Wide Field-of-View (FOV) Light-Diffusing Fiber Optical Transmitter for Rolling Shutter based Optical Camera Communication (OCC)

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Abstract: We propose a wide field-of-view (FOV) light-diffusing-fiber (LDF) transmitter optical-camera-communication (OCC). Pixel-row-per-bit-neural-network (PRPB-NN) is employed for rolling-shutter-pattern decoding. PRPB-NN provides efficient decoding at 360° around LDF circumference and 160° Rx rotation-angle at 2100-bit/s. © 2022 The Author(s)
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1. Introduction

While the demands of wireless communication are now depleting the radio frequency (RF) spectrum capabilities, optical wireless communication (OWC) has been proposed to provide large communication spectrum in the optical domain. OWC has the advantages that it is license-free and electromagnetic-interference (EMI) free. It does not interfere with the RF signals and so it can be used to augment RF communication to provide extra communication bandwidths. To increase the OWC applicability and popularity, the OWC transmitters (Txs) and receivers (Rxs) should be low cost, handy and convenient. One kind of simple OWC implementation is to use the cameras or image sensors for optical Rxs, which is known as optical camera communication (OCC) [1, 2]. OCC can be easily deployed using the smart-phone camera, vehicle cameras or surveillance cameras. There is no need of significant hardware modification on the OCC Rx. Besides, in order to increase the applicability of OWC, the availability of large field-of-view (FOV) Tx and Rx is also important. Recently, large FOV optical Txs based on optical beam steering were proposed, covering beam steering angles of 20° and 12° respectively [3, 4]. Besides, a wide FOV Rx using fluorescent fiber optical concentrator was demonstrated [5], achieving a FOV of 240°.

In this work, we propose and demonstrate for the first time up to the authors' knowledge a wide FOV light-diffusing fiber (LDF) optical Tx for the rolling shutter OCC system. The LDF is a glass optical fiber made for decorative lighting or embedded into small areas where bulky light sources cannot fit. The LDF Tx can provide a wide 360° FOV around the circumference of the fiber and 120° FOV along the length of the fiber if viewed from either end of the fiber. It is similar to an "omnidirectional optical antenna". Moreover, decoding the high data rate rolling shutter OCC pattern is challenging due to the high inter-symbol interference (ISI) generated from the low pixel-row per bit (PRPB). Inspired by the decoding idea proposed in [6] based on the pixel-per-symbol labeling for the 4-level pulse-amplitude-modulation (PAM4) decoding, we propose and utilize the pixel-row per bit based neural network (PRPB-NN) for the on-off keying (OOK) rolling shutter decoding. Experimental results show that the proposed PRPB-NN can provide efficient rolling shutter decoding at 360° around the Tx circumference and 160° Rx rotation angle at data rate of 2100 bit/s, fulfilling the pre-forward error correction bit-error-ratio (pre-FEC BER = 3.8×10^{-3}) threshold.

2. Experiment and PRPB-NN Algorithm

Fig. 1(a) shows the experiment of the wide FOV OCC system using LDF optical Tx and rolling shutter camera Rx. The LDF (Corning® Fibrance®) has a light-diffusion length of 1 m. The core, cladding and outer jacket diameters are 170 μm, 230 μm and 900 μm respectively. The LDF is attached to a blue laser diode (LD), which is connected to an arbitrary waveform generator (AWG, Tektronix® AFG3252C) to produce the OOK signal. The OCC signal is received by a complementary-metal-oxide-semiconductor (CMOS) image sensor with resolution of 1920 × 1080 pixels and frame rate of 30 frame per second (fps). As indicated in Fig. 1(a), the LDF can provide a wide 360° FOV around the circumference of the fiber and 120° along the length of the fiber if viewed from either end of the fiber. It is similar to an "omnidirectional optical antenna". Our experimental results also show that the decoding of rolling shutter pattern can be achieved even the smart phone is rotated by ± 80°. Figs. 1(b) and (c) show the photos of the LDF optical Tx and received rolling shutter pattern on the screen of smart-phone at 0° and 45° rotation angles respectively. In both cases, clear rolling shutter pattern can be observed at the screen of the smart-phone. The CMOS camera is working at rolling shutter mode [1, 2], in which it does not collect all the optical signal at the same time. Instead, different pixel-rows in the camera are activated sequentially depending on the row-by-row exposure time. When the LDF optical Tx is modulated faster than the frame rate but slower than the row-by-row exposure time, bright and dark fringes representing optical signal "ON" and "OFF" can be observed in each image frame. When the optical Tx is modulated at high speed, only a few pixel-rows in the CMOS image sensor can be used to represent one logic bit (i.e. low PRPB); hence, high ISI is observed.

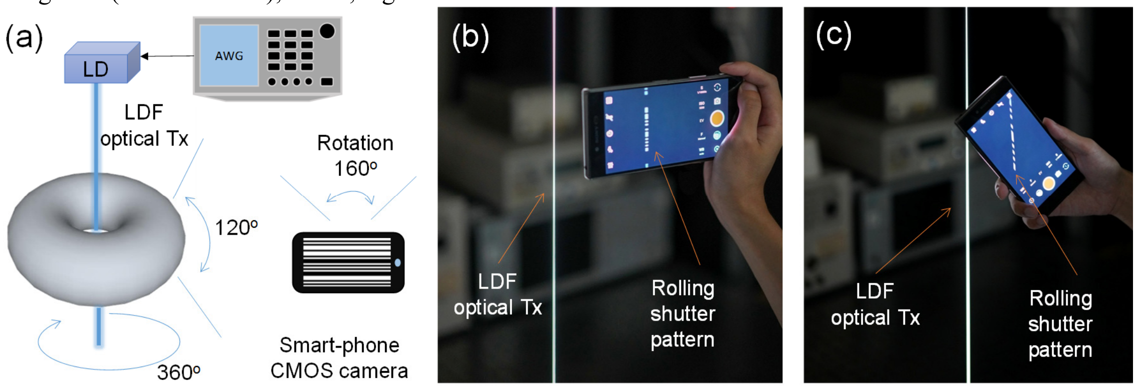

Fig. 1. (a) Experiment of wide FOV OCC system using LDF optical Tx and rolling shutter camera Rx. (b) (c) Photos of the LDF optical Tx and received rolling shutter pattern by the smart-phone at different rotation angles.

Fig. 2(a) shows the architecture of the decoding mechanism. It consists of the training and testing phases. First, training images are launched to the Image-to-Data Preprocessing module. In this module, the image frames are changed into grayscale values: 0 (dark) to 255 (bright). Since the light source image is thin and only occupies a few horizontal pixels, noise reduction is needed [2]. Then the grayscale values representing the LDF in each pixel-row are extracted to form a column matrix of grayscale values. In the column matrix of grayscale values, the packet payload can be identified between two headers. Finally, PRPB calculation and re-sampling are performed. The PRPB re-sampling is to guarantee the same number of pixels is utilized in each logic bit for the PRPB-NN label. When the PRPB-NN model is built; testing phase can be implemented. In the experiment, the training and testing images are different. Finally, the PRPB-NN model is evaluated by BER measurement. Fig. 2(b) illustrates the proposed PRPB-NN. It consists of 6 fully connected layers. The first input layer has the number of nodes the same as the PRPB of payload data. There are 4 fully connected hidden layers, in which ReLu is the activation function. At the output layer, Softmax is used to obtain the probabilities of logic 0 and 1. Here, loss function used is based on sparse categorical cross entropy [7]. Adam optimizer is utilized for parameter update in the training phase. The number of frames used for training, validation and testing are 16, 4 and 200 respectively.

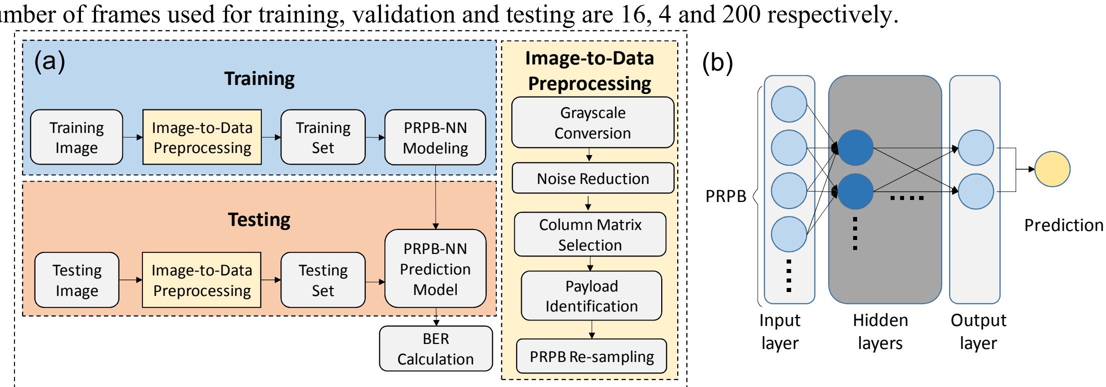

Fig. 2. (a) Proposed architecture of the decoding mechanism. (b) Proposed PRPB-NN.

3. Results and Discussion

Figs. 3 (a)-(c) show the measured BER of the wide FOV OCC system at different data rates and free-space transmission distances (100 cm and 35 cm) using the traditional artificial neural network (ANN) and the proposed PRPB-NN respectively. We can observe that the proposed PRPB-NN can provide efficient distortion mitigation at high ISI when both data rate and transmission distance are high. PRPB-NN decoding scheme can satisfy the pre-

FEC BER at data rate of 3300 bit/s when the transmission distance is 35 cm. When the traditional ANN decoding scheme is used, only 1500 bit/s is achieved. When the free-space transmission distance is extended to 100 cm, the PRPB-NN can still achieve 2100 bit/s fulfilling the pre-FEC BER, while the ANN can only achieve 1500 bit/s.

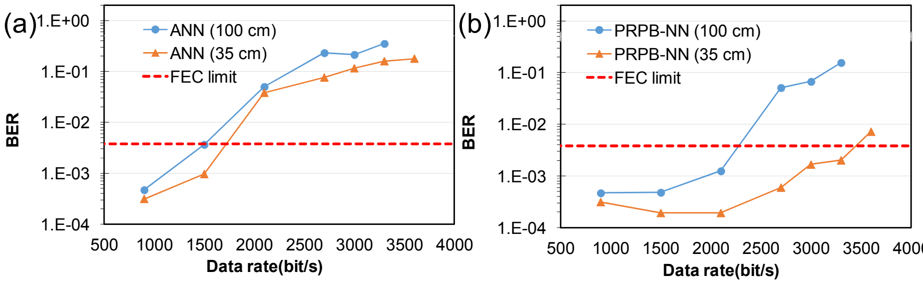

Fig. 3. Measured BER of the wide FOV OCC system at different data rates and free-space transmission distances (100 cm and 35 cm) using (a) traditional ANN and (b) proposed PRPB-NN.

Then we evaluate the FOV of the LDF optical Tx by measuring the BER around the circumference. PRPB-NN is employed and the transmission distance is at 35 cm. The measured BER is nearly the same around the LDF circumference as shown in Fig. 4(a). Then, we evaluate the rotation angle of the smart-phone with respected to the LDF optical Tx. The transmission distance is also 35 cm. At the data rates of 3000 bit/s and 2100 bit/s, rotation angles of < 70^{o} and 80^{o} can be supported. When the smart-phone rotation angle is increased, the observed rolling shutter pattern on the smart-phone screen will be tilted as illustrated in the photo of Fig. 1(c). As shown in Fig. 4(b), when the rotation angle is within certain range (about 45^{o}), the BER performance is similar. When the rotation angle is large, the rolling shutter pattern decoding will become difficult and more PRPB is needed for successful decoding. Hence, the OCC data rate should be decreased accordingly. Here, at the OCC data rate of 3000 bit/s and 2100 bit/s, the PRPB values are 4 and 7 respectively. It is also worth to note that as the LDF is bendable, higher rotation angle may be achieved by bending the LDF optical Tx. We hope that could be reported in the conference.

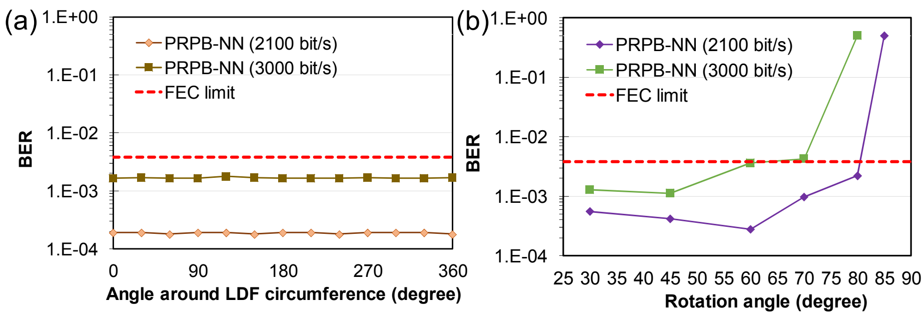

Fig. 4. Measured BER (a) around the LDF Tx circumference and (b) at different rotation angles when the transmission distance of 35 cm.

4. Conclusion

We proposed and demonstrated for the first time a wide FOV LDF optical Tx for the rolling shutter OCC system. Moreover, the PRPB-NN was employed for efficient rolling shutter decoding at high ISI. Experimental results showed that the proposed PRPB-NN can provide efficient decoding at 360^{o} around the Tx circumference and 160^{o} Rx rotation angle at data rate of 2100 bit/s.

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5. References

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