Net 1 Tbps Multi-user Indoor FSO Downlink Over 25 m based on cost-effective point-to-multipoint coherent optics and probabilistic shaping

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Abstract: We demonstrate a cost-effective point-to-multipoint free-space optical downlink using digital subcarriers and achieve an aggregated net data rate beyond 1 Tbps over 25 m with 8 edge nodes while meeting the eye-safety standard.

1. Introduction

There is an increasing bandwidth demand in short-range wireless indoor communications due to the saturation of the RF spectrum along with the emergence of high-speed wireless indoor data transfer such as high-definition AR/VR and the internet of things. Free-space optical (FSO) communications offer a promising alternative to complement conventional RF communication due to nearly unlimited spectrum resources, physical security, and immunity to electromagnetic interference. FSO communications in the visible and infrared spectrum have attracted increasing attention in recent years [1-5]. Compared to visible light communication, indoor FSO communication in the telecom C-band can exploit the readily available devices and has relaxed eye-safety regulations, i.e. less than 10 dBm of optical power for wavelengths greater than 1400 nm [6]. Furthermore, infrared indoor FSO communication systems could be seamlessly integrated with the passive optical network for indoor wireless connections.

Multiplexing techniques including wavelength-division multiplexing (WDM) and time-domain multiplexing (TDM) widely used in the telecom band have been demonstrated in FSO communications to enable multiuser downlinks [7-8]. A virtually imaged phased array (VIPA) based TDM multi-user optical wireless system is demonstrated and reports direct detection (DD) of an on-off-keying (OOK) signal at 12.5 Gb/s interface rate for each end user over 3.6 m achieving a total data rate of 63 Gb/s [7]. In [8], an indoor DD FSO system using WDM- orthogonal frequency division multiple access (OFDMA) over 4 m is realized and achieves an interface rate of 28 Gb/s per user corresponding to an aggregated 56 Gb/s. Most infrared FSO links for indoor short-range communications are based on the intensity modulation and direct-detection scheme having limited link capacity and spectral efficiency. Employing coherent detection (COHD) in the C-band for multi-user FSO communications presents an important opportunity to exploit the performance advantages of COHD and commercially mature components to scale the link capacity and improve the quality-of-service.

In this paper, we propose a cost-effective multi-user indoor FSO downlink based on digital subcarrier modulation (SCM)-assisted point-to-multipoint (PTMP) coherent optics achieving a net data rate beyond 1 Tb/s. The benefits of the proposed FSO downlink architecture are in 3 aspects: (1) high spectral efficiency due to phase- and polarization diversity; (2) hardware efficiency since the number of coherent transmitters is reduced to one that connects to multiple coherent edge receivers; (3) high receiver sensitivity due to the amplification from the Rx local oscillator (LO) and probabilistic shaping (PS) based on enumerative sphere shaping (ESS). Note that the improved receiver sensitivity translates to an additional power margin for eye safety and extended transmission reach. The flexible information rate allowed by PS also improves the aggregated downlink capacity since higher data rate can be achieved for the edge nodes having higher SNRs. In the experiment, a net 1 Tbps signal having 8 aggregated subcarriers is sent to 8 edge nodes, each detecting a net 127 Gb/s PS-QAM-64 signal over 25 m. In addition, the -8 dBm output power from the transmitter is far lower than 10 dBm as required for eye-safety operation.

2. SCM-assisted PTMP coherent FSO downlink architecture

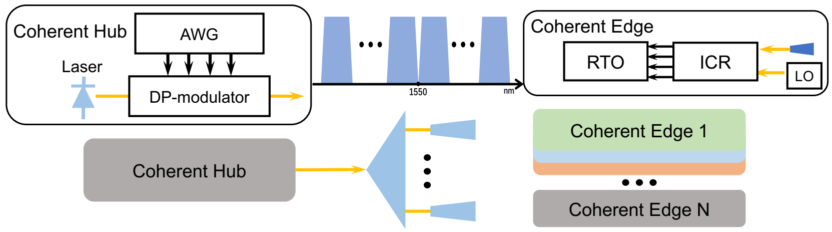

Fig. 1 The proposed architecture of the SCM-assisted PTMP coherent FSO downlink.

Figure 1 shows the architecture of the PTMP coherent FSO communication system. N subcarriers are generated in the baseband and upconverted to intermediate frequencies forming a multi-subcarrier signal. The optical signal is split into N portions and sent to N corresponding coherent edge nodes, respectively. Since each coherent edge receives the broadcasted optical signal, the desired digital subcarrier is selectively down-converted to the baseband by use of a local oscillator (LO) operating at a wavelength conditioned for homodyne coherent detection. For the upstream communication, a portion of the Rx LO power is split for intensity modulation. Multiple intensity modulated signals from the edge nodes are aggregated and simultaneously received by a high bandwidth coherent receiver [9].

3. Experimental Setup and Results

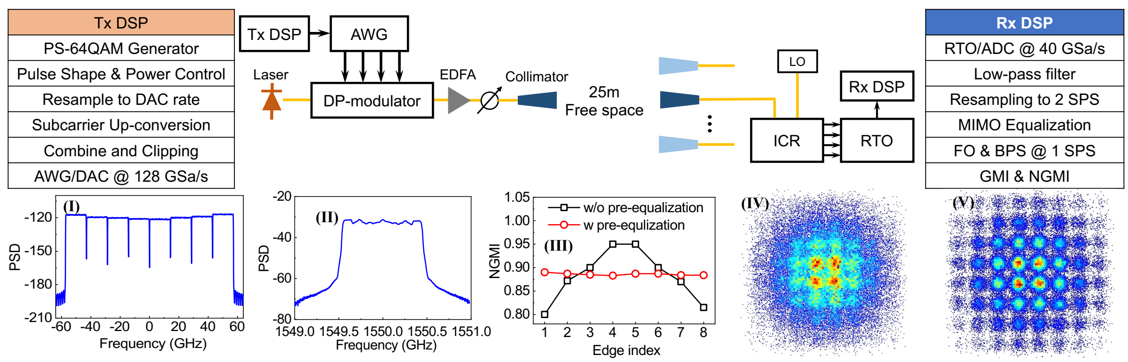

Fig. 2. Experimental setup of the coherent PTMP FSO downlink. (I) The power spectral density of the baseband digital signal sent to AWG; (II) the measured optical spectrum of the signal before EDFA; (III) the measured NGMI of eight edges with and without pre-equalize; (IV) and (V) are the constellations of Edge1 and Edge 4 without pre-equalize, respectively.

Figure 2 shows the experimental setup of the FSO system. The 1550 nm laser at the transmitter provides a continuous-wave optical carrier for optical modulation using a dual-polarization Mach Zehnder modulator (DP-MZM). This DP-MZM is driven by a 4-channel 65 GHz arbitrary waveform generator (AWG) operating at 128 GSa/s and imprints an optical signal with eight digital subcarriers onto the CW light. Each of the digital subcarriers carries 14 Gbaud of PS-64 QAM signal, which corresponds to an aggregate symbol rate of 112 Gbaud. The modulated signal is amplified by an Erbium-doped fiber amplifier (EDFA) with an output power set to a constant 10 dBm. A variable optical attenuator (VOA) is employed to emulate 9 dB splitting loss due to a 1-to-8 optical power splitter and in the meantime incurs additional attenuation to ensure eye-safety operation. The optical signal is coupled to free space using a collimator and travels over 25 m of reach before coupling to another collimator at the coherent edge node. The target subcarrier is selectively detected without optical filtering due to a 16 dBm LO tuned at a proper wavelength. The received electric signal is sampled by a real-time oscilloscope (RTO) operating at a sampling rate of 40 GSa/s. In the transmitter DSP part, 8 digital subcarriers each carrying 14 Gbaud of probabilistically shaped (PS) QAM-64 signal are generated using Enumerative Sphere Shaping (ESS) requiring a short block length of 28 for low-latency communication [10]. After raised-cosine pulse-shaping, the power of different subcarriers is pre-equalized by a scaling factor in order to enhance the power of digital subcarriers at higher frequencies. The baseband signal is resampled to the DAC sampling rate of 128 GSa/s and up converted to the corresponding intermediate frequencies. The eight subcarrier signals are combined and clipped before digital-to-analog conversion. In the receiver DSP part, the captured digital signal is filtered by a 7.5 GHz brick-wall digital filter to reject out-of-band noise. The filtered signal is resampled to 2 samples per symbol and then sent to a linear MIMO equalizer. Next, frequency offset (FO) compensation and carrier phase recovery by blind phase search (BPS) are implemented, and generalized mutual information (GMI), normalized GMI (NGMI), and net data rate are obtained as performance metrics [11]. The digital power pre-equalizer performed in the transmission DSP offsets the NGMI difference between among different edges. The power spectral density of the digital signal is shown in Fig. 2 (I) and the optical spectrum is shown in Fig. 2 (II). The NGMI at entropy of 5.386 bits/symbol per polarization is shown in Fig. 2 (III) with and without pre-equalization.

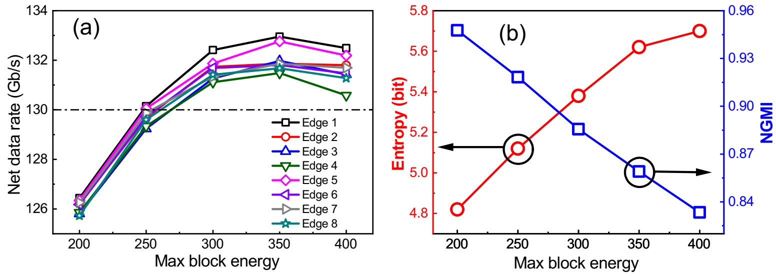

Fig. 3. (a) The net data rate of eight edge nodes versus the ESS block energy, (b) the entropy and NGMI calculated versus the ESS block energy.

Firstly, we test the transmission performance at a received optical power (ROP) of -10 dBm, which is 20 dB lower than the eye safety power of 10 dBm. To maximize the capacity of the PTMP coherent FSO downlink, we sweep the ESS block energy and measure the net data rate for all coherent edge nodes in Fig. 3 (a) and plot in Fig. 3 (b) the corresponding average entropy per polarization as well as the average NGMI. As the ESS block energy increases from 200 to 300, a higher net data rate is obtained since the entropy increases from 4.8 bits/symbol to 5.4 bits/symbol to better approach the link capacity at a given SNR. Further increase of the block energy beyond 300 leads to marginal increase of the net data rate since the PS-QAM-64 constellation gradually approaches a uniform QAM-64 signal and the shaping gain decreases. It can be observed from Fig. 3 (a) and Fig. 3 (b) that all eight edges can achieve a net data rate beyond 130 Gb/s at an NGMI greater than 0.85, which leads to an aggregated net data rate beyond 1 Tb/s.

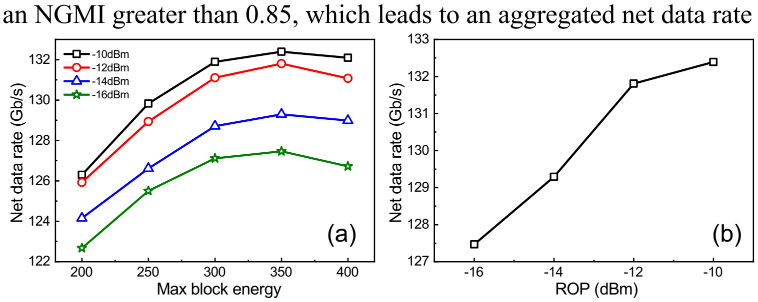

Fig. 4. (a) Net data rate versus block energy at different ROPs, (b) Aggregated downlink net data rate versus ROPs.

Next, to evaluate the eye-safety power margin of the coherent PTMP FSO communication setup, we further decrease the output power at the transmitter from -10 dBm using a VOA and measure the corresponding ROP alongside the corresponding net data rate in Fig. 4 for the 5th edge node. At an ROP of -16 dBm, the maximum net data rate is beyond 127 Gb/s at an ESS block energy of 350. The corresponding aggregated net data rate of 8 edge nodes is measured beyond 1 Tb/s. In addition, the corresponding optical power in the free space is below -8 dBm, which is far lower than the 10 dBm power threshold required by the eye safety standard [6].

4. Conclusions

We demonstrate an SCM-assisted PTMP coherent FSO downlink over 25 m achieving a net data rate beyond 1 Tb/s. The proposed architecture has the advantage of high spectral efficiency, hardware efficiency, and high receiver sensitivity, manifesting its potential for high-speed and cost-effective multi-user indoor FSO communications.

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