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Non-line-of-sight beam reconfigurable optical wireless system for energy-efficient communication

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Abstract *By aligning chaotic processes on rough walls, the diffused power of a non-line-of-sight link is focused with >17-dB gains, in an angular range of 20º. A record-breaking 30-Gb/s OFDM signal is transmitted over an indoor diffused link.*

Introduction

Coherent Wireless communication by means of light (a.k.a. 'optical wireless communication', OWC)[1-4] instead of radio waves can bring a breakthrough in communication capabilities, both in terms of ultra-high capacity per user and in terms of electromagnetic interference-free communication, without requiring spectrum licenses. As a light beam cannot bend around an obstacle, line-of-sight (LoS) is typically required. However, for ubiquitous coverage, OWC also needs to work with non-line-of-sight (NLoS) links. A widely-recognized challenge for OWC is the large power diffused in an NLoS link, which is associated with diffuse reflection. When a coherent optical pencil beam is incident on a rough wall (diffuse reflector), every tiny facet in the illuminated spot of the wall reflects the light in a chaotic way, which results in near-omni-directional distribution (diffusion) of the reflected beam. The optical power is thus scattered strongly, but only weakly absorbed at the wall. The intensity of the diffused light is inherently much lower than that of the incident light. The solutions proposed so far usually do not address the diffusion mechanism itself but focus on: 1) compensate diffusion losses by increasing the incident power, or 2) avoid diffuse reflection, i.e. use a near-perfect mirror as a reflector. However, the maximum allowed power is limited by eye safety regulations while implementing mirrors is not practical in terms of convenience and cost. As a long-standing challenge, such diffusion losses critically hinder the wide application of OWC. Any technology which directly addresses the diffusion itself will create a breakthrough in the wireless communication domain. The issue is whether the diffusion is insurmountable or whether it can be relaxed/eliminated while keeping a ubiquitous coverage. In this paper, we present a novel breakthrough solution for this major issue. By aligning the quasi-chaos process of every facet on a diffused reflector, the near-omni-directional diffusion can be focused to a desired direction, i.e. towards the users' receiver. We demonstrate this technique, which we dubbed 'chaos aligned optical transmitter' (CAO-Tx), experimentally and we demonstrated a record capacity of 30 Gb/s in a diffused infrared OWC link. We believe that this approach, which breaks the NLoS limitation of OWC, will provide a new game-changing direction for optical wireless communication.

Operation principle of CAO-Tx

Figure 1 depicts the operation principle of a CAO-Tx. In an indoor OWC system as shown in Fig. 1 (a), LoS links (with pencil beams) can only cover users' devices to a limited extent since the barriers (e.g., obstacles, bodies...) in between block such links. With the assistance of rough walls, ubiquitous coverage can become possible by diffuse reflection. To focus the diffused beam, a CAO-Tx is introduced with its operation principle shown in Fig. 1 (b) and (c). As shown in Fig. 1 (b), a collimated beam incident on a rough surface (e.g. walls) is scattered with heavy intensity losses. When applying a proper phase

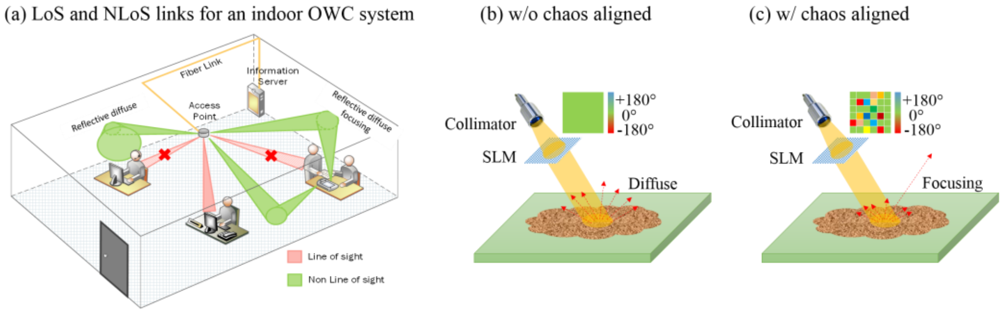

Fig. 1 Operation principle of chaos aligned optical transceiver for NLoS links. (a) Application scenario of an indoor OWC system including LoS and NLoS; diffuse reflection (b) without and (c) with chaos alignment.

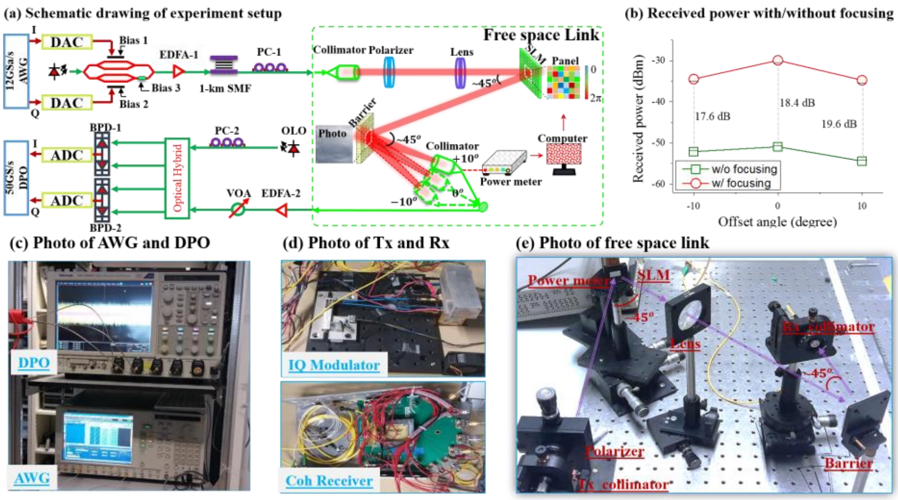

Fig. 2 Experimental setup of 30 Gb/s NL-BROWSE system enabled by the CAO-Tx. (a) Schematic setup; (b) received power of reflectively diffused light; (c) to (e) photos of experimental setup.

pattern to the incident beam via an SLM, the reflected scattered beam can be focused into a desired direction as shown in Fig. 1 (c). This phase pattern can be established by a wavefront-shaping algorithm which is dynamically adapted by feedback of the measured intensity. We use the iterative wavefront-shaping method proposed for focusing light in transmission[5], which has later been validated for focusing a reflected diffuse beam[6].

Experimental setup and results

In this section, a 30-Gb/s indoor non-line-of-sight beam reconfigurable optical wireless system for energy-efficient communication (NL-BROWSE) based on a CAO-Tx is proposed and experimentally studied. Figure 2 depicts the experimental setup and photos thereof. The system includes a 1-km single mode fibre and a diffused free-space link. As shown in Fig. 2 (a), the transmitted OFDM signal is generated by an arbitrary waveform generator (AWG, shown in Fig. 2(c)) with a 12-GSa/s sampling rate. Each OFDM symbol contains 256 subcarriers where 188 convey data. The modulation format of the data subcarriers is 16-QAM. The net bit rate is 30 Gb/s, which is the highest with respect to the experimental diffused OWC systems reported up to now, to the best of our knowledge. Through an optical I/Q modulator, the in-phase and quadrature components are modulated onto an optical carrier generated by an external cavity laser as shown in Fig. 2 (d). The central wavelength and power of the optical carrier is 1550 nm and 14 dBm. The modulated signal with -10-dBm power is amplified to 14.5 dBm via the first Erbium-doped Fibre Amplifier (EDFA-1). A 1-km bend-insensitive single mode fibre is used to emulate indoor applications. Its insertion loss is 0.8 dB. After fibre transmission, a polarization controller (PC-1) is used to tune the polarization of the optical signal before being launched by a collimator. The collimated Gaussian beam is incident on a free-space polarizer to match the polarization axis of a SLM (HOLOEYE, PLUTO Phase Only SLM). A lens (focal length f=200mm) is used to adjust the beam aperture incident on the SLM. It can be removed if the aperture has the proper size. The angle between the incident beam and the reflected beam is 45º as shown in Fig. 2 (a) and (e). The resolution of the SLM is 1920×1080 pixels. Its pixel pitch is 8 µm square and capable of 256 discrete levels of a 2π phase range. To match the projected Gaussian beam, 1024×1024 pixels are activated. These pixels are further grouped into 64×64 pixels blocks to be modulated as single super pixels. Then the spatial resolution of SLM is 16×16 super pixels with 256 segments. All pixels in a super pixel are equally modulated from 0 to 2π, in increments of π/4. After the phase modulation of these super pixels, the reflected light with 10-dBm power shines on a barrier, to emulate the rough walls in an indoor scenario. The utilized barrier is a cardboard covered by a sandblasted aluminium film with its photo shown in Fig. 2 (a). The angle between the SLM-modulated beam and the normal of the barrier is 22.5º. Here we define the angle between reflected beam and the normal of the barrier as the principal reflection angle, if it is equal to the angle of incident. To evaluate beam focusing, the power and data transmission at angles of ±10º offsets to the principal reflection angle are measured as marked in Fig. 2 (a). The light is reflectively diffused by the barrier, resulting in large power diffusion and angle divergence. To collect the reflected optical signal, a collimator is mounted at the principal reflection angle (0º offset) and angles of ±10º offsets. The

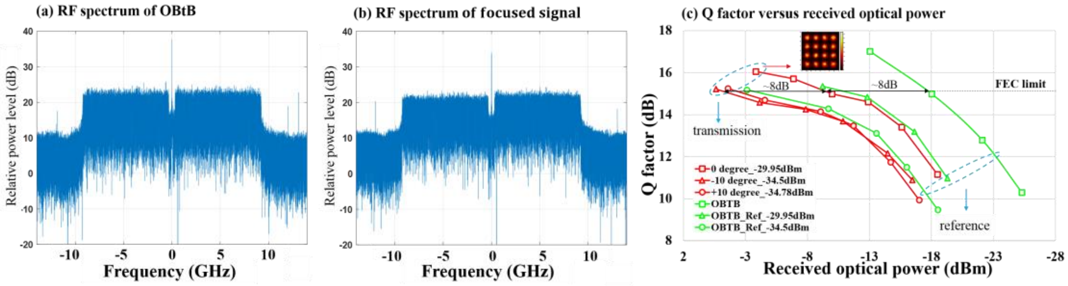

Fig. 3 Measured results of 30 Gb/s optical OFDM transmission with the focusing of a diffused beam. RF spectrum for (a) the OBTB case and (b) the focusing case; (c) Measured Q factor versus received optical power.

distance between the barrier and the collimator is 110 mm. A power meter measures the optical power and feeds it to a computer for an iterative wavefront-shaping algorithm. Its core idea is to iteratively search the optimized received power in a desired direction. In this way, the diffused beam will be steered and focused. The photo of the whole free-space link is shown in Fig. 2 (e). The received power versus angles of 0º and ±10º offsets is shown in Fig. 2 (b) with and without focusing. After the focusing enabled by the iterative wavefront shaping, the optimized powers are -29.95 (0º), -34.5 (-10º) and -34.78 dBm (+10º). The beam focusing of diffused beam is demonstrated with an angular range of 20º. More than 17 dB focusing gain (power enhancement) is achieved without an increase of transmitted power. The received optical signal is pre-amplified via the second EDFA (EDFA-2) before it is detected by an optical coherent receiver. Its photo is shown in Fig. 2 (d). A variable optical attenuator (VOA) is placed in between to obtain different received powers for measurement. An external cavity laser with 14-dBm power is used as an optical local oscillator (OLO). A polarization controller (PC-2) is employed to align the signal polarization and the OLO one. Finally, the detected signal is sampled by a digital phosphor oscilloscope (DPO) operating at a 50-GSa/s sampling rate. Its photo is shown in Fig. 2 (c). The sampled signal is then processed through an offline digital signal processing (DSP) algorithm. Figure 3 illustrates the coherent optical OFDM transmission results. The received RF spectra are generated from the digital Fourier transform of the sampled OFDM signal as shown in Fig. 3 (a) and (b), for the optical back-to-back (OBTB) case (without the free-space link) and the focusing case. Compared with the OBTB case, no frequency fading is found for the focusing case. The Q factor versus received power curves are also measured for the focusing cases (in red) and the OBTB cases (in green) as shown in Fig. 3 (c). Except for the curve of the default OBTB case (13.7 dBm after fibre), two reference curves are measured for the OBTB cases but with the power (after fibre) attenuated to -29.95 (0º) and -34.5 dBm (±10º). We assessed power penalties at the FEC threshold of 3.8×10^{-3} (Q=15.17 dB). The power penalties between the focusing cases and their references (0º, OBTB_Ref_-29.95 dBm; ±10º, OBTB_Ref_-34.5 dBm) are less than 1.5 dB. This suggests that the free-space link with the focusing of a scattered beam does not introduce notable impairment. The power penalty between the case of 0º and the cases of ±10º is 8 dB, which is the same for the penalty between the OBTB case and the cases of ±10º. The 4.55 dB power difference results in 8 dB power penalty when the received power is low (~ -30 dBm). It suggests that the improvement of received power by CAO-Tx is critically important for diffused OWC links. As shown in Fig. 3 (c), for all cases, a bit error rate below the FEC threshold of 3.8×10^{-3} can be achieved.

Conclusions

Enabled by the CAO-Tx, a 30 Gb/s indoor non-line-of-sight beam reconfigurable optical wireless system for energy-efficient communication (NL-BROWSE) has been demonstrated. A record-breaking 30-Gb/s OFDM data signal is transmitted over an indoor diffused optical wireless link with >17-dB gain, in an angular range of 20º.

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