Lightweight Light-Diffusing Fiber Transmitter Equipped Unmanned-Aerial-Vehicle (UAV) for Large Field-of-View (FOV) Optical Wireless Communication

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Abstract: We propose a light-diffusing-fiber transmitter (LDF-Tx) equipped unmanned-aerial-vehicle (UAV) for optical-wireless-communication (OWC). Long-short-term-memory-neural-network (LSTMNN) provides efficient rolling-shutter-pattern decoding at 360^o around LDF-Tx circumference.

OCIS codes: (060.2605) Free-space optical communication; (060.4510) Optical communications

1. Introduction

Recently, utilizing unmanned aerial vehicles (UAVs) in the area of wireless communication has attracted much attention. UAV-assisted wireless communication can efficiently support the already existing terrestrial networks, by providing high mobility and flexibility platforms for data offloading or covering the network "blind spots". It is also suitable for the fronthaul and backhaul networks [1]. In addition, UAV-assisted communication has been considered as a promising method to handle unexpected or temporarily large amounts of information, and it can be used to provide urgent communication during catastrophic disasters, such as earth quakes or hurricanes [2]. Apart from using the highly congested radio frequency (RF) spectrum, optical wireless communication (OWC) can provide large communication bandwidth using the optical spectrum. OWC can also provide several advantages, such as it does not interfere with the RF signal and can be used to augment RF communication for providing additional bandwidths [3]. UAV-assisted OWC systems have been studied extensively for the future networks, for instance, ref. [4] investigated the performance of UAV-based OWC systems when subjected to different weathers, showing that this can satisfy the backhaul/fronthaul requirements [4]. Although UAV-assisted OWC systems can provide many advantages and can carry out various specific missions, challenges exist affecting the transmission performance. One major challenge is the presence of pointing error [5], which is caused by the random fluctuation of the angle-of-arrival at the receiver (Rx), leading to optical power loss in the Rx. Besides, from the battery lifetime and government regulation points of view, the installed OWC Tx and Rx should be lightweight, and this introduces additional challenge to the UAV-assisted OWC systems.

In this work, we put forward and demonstrate for the first time up to our knowledge using a light-diffusing-fiber transmitter (LDF-Tx) mounted on a UAV to provide wide field-of-view (FOV) OWC. The LDF is an optical glass fiber primarily made for decorative lighting; here, we use it for the OWC Tx. The LDF-Tx is very lightweight, bendable, flexible and has low power consumption. It can act as an "omnidirectional optical antenna" providing a wide 360^o and 120^o FOVs around the fiber circumference and along the fiber respectively. The complementary-metal-oxide-semiconductor (CMOS) optical cameras in the ground stations or the front cameras of another UAVs can act as the OWC Rxs by extracting the optical signal in the rolling-shutter patterns from the captured videos. The rolling shutter operation in CMOS camera allows the OWC data rate can be much higher than the camera frame rate [6]. Since the LDF-Tx light source is thin and occupies only a few horizontal pixels in the image frame, long short term memory neural network (LSTMNN) is used to decode the rolling shutter pattern. The LSTMNN can also mitigate the signal fluctuations in the flying platform using the temporal memory characteristics [7]. Experimental results show that 3,300 bit/s, satisfying the pre-forward error correction bit-error-rate (pre-FEC BER = 3.8×10^{-3}) can be achieved at 360^o around the LDF-Tx circumference.

2. UAV-assisted OWC Experiment and LSTMM Model for Rolling Shutter Decoding

Fig. 1(a) shows the experimental setup of the LDF-Tx equipped UAV for the wide FOV OWC system. The UAV (Ryze® Tello®) has the dimensions of ~ 9.8 × 9.3 × 4.1 cm and weight of ~ 80 g including battery. According to the specification, it has the maximum flying distance and flying height of 100 m and 30 m respectively, with speed of 8 m/s. The LDF (Corning® Fibrance®) used has a 1-m light-diffusion length, with core and cladding diameters of 170 μm and 230 μm respectively. The LDF is pigtailed to a blue laser-diode (LD) and a laser driver circuit with microcontroller unit (MCU) to produce on-off-keying (OOK) signal. The LDF-Tx module has weight of < 20 g. The blue LD has the wavelength and output power of 450 nm and 20 mW respectively. The phosphor coating of the LDF produces white-light emission from the blue LD allowing OWC and illumination simultaneously. As illustrated in Fig. 1(a), the LDF can act as the bendable, flexible and extended light source providing a wide 360° FOV around the fiber circumference and 120° FOV along the fiber length if viewed from either end of the fiber. It is similar to an "omnidirectional optical antenna". The OWC signal emitted by the LDF-Tx can be captured by optical cameras in the ground stations or the front cameras of another UAVs. Here, the optical Rx is the smart-phone CMOS camera with resolution and frame rate of 1920 × 1080 pixels and 30 frame per second (fps) respectively. Figs. 1(b) and (c) show the experimental photos showing the UAV equipped with the LDF-Tx and the rolling shutter pattern of the LDF-Tx received on the screen of smart-phone respectively. It is worth to note that during the UAV flying, the LDF-Tx is tilted and is not pointing downward perpendicular to the ground. Hence, offering large FOV as well as supporting large Rx tilting angle are particularly important.

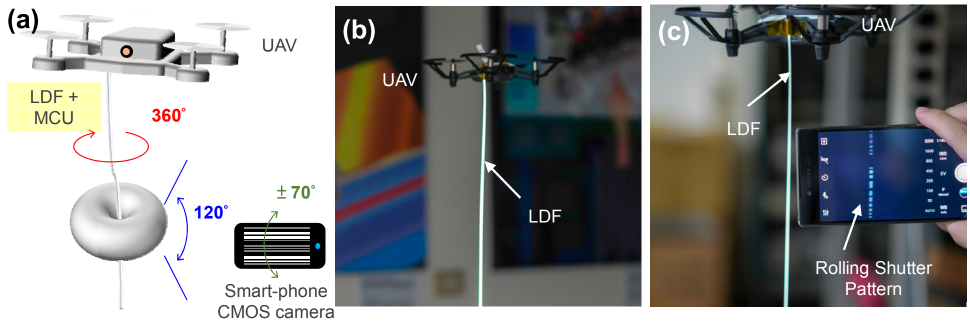

Fig. 1. (a) Experiment of the LDF-Tx equipped UAV for wide FOV OWC system. (b) (c) Photos of the UAV equipped with the LDF-Tx and rolling shutter pattern of the LDF-Tx received on the smart-phone screen.

In the CMOS image sensor rolling shutter operation [6], optical signal is not captured simultaneously, but different pixel-rows are activated sequentially. Hence, if the LDF-Tx is modulated quicker than the camera frame rate but slower than the image sensor row-by-row exposure time, bright and dark patterns representing light "ON" and "OFF" are received as illustrated in Fig. 1(c). If the LDF-Tx is modulated at higher speed, only a very few pixel-rows in the image sensor can be used to represent one logic bit, producing high inter-symbol interference (ISI). Fig. 2(a) illustrates the flow diagram of the rolling shutter decoding scheme. It has the training phase and testing phase. First, images for training are input to the "Data Preprocessing Module" (i.e. green block) as shown in Fig. 2(b), in which the LDF-Tx light source is identified. Then, the image frames are converted into grayscale values from 255 (total brightness) to 0 (total darkness). Since the LDF-Tx light source image is thin and occupies only a few horizontal pixels, LSTMNN (i.e. orange block) will be used for the effective rolling shutter decoding. Then, the grayscale values representing the LDF-Tx in each pixel-row are arranged to produce a column matrix with grayscale values. After this, the OWC packet payload can be obtained by looking for headers. Finally, pixel-row per bit (PPB) calculation as well as re-sampling are executed. The PPB re-sampling is to guarantee that same number of pixels is employed in each logic bit of the OOK signal.

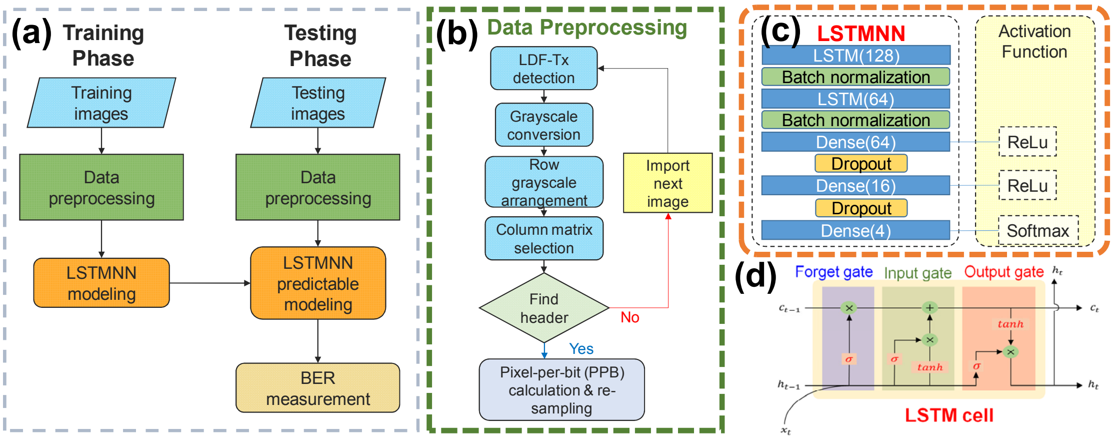

Fig. 2. (a) Flow diagram of the rolling shutter decoding scheme. Structures of (b) Data Processing, (c) LSTMNN, (d) LSTM cell.

Fig. 2(c) shows the proposed LSTMNN model. Here, adjacent 3 logic bits are used for the feature extraction. The LSTMNN contains 5 hidden layers. The first 2 layers are LSTM layers with neuron number of 128 and 64 respectively. Batch normalization is performed after each LSTM layer. The last 3 layers are fully-connected dense layers, with neuron number of 64, 16 and 4 respectively. ReLU and Softmax functions are used as the activation functions in these layers. The loss function is based on sparse categorical cross entropy and the optimizer is Adam for parameter update during the training phase. The number of training and testing frames are 100 and 150 respectively. Fig. 2(d) shows the structure of a LSTM cell. x_t, σ, C_{t-1}, C_t, h_{t-1},h_t, are the current input, Sigmoid function, memory from last LSTM cell, newly updated memory, output from last LSTM cell, and current output respectively. There are 3 internal gates, named as forget, input and output gates inside each LSTM cell. Forget gate determines what information to erase; input gate determines what new information to stored; and output gate generates output based on the cell state.

3. Results and Discussion

Figs. 3(a) and (b) shows the BER measurements of the LDF-Tx equipped UAV during the UAV flying experiment. The BER performance of an artificial neural network (ANN) is also included for comparison. The ANN has 7 fully-connected layers with neuron number of 1, 40, 63, 138, 512, 138, 2. ReLU and Softmax activation functions are applied for the first 6 layers and the last layer respectively. The loss function and optimizer are the same as that in LSTMNN. it can be observed that the proposed LSTMNN provide significant BER enhancement to mitigate the signal distortion due to signal fluctuations in the flying platform. The data rate can be enhanced from 2,000 bit/s to 3,300 bit/s meeting the pre-FEC BER when the LSTMNN is utilized. We also evaluate the FOV of the LDF-Tx by measuring the BER around the fiber circumference. Similar BER performance is achieved in 360^o FOV around the fiber circumference. Finally, we evaluate the Rx rotation angle of the smart-phone with respected to the LDF-Tx, and the results show pre-FEC BER can be achieved with the Rx rotation angles is within ± 70^o, as shown in Fig. 3(b). When the rotation angle is large, more PPB is needed to decode the rolling shutter pattern, resulting in higher BER.

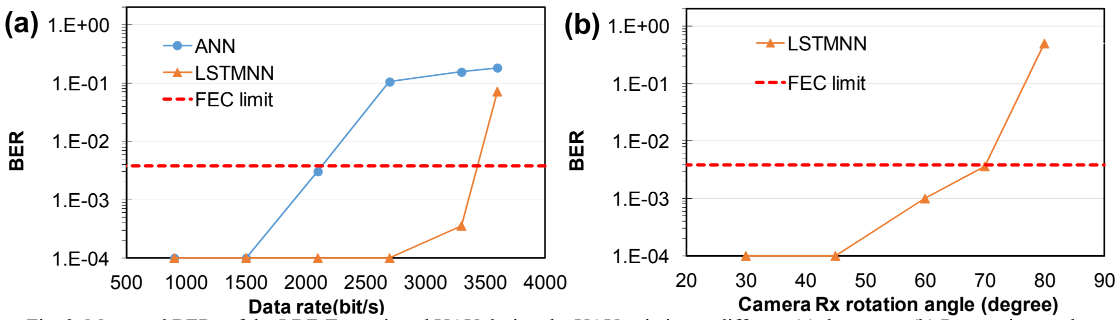

Fig. 3. Measured BERs of the LDF-Tx equipped UAV during the UAV aviation at different (a) data rates; (b) Rx rotation angles.

4. Conclusion

We proposed and demonstrated a LDF-Tx equipped UAV for wide FOV OWC system. The LDF can act as the bendable, flexible and extended light source, and could provide solutions to the weight regulation, as well as large FOV needed of the UAV. During the UAV flying, the LDF-Tx was tilted; hence, offering large FOV as well as supporting large Rx tilting angle were particularly important. Since the LDF-Tx light source image is thin and occupies only a few horizontal pixels, LSTMNN was used to decode the rolling shutter pattern. LSTMNN can also mitigate the signal fluctuations in the flying platform. Experimental results showed that 3,300 bit/s can be achieved at 360^o around the LDF-Tx circumference, and ± 70^o of the Rx rotation.

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5. References

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