Seven-Aperture Direct-Detection Receiver for Free-Space Optical Communication Systems

Mat Nguyen Thi, Vuong Mai, and Hoon Kim
School of Electrical Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon, Korea
Email: hoonkim@kaist.ac.kr

Abstract: We experimentally demonstrate a free-space optical communication system utilizing seven-aperture direct-detection receiver. We estimate the instantaneous SNR from the AC-coupled photo-currents and implement the maximal ratio combining by optimizing the averaging time of the photo-current.

1. Introduction

Free-space optical communications (FSOC), due mainly to their capability to transmit multi-gigabit signals over unlicensed spectrum, have received considerable attention as an alternative transport technology to radio-frequency (RF) wireless communications [1]. However, the performance of FSOC systems is severely limited by channel effects including absorption, scattering, and turbulence of atmospheric channel. Even in clear weather conditions, the light intensity experiences the spatiotemporal fluctuations induced by turbulent airflow and temperature gradient of the channel. Several techniques have been proposed to mitigate and/or compensate for the adverse effects of atmospheric turbulence. For example, the adaptive optics is employed at the receiver to compensate for the wavefront distortions induced by atmospheric turbulence [2]. However, this technique not only needs expensive optical devices such as wavefront sensor and deformable mirror, but also their operation speed should be fast enough to compensate for the temporal fluctuations of the wavefront. Aperture averaging is a common technique to mitigate scintillation. By using a large aperture receiver, the spatial fluctuations of light intensity can be averaged out, and as a result, it reduces the variance of intensity fluctuations. The major drawback of this scheme is that it becomes quite difficult to couple the received light into a tiny area of detector or single-mode fiber (SMF) at the receiver as the aperture size increases.

Instead of utilizing a single large aperture, multiple small apertures can be employed. The major advantages of this scheme over the aperture averaging include the effective mitigation of scintillation under strong turbulence, low implementation cost, and ease of scalability [3]-[5]. Recently, a four-aperture coherent receiver was experimentally demonstrated in [5] to decrease the required number of photons per bit impinging on the aperture. Here, the detected signals were combined with their phases aligned in the digital signal processing (DSP) after the intradyne detection. In another example, the optical signals collected by using 4 apertures were combined coherently in the optical domain by using optical couplers and fiber phase shifters [6]. In both works, the number of apertures is limited to 4 due to the high implementation cost of coherent receivers. Multi-aperture receiver can also be used for direct-detection (DD) systems. For example, two-aperture DD receiver was experimentally demonstrated for light-emitting diode-based visible light communication system [7], [8].

The most common techniques for combining multiple signals at the receiver are selection combining, equal gain combining (EGC), and maximal ratio combining (MRC). It is well known that the MRC outperforms the other two, but the tricky part of implementing the MRC is to estimate the instantaneous signal-to-noise ratio (SNR) of each signal. This is especially troublesome when the information about the average signal power is not available, for example, by using the AC-coupled high-speed photo-detectors. In this regard, the majority of experimental demonstrations have employed the EGC in FSOC systems [5]-[7].

In this paper, we demonstrate a 1.25-Gb/s FSOC system using a 7-aperture DD receiver. To the best of our knowledge, this is the largest number of apertures experimentally demonstrated in FSOCs. In this work, we utilize 7 off-the-shelf, AC-coupled photo-receivers where the DC photo-current is not available. Thus, we estimate the instantaneous SNR from the AC-coupled photo-currents and implement the MRC scheme by optimizing the average time of the signal for the bit-error ratio (BER) performance. We show that we can achieve a transmitter power gain of 7 dB in comparison with a single-aperture receiver.

2. Experimental Setup

Fig. 1 shows the experimental setup. A 1.25-Gb/s on-off keying signal is first generated by using an electro-absorption modulated laser (EML) operating at 1.55 μm. After the signal is amplified by using an erbium-doped fiber amplifier, the signal is sent to the free-space channel through the center aperture (i.e., labeled as ‘1’ in the inset of Fig. 1). The optical signal propagates along the corridor of a building to a retroreflector placed 52 m away from the transmitter and then comes back to the receiver. Thus, the total transmission distance of the channel is 104 m. Electric fans and heaters are distributed along the transmission channel to emulate atmospheric turbulence. The diameter of the optical beam on the aperture plane is about 20 cm. The receiver is composed of seven lenses having a diameter of 2.54 cm and seven off-the-shelf, AC-coupled PIN-FET receivers. Six apertures are located at the vertices of a regular hexagon with a side length of 6.75 cm. Those six apertures are labeled from 2 to 7 in the inset of the figure. An optical circulator is inserted between the transmitter and the aperture #1 so that this center aperture transmits and receives the optical signal. The optical signals collected by the apertures are coupled into the SMF-pigtailed receivers and then digitized simultaneously by using a 7-channel real-time oscilloscope (sampling rate = 10 Gsample/s). In the off-line signal processing and BER measurement, the amplitude and phase of each receiver are first calibrated to adjust the gain and path length mismatch of each path. Then, the seven signals are resampled at 1 sample/symbol before we combine them using the MRC. Finally, the BER performance is evaluated by direct error counting.

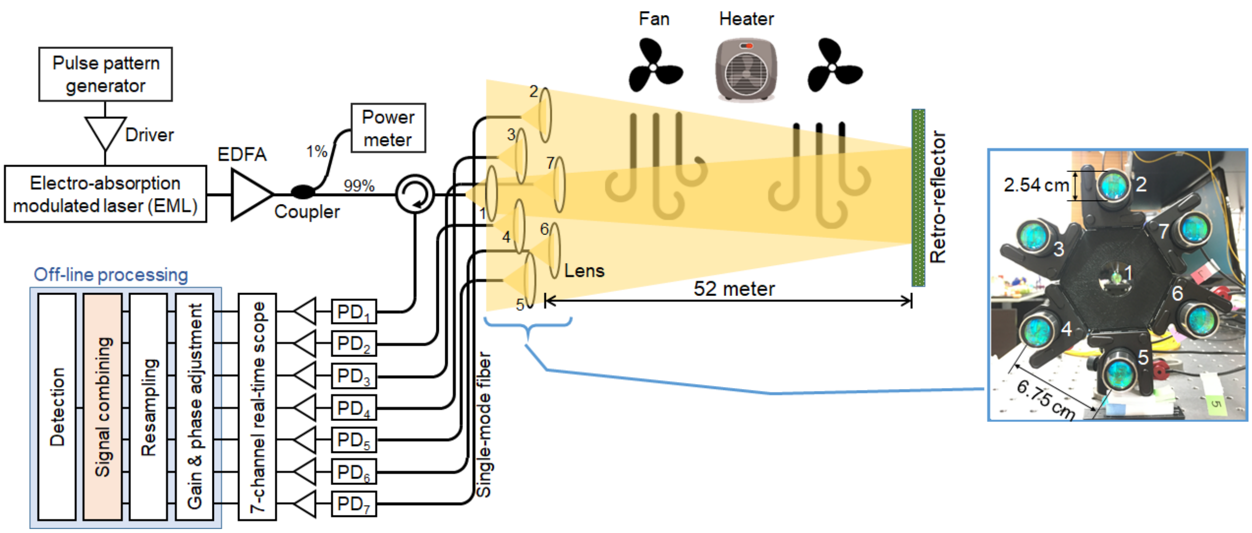

Fig. 1. Experimental setup.

For the implementation of MRC, we first estimate the instantaneous SNR of each signal. Since the additive noise in our system is the thermal noise at the receiver, the SNR would be proportional to the average signal power. However, since the DC photo-currents (which are proportional to the average received signal powers) are not available in our AC-coupled high-speed photo-receivers, we utilize the following equation to estimate the SNR.

$$SNR_i \propto \left\{ \sum_{k=1}^{N} v_i^2(k) \right\}^{1/2} \tag{1}$$

where the subscript i indicates the aperture index and v is the voltage amplitude of the signal. Also, N is the total number of samples to be averaged. Since we resample the signal at 1.25 Gsample/s, the averaging time amounts to 800N ps. In the MRC scheme, the signals are combined linearly with weights proportional to the SNR of each signal. Thus, we determine the weight of each signal using (1). The major advantages of the proposed scheme are that a large amount of sampled signals is not required to estimate the noise variance and it can be applied to AC-coupled receivers where the DC photo-current is not available.

3. Experimental results

We first optimize the averaging time (i.e., 800N ps) for BER performance. Fig. 2 shows the measured BERs as a function of averaging time under a couple of channel conditions. The transmitter power is set to be 3 dBm. The strength of the turbulence is quantified by the scintillation index measured at the aperture #1. The results show that the optimum averaging time for BER performance is about 10~100 μs for all the channel conditions we emulated. The averaging time should be short enough to track the temporal variation of intensity fluctuations, but long enough to average out the noise. The intensity fluctuation induced by scintillation is measured to have spectral components up to 1 kHz in our experiment. Thus, we set the averaging time to be 40 μs (i.e., N=50,000).

We next measure the BER performance. Fig. 3 shows the measured BER as a function of the transmitter power. At a weak turbulent channel (i.e., scintillation index = 0.0089), the transmitter power required to achieve a BER of 10^{-3} for the 7-aperture receiver is measured to be 2.6 dBm. This is 3.7 dB lower than the case where we use only aperture #1 at the receiver (i.e., single aperture case). As the turbulence gets stronger, this gain increases. For example, under a relatively strong turbulent condition (i.e., scintillation index = 0.2615), we need the transmitter power of 7.0 dBm to have a BER of 10^{-3} using the 7-aperture receiver. However, when the aperture #1 is used at the receiver, we have to increase the transmitter power to 14 dBm. We expect that as the turbulence gets stronger the gain would level out at around 8.45 dB (=10·log7) since the atmospheric turbulence would make the received signal at each aperture uncorrelated statistically.

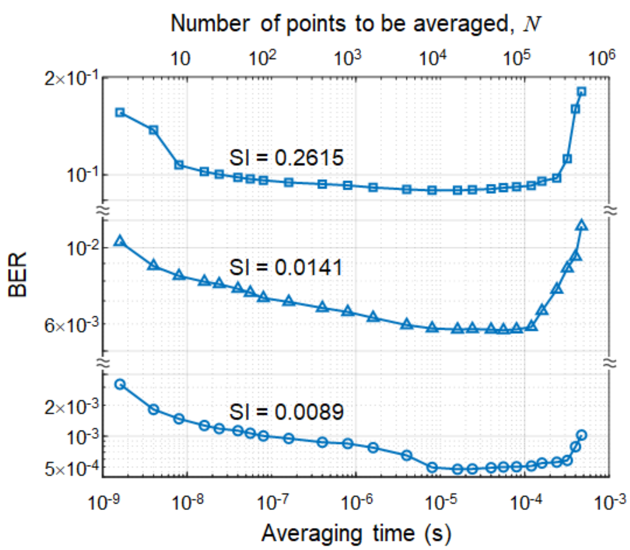

Fig. 2. Optimization of averaging time to estimate the instantaneous SNR

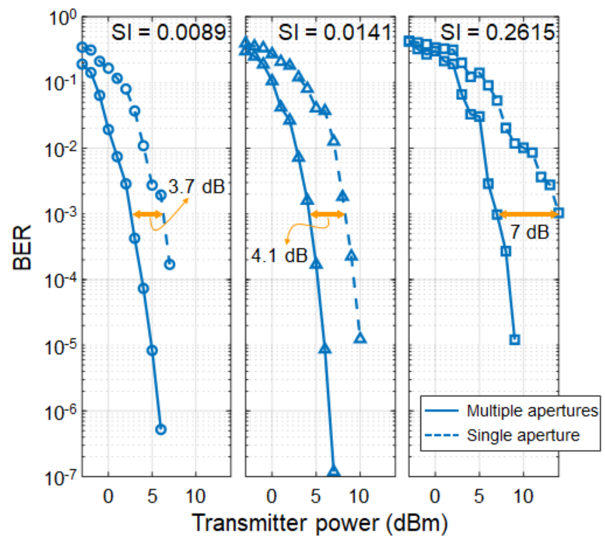

Fig. 3. Measured BER in three channel conditions

4. Conclusions

We have experimentally demonstrated the seven-aperture direct-detection receiver employing the maximal ratio combining scheme for free-space optical communications. Since the information about the average received optical power is not available in AC-coupled photo-receivers, we estimate the instantaneous SNR from the photo-currents and optimize the averaging time of the electrical signals for BER performance. We have demonstrated that the transmitter power required to achieve the desirable BER performance can be reduced in proportion to the number of apertures as the turbulence gets stronger.

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