European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

# 166-m Rolling Shutter Based Free Space Optical Communication (FSO) Utilizing Long Short Term Memory Neural Network (LSTM-NN) for Decoding PAM4 Signal

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**Abstract** *We propose and preset the first demonstration of a record high 298.8-kbit/s•m bit-rate distance product rolling-shutter image-sensor based free-space-optical-communication (FSO) system. Long-short-term-memory-neural-network (LSTM-NN) is utlized to decode the 4-level pulse-amplitude-modulation (PAM4) rolling-shutter pattern.*

## Introduction

Optical wireless communication (OWC) technologies have attracted increasing attention recently [1-4]. Free-space optical communication (FSO), which is a kind of OWC, allows optical communcation over long distances. Besides the terrestial applications, FSO allow non-terrestrial applications, such as optical commuication among satellites and unmanned aerial vehicles (UAVs). It is also considered as one of the promising technologies for 6G network [5]. Moreover, image sensor based OWC [6] can utilize mobile-phone, vehicle or surveillance cameras as optical receivers (Rxs); enabling low-cost and flexible OWC. The typical complementary-metal-oxide-semiconductor (CMOS) image sensors used in mobile phones are operated in rolling shutter mode. It controls the image sensor exposure time row by row. Although the rolling shutter allows the data rate can be much higher than the camera frame rate, the row by row exposure delay will create decoding challenge. When the light emitting diode (LED) transmitter (Tx) is modulated at high speed, only a small number of pixel-rows in the image sensor can represent one logic bit (i.e. low pixel-row per bit, PPB). Hence, high inter-symbol interference (ISI) will result. Besides, multi-level modulation, such as 4-level pulse-amplitude-modulation (PAM4) can increase the data rate; however, it is also a great challenge to identify the multiple intensity levels in the rolling shutter pattern.

Table 1 summaries different rolling shutter image sensor based OWC systems. Threshoulding schemes, such as polynomial curve fitting [6], extreme-value-averaging (EVA) [7], beacon-jointed packet reconstructrion [8] were proposed to decode the rolling shutter pattern and to improve the performance; however, the transmission distance is limited. Machine learning techniques, such as logistic regression [9] and 2-D convolutional neural network (CNN) [10] were also proposed, and a data rate of 47 kbit/s using red-green-blue (RGB) LEDs was achieved [10]. Besides, a 111 kbit/s RGB rolling shutter OWC with 0.4 m transmission distance was reported, achieving a bit-rate distance product of 44.4 kbit/s • m [11]. Recently, telescope based image sensor Rx has been proposed for combining the advantages of the image sensor based OWC and FSO [12], and a high bit-rate distance product of 180 kbit/s • m was achieved [12].

Table 1 Different Rolling Shutter OWC systems

| Ref. | Scheme | Data-rate (kbit/s) | Distance (m) | Bit-rate × Distance (kbit/s.m) |
|---|---|---|---|---|
| [6] | OOK (Poly. Curve fitting) | 3.1 | 0.35 | 1.085 |
| [7] | OOK (EVA) | 7.68 | 0.3 | 2.304 |
| [8] | OOK (Beacon Jointed Packet Reconstruction) | 10.32 | 0.2 | 2.064 |
| [9] | OOK (Logistic Regression) | 1.02 | 1.5 | 1.53 |
| [10] | OOK & RGB (2D-CNN) | 47 | 0.4 | 18.8 |
| [11] | OOK & RGB (Double-EQ) | 111 | 0.4 | 44.4 |
| [12] | OOK (Telescope) | 0.45 | 400 | 180 |
| This Work | PAM4 (Telescope & LSTM-NN) | 1.8 | 166 | 298.8 |

In this work, we propose and preset the first demonstration up to the authors' knowledge of a record high bit-rate distance product rolling shutter image sensor based FSO system,

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achieving 298.8 kbit/s • m. 166 m free-space transmission at data rate of 1.8 kbit/s are realized. Long-short-term-memory neural-network (LSTM-NN) is utlized to decode the high ISI PAM4 rolling shutter pattern. Besides, as the Tx and Rx are not at the same height, we also propose the Rolling-Shutter-Strength-Enhancement (RSSE) scheme for the grayscale waveform equalization.

## Algorithm, Experiment and Results

Fig. 1 shows the mechanism of rolling shutter mode operation, in which different pixel-rows in the image sensor are activated sequentially with different start-time-delay. This means that when the LED is modulated quicker than the camera frame rate, dark and bright stripes representing LED "OFF" and "ON" can be observed in each frame. After the activation of all the pixel-rows, there is a frame-to-frame time, which is used to combine different pixel-rows into an image frame. At this time, no optical signal can be detected. As illustrated in Fig. 1, the first pixel-row is a bright stripe since the LED is ON for most of the exposure time. In the second pixel-row, ambiguity occurs due to the uneven aggregated light exposure of the pixel-row since only half of the exposure time is at LED ON state, producing a grey stripe. This ambiguity issue will be more severe for decoding PAM4.

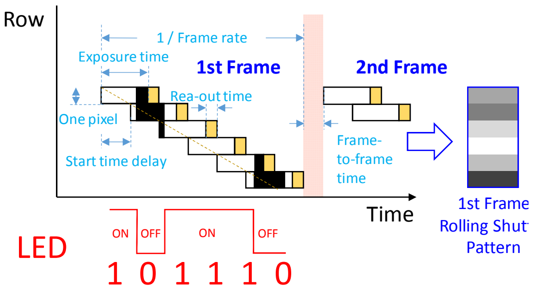


**Fig. 1:** Mechanism of rolling shutter operation.

Fig. 2(a) shows the experimental setup of the proposed rolling shutter image sensor Rx based FSO system. An arbitrary waveform generator (AWG, Tektronix® AFG3252C) is attached to a 22 W LED display light panel (Li-Cheng® Corp.) to modulate the backlight LED with PAM4 signal. The PAM4 signal has a 8-bit header and a variable bit-length payload. After 166 m free-space transmissions, the signal is received by a mobile phone mounted on a commercially available telescope (Vixen® SD103S). The image sensor has the resolution of 1920 × 1080 pixels. Fig. 2(b) shows the photo of the experiment, indicating the LED light panel and the telscope based Rx.

Fig. 3(a) shows the flow diagram of the LSTM-NN algorithm for decoding the PAM4 rolling shutter pattern. Different image frames are read-in for transforming into grayscale values, where grayscale 0 and 255 represent completely dark and bright stripes respectively. The highest grayscale value in each pixel-row will be selected to from a column matrix to produce the grayscale waveform. The headers are located and the payload are identified in the grayscale waveform. Then it is sent to data pre-processing module, in which several features of the input signal should be extracted. They include the features of present symbol value, symbol relationship and symbol average. LSTM-NN model contains five hidden layers. There are two LSTM layers with neuron number of 128 and 64 respectively. Batch normalization is performed after each LSTM layer. The last three layer are dense layers, with neuron number of 64, 16 and 4 respectively. The output of first and second dense layers will pass through Sigmoid function as activation function. Finally, Softmax is the activation function in the last layer.

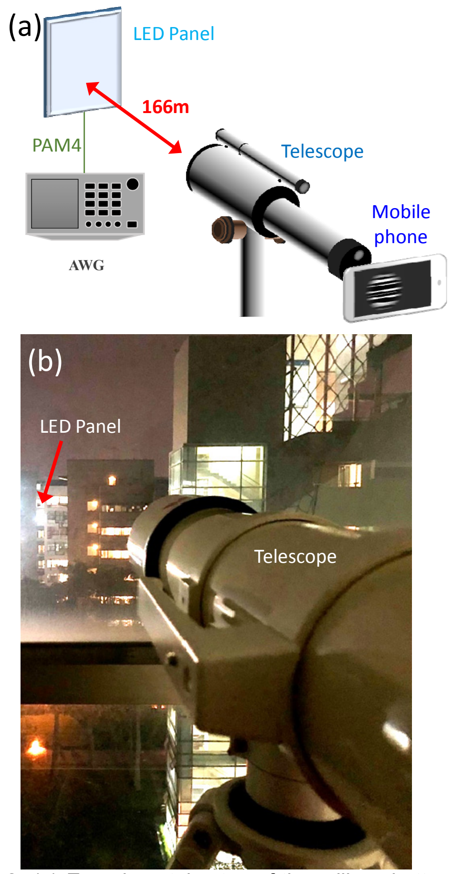


**Fig. 2:** (a) Experimental setup of the rolling shutter Rx based FSO system. (b) Photo of the experiment.

Fig. 3(b) shows the structure of a LSTM cell. $C_{t-1}$, $C_t$, $x_t$, $\sigma$, $h_{t-1}$,$h_t$, are the memory from the last LSTM cell, newly updated memory, current input, Sigmoid operation, output of last LSTM cell, and current output respectively. Inside each LSTM cell, there are 3 internal gates: forget, input and output gates. The forget gate decides what information to store and what to erase. The input gate decides what new information will be stored. The output gate produces output based on the cell state after filtering.

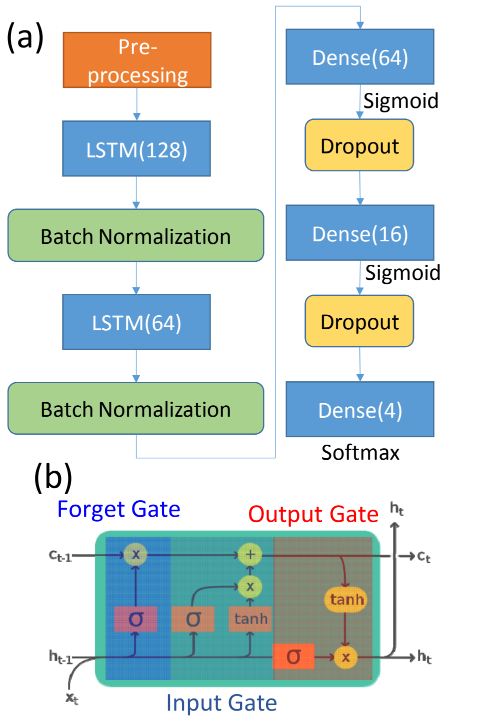


**Fig. 3:** (a) flow diagram of the LSTM-NN algorithm. (b)

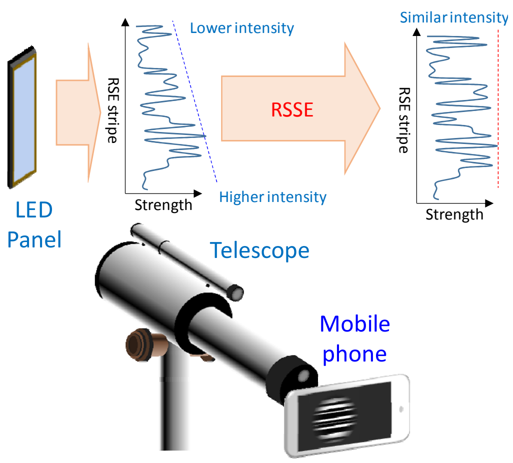


**Fig. 4:** Illustration of using RSSE to enhance the low intensity region of the grayscale waveform.

As the Tx and Rx are not at the same height, the grayscale waveform will have an uneven intensity distribution as illustrated in Fig. 4. We propose the RSSE to enhance the low intensity region of the grayscale waveform using Eq. (1),

$$y_n^* = \frac{y_n}{\Delta + \dfrac{(1-\Delta)(n-1)}{L_{stripe}}} \qquad (1)$$

where $n$ is the row index of stripe. $y_n$ and $y_n$* are the strength of stripe before and after the RSSE at index $n$. $\Delta$ is the strength ratio between the low and high intenstiy regions, and $L_{stripe}$ is the total length of the grayscale waveform. Besides the vertical offset, we also study the horizontal offset between the Tx and Rx. Unlike the vertical offset producing signal strength uneven in the grayscale waveform, the horizontal offset will not produce this uneven. As long as a column matrix of rolling shutter pattern from the LED panel can be observed in the image sensor, the grayscale waveform can be retrieved. As the distance between the Tx and Rx is 166 m long, we measure the horizontal offset tolerence of the telescope based Rx is about 2$^{o}$.

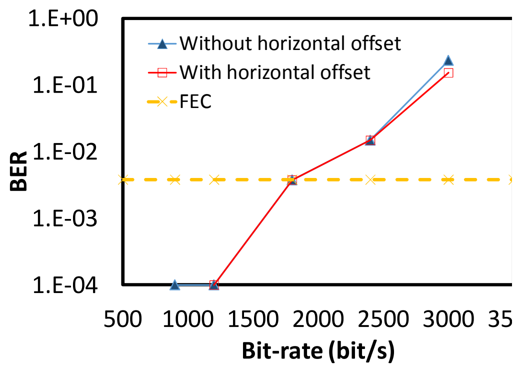


**Fig. 5:** Measured BER of the rolling shutter image sensor based FSO system without and with the horizontal offset.

Fig. 5 show the measured BER of the rolling shutter image sensor based FSO system without and with the horizontal offset. We can observe that the proposed LSTM-NN can successfully decode PAM4 rolling shutter pattern even with horizontal offest of 2$^{o}$ and can achieve 1.8 kbit/s and 166 m free-space transmission, satisfying the pre-forward error correction (FEC) bit-error-rate (BER) threshould (BER = 3.8 × $10^{-3}$).

## Conclusions

We proposed and demonstrated for the first time a record high 298.8-kbit/s • m bit-rate distance product rolling-shutter image-sensor based FSO system. 1.8 kbit/s and 166 m free-space transmission were achieved satisfying the pre-FEC BER threshold. LSTM-NN was utlized to decode the high ISI PAM4 rolling-shutter pattern. As the Tx and Rx were not at the same height, the grayscale waveform had an uneven intensity distribution, and RSSE was proposed for the grayscale waveform equalization. Besides, we also studied the horizontal offset between the Tx and Rx, and the measured offset tolerence of the telescope based Rx is about 2$^{o}$

## Acknowledgements

We would like to acknowledge the Ministry of Science and Technology, Taiwan (MOST-110-2221-E-A49-057-MY3, MOST-109-2221-E-009-155-MY3).

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