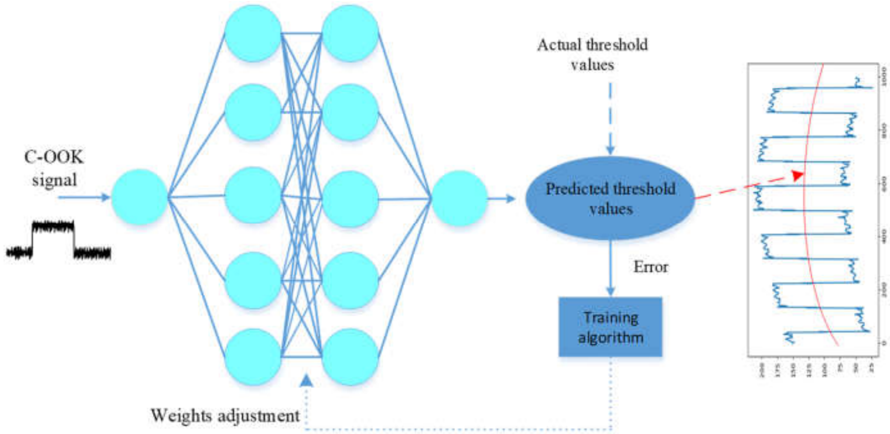

Fig. 2. The deep learning neural network model for threshold prediction.

Upon LED detection, the Optical Camera Communication (OCC) signal has been isolated from milti-LEDs of LED area. MIMO-COOK signal has identified by extracting the center position of light sources, and the neural network has been employed for predicting threshold instead of zero crossing in conventional algorithm.

The raw data, comprising 5,000 samples, was captured by the difference image sensors at varying ranges (2 m, 4 m, 6 m, and 8 m) and diverse velocity speeds, encompassing both the preamble and payload segments. A fundamental deep learning model with three hidden layers was utilized to prevent overfitting case in DL model. By prediting high accurate threshold, this approach can enhance OCC performance in a mobile environment when compared to conventional technologies. It should be noted that in overfitting case in DL model, the accuracy of the test dataset is compromised, particularly once employing 7 or more hidden layers.

III. Implementation Results

In this study, we executed the DL model for a MIMO-COOK technology in multiple times employing various cameras to assess the impact of frame variations. Moreover, meticulous consideration was given to selecting the suitable SN length to improve the total processing time and commicaiton performance. Figure 3 shows the experimental implementation setup to deploy this approach. In Figure 4, the interface of Labview programming for MIMO-COOK decoder was shown considering two LEDs in transmitter side. Table 1 shows the parameters of implementation results considering 3 m/s velocity using three and four LEDs to transmit data. From table 1, we make sure that the data rate can be achived up to 10.8 kbps if we apply 4 LEDs for MIMO technique, and just 8.1 kbps with 3 LEDs in MIMO-COOK scheme. Then, to improve data rate in MIMO-COOK, we can increase the number of LED, however, the localization and senquence of payload in each LED should be considered before we design OCC system.

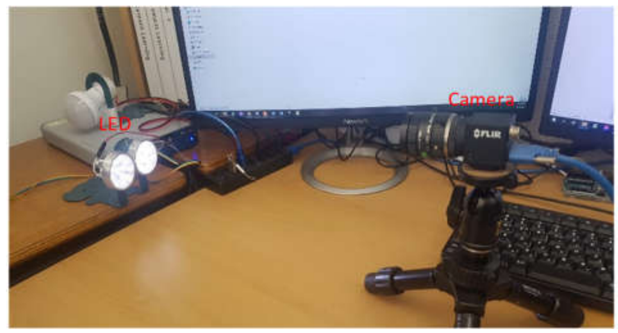

Fig. 3. The experiment implementation environment.

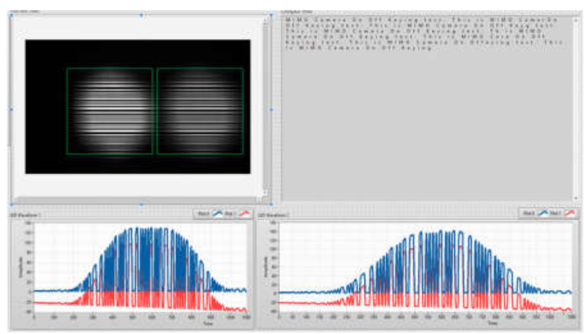

Fig. 4. The receiver interface.

Table 1. MIMO-COOK parameters

Transmitter		
Clock rate	10 kHz	15 kHz
RLL	Manchester	4B6B
FEC	CC(3,4)	RS(15,11)
Light Sources	LED (7V-5W)	
No. of LEDs	3	4
Receiver		
Camera	Rolling shutter camera (60 fps)	
Data rate (kbps)		
Uncode bit rate	8.100	10.800
Code bit rate	6.075	7.920

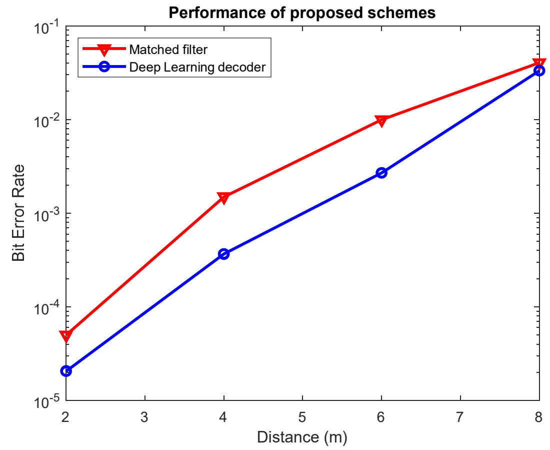

Fig. 5. BER performance of the MIMO-COOK system considering a velocity of 3 m/s.

Figure 5 shows BER values of MIMO-COOK scheme in difference distance and mobile environment. As revealing in Figure 5, we can see that: by using Deep learning decoder for MIMO-COOK scheme, the BER can achive 10^{-3} at 6 m distance, however, the BER at 4 m distance with matched filter considering velocity of 3 m/s. Then we can make sure that our approach can be achieved good performance compared conventional algoritm.

IV. Conclusion

In this study, the MIMO C-OOK scheme that employed a deep learning neural network to tracking multiple light sources, was proposed. For rolling shutter camera, the LED will be shown in pictures as black/white strips, that confuses evidently tracking LEDs compared with RoI detection. Besides that, a deep learning decoder is good candidate in the case of long ranges, especially about the mobile environment. Lastly, we calculated the BER of the proposed scheme using different distances and compared the results with conventional decoder algorithm.

Acknowledgment

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References

[1] D. Surender *et al.,* "5G/Millimeter-Wave Rectenna Systems for Radio-Frequency Energy Harvesting/Wireless Power Transmission Applications: An overview," in *IEEE Antennas and Propagation Magazine*, vol. 65, no. 3, pp. 57-76, June 2023.

[2] N. Van Hoa *et al.,* "OCC Technology-based Developing IoT Network," *2020 International Conference on Information and Communication Technology Convergence (ICTC), Jeju, Korea (South)*, 2020, pp. 670-673.

[3] *IEEE-SA. IEEE Std 802.15.7-2018- IEEE Standard for Local and metropolitan area networks-Part 15.7: Short-Range Optical Wireless Communications*; IEEE-SA: Piscataway, NJ, USA, 2018.

[4] H. Nguyen *et al.,* "Enabling Technologies and New Challenges in IEEE 802.15.7 Optical Camera Communications Standard," *IEEE Communications Magazine*, 2023.

[5] H. Nguyen *et al.,* "Rolling OFDM for Image Sensor Based Optical Wireless Communication," in *IEEE Photonics Journal*, vol. 11, no. 4, pp. 1-17, Aug. 2019.

[6] H. Nguyen *et al.,* "The Impact of Camera Parameters on Optical Camera Communication," *2019 International Conference on Artificial Intelligence in Information and Communication (ICAIIC)*, Okinawa, Japan, 2019, pp. 526-529.

[7] Cahyadi, W.A *et al.,* "Optical Camera Communications: Principles, Modulations, Potential and Challenges," *Electronics* 2020, 9, 1339.

[8] Nguyen, V.L *et al.,* "An Experimental Demonstration of MIMO C-OOK Scheme Based on Deep Learning for Optical Camera Communication System," *Appl. Sci.* 2022, 12, 6935.

[9] H. Nguyen *et al.,* "Design and Implementation of Deep Learning for MIMO C-OOK Scheme-based Optical Camera Communication," *13th International Conference on Information and Communication Technology Convergence (ICTC)*, Jeju Island, Korea, Republic of, 2022, pp. 1905-1908.

[10] J. -K. Lain *et al.,* "Experimental DCO-OFDM Optical Camera Communication Systems With a Commercial Smartphone Camera," *IEEE Photonics Journal*, vol. 11, no. 6, pp. 1-13, Dec. 2019.

[11] Y. Goto *et al.,* "A New Automotive VLC System Using Optical Communication Image Sensor," in *IEEE Photonics Journal*, vol. 8, no. 3, pp. 1-17, June 2016.

[12] H. Nguyen *et al.,* "Design and Implementation of Rolling Shutter MIMO-OFDM scheme for Optical Camera Communication System," *2021 International Conference on Information and Communication Technology Convergence (ICTC)*, Jeju Island, Korea, Republic of, 2021, pp. 798-800.

[13] B. Selcuk *et al.,* "Brain Tumor Detection and Localization with YOLOv8," *2023 8th International Conference on Computer Science and Engineering (UBMK)*, Burdur, Turkiye, 2023, pp. 477-481.

[14] Heng Zhang *et al.,* "The optical fringe code modulation and recognition algorithm based on visible light communication using convolutional neural network," *Signal Processing: Image Communication*, Volume 75, 2019, Pages 128-140.

[15] M. Pulipalupula *et al.,* "Object Detection using You Only Look Once (YOLO) Algorithm in Convolution Neural Network (CNN)," *2023 IEEE 8th International Conference for Convergence in Technology (I2CT)*, Lonavla, India, 2023, pp. 1-4.

[16] H. Nguyen *et al*., "Rolling Shutter OFDM Scheme for Optical Camera Communication Considering Mobility Environment Based on Deep Learning," *Appl. Sci*. 2022, 12, 8269.

[17] Z. Wang *et al.,* "Sparse-YOLO: Hardware/Software Co-Design of an FPGA Accelerator for YOLOv2," *IEEE Access*, vol. 8, pp. 116569-116585, 2020.

[18] H. Nguyen *et al.,* "Design of MIMO C-OOK using Matched filter for Optical Camera Communication System," *2021 International Conference on Artificial Intelligence in Information and Communication (ICAIIC)*, Jeju Island, Korea (South), 2021, pp. 474-476.

[19] T. L. Pham *et al.,* "An Artificial Intelligence-based Error Correction for Optical Camera Communication," *2019 Eleventh International Conference on Ubiquitous and Future Networks (ICUFN)*, Zagreb, Croatia, 2019, pp. 137-140.