Tailoring rate and latency of free space optical systems to turbulence conditions with probabilistic constellation shaping and data interleaving

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Abstract: We show up to 250 Gbps per carrier transmission is achievable with digital coherent technologies at 65dB link-loss. We jointly optimize symbol-rate, probabilistic shaping and interleaving while replicating strong turbulence conditions. © 2024 The Author(s)

1. Introduction

As radio frequency (RF) spectrum becomes scarce, light spectrum appears as a natural complement or alternative in order to keep up with the capacity growth of transmission systems, especially with free-space optics (FSO) [1]. However, light can be attenuated by water (clouds, droplets, and vapor) and impaired by turbulence in atmosphere [2]. As a result, and unlike the fiber channel, the capacity of the FSO channel is variable, but, to some extent, can be predicted and monitored. Even when the network is capable of handovers to other multiple sites (e.g., with FSO over ground-to-satellite feeders) when weather changes, the backup paths may have different and known histories with cloud coverage and turbulence strengths and could support different channel capacities [3].

In this paper, we propose and demonstrate the use of probabilistic shaping, based on 16-QAM format in this context. Whereas this technology was investigated in the past years to maximize system capacities of fiber systems, the problem is particularly complex for FSO, because, even under blue sky, the air refractive index modifies the spatial amplitude and phase of the optical beam during propagation as a result of turbulence. This effect translates into a non-constant power coupling into the optical fiber in the reception terminal [2], leading to the capacity of the channel becoming stochastic with intermittent signal interruptions (e.g., for ~1ms), called fading events. We show that one could transmit data rates reaching 250 Gbps per carrier while not exceeding the commercial optical amplifier power constraints with a link budget loss of 65 dB, at the expense of a relatively large interleaver time, adding latency. We discuss the trade-offs between capacity and latency for a given link budget and turbulence conditions.

2. System description

We consider a link with a total link loss of 65 dB as reference scenario. Such a loss could correspond to geostationary downlink system designed for feeder links or relay links such as bend-pipe systems with link budget designed by the German space agency [1], where the received optical power (ROP) reaches ~-26 dBm in still atmosphere if space qualified commercial amplifiers at 10W/lambda are used at the transmitter. ROP is further degraded by turbulence, especially when it is strong [4], which we replicate over a testbed, where 2D-wavefronts video from the model are played at the refresh rate of 2 kHz. In Fig. 1, we outline the experimental setup, explained with details in [5]. The light from a 1.55 µm laser is sent to a polarization-division multiplexed (PDM) I/Q modulator. The output beam is expanded and steered in free space onto a digital micromirror device to cover its surface (0.8mm x 0.8mm). In Fig. 1b, we show different order of Zernike target modes (top) generated using the turbulence emulator and measured using a Shack

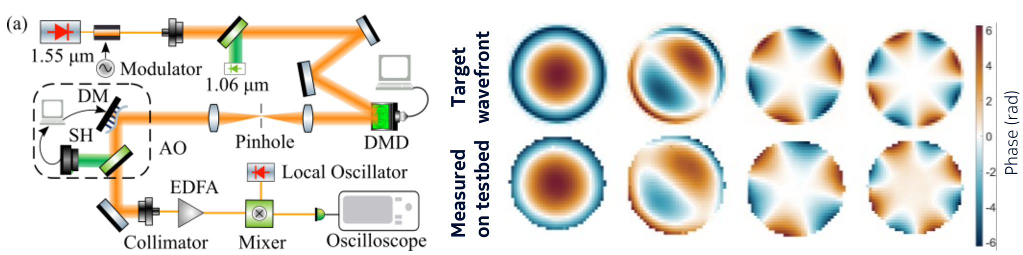

Fig. 1: (a) Schematics of the optical emulator testbed. **(b)** Replication of a few Zernike phase patterns by the testbed

Hartman (SH) wavefront sensor [6], with root-mean-square errors <λ/100. We measured an excellent wavefront emulation fidelity (>95%). The optical beam is then passed into an adaptive optics (AO) system also described in [5] capable of working at 800 Hz which dynamically controls the 43 actuators of a piezoelectric deformable mirror (DM) of 10 mm diameter based on the wavefront readings from a 11x11 SH. Note these readings had to be provided with a colinear light source at a wavelength 1.06µm, falling below the upper wavelength operation limit of this SH. At the output of the testbed 1.55µm light is coupled into a fiber using a collimator, sent either to a power meter or to the receiver before being amplifier by an Erbium Doped Fiber Amplifier (EDFA) where it is mixed with a local oscillator (LO), detected by a set of 4 balanced photodiodes and sampled by 80 GS/s real-time oscilloscope. The recorded signals are offline processed by resampling at 2 samples per symbol, constant-modulus-algorithm with 3 taps is used to detect the position of the pilots and then pilot aided (QPSK) multi-modulus algorithm is applied with 35 taps, decimation to 1 sample per symbol and undergo frequency and phase offset correction.

In Fig. 2a, we recall the cumulative distribution function (CDF) [5] of the received power when impaired by the strong turbulence pattern used in our scenario. One can observe that the deepest fades are not completely eliminated by adaptive optics, but their probability is reduced by an order of magnitude. The residual power fluctuations exhibit more than 30 dB power variations (-60 dBm to -26 dBm) at the receiver.

In Fig. 2b, we estimate the generalized mutual information (GMI) for different modulation formats from QPSK to Probabilistic Constellation Shaping (PCS) 16QAM with different entropies for a symbol rate of 60 Gbaud and assuming a noise figure of 4 dB at the receiver amplifier. We can observe that the GMI is saturated (~2) at received powers greater than -40 dBm for QPSK and which corresponds to >10% of the time in Fig. 2a. In order to maximize the target capacity, it is preferable to use higher order modulation formats to transmit higher capacity. However, we lose the information blocks every time GMI is lower than the forward error correction (FEC) limit.

Data interleaving can distribute the error bursts from fading events (~ few ms), by redistributing the errors over a predefined time window, it reduces the number of errors per FEC block (<1µs), making uninterrupted transmission possible despite fades. However, this process requires buffering data for as long as the window duration, hence adds a latency of the same order. This extra latency can be detrimental to some applications such as real time services but can be tolerated for data downloads.

To account for the FEC, we estimate the normalized generalized mutual information (NGMI) as a function of the received power. To replicate the effect of interleaver we make a moving average of NGMI in time over various durations (25, 50, 100 ms) for PCS-16QAM as shown in Fig. 2c. We fixed the symbol rate for different modulation formats, i.e., QPSK, PCS-16QAM with entropies 3.2, 3.7, 16QAM. We estimate the minimum NGMI found for different interleaver sizes and compare it with different FEC NGMI threshold for different coderates from [1/3, 2/5, 1/2, 2/3, 3/4] [7]. The various FEC thresholds considered here take into account the implementation penalty. We then estimate the achievable data after FEC correction for different coderates as a function of interleaver time as shown in Fig. 2d. One can observe that the QPSK provides lower latency at the cost of the achievable rate but cannot increase the capacity significantly if the interleaver increases. By using PCS-16QAM, it allows us to increase the capacity more finely without having to increase the interleaver longer than 50ms. In addition, we observe that with 16QAM the maximum achievable capacity is limited. The maximum achievable capacity for a fixed symbol rate of 60Gbaud is found to be with PCS-16QAM at entropy 3.7 without exceeding interleaver duration longer than 100 ms.

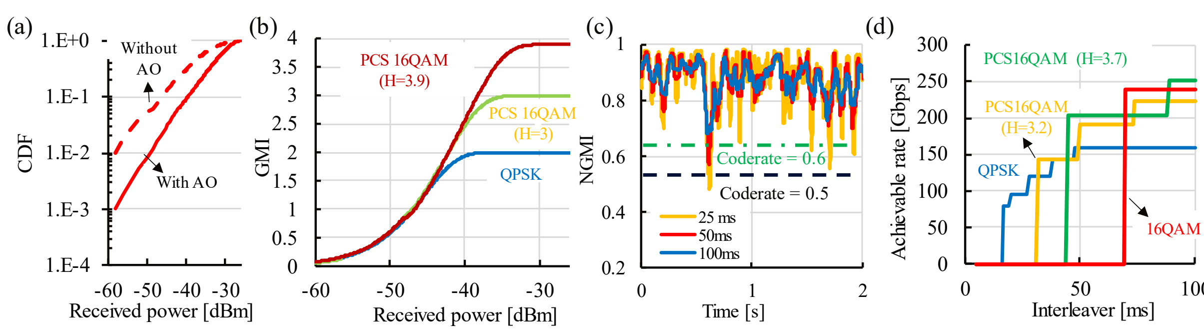

Fig. 2: (a) Cumulative distribution function of received loss time series with/without adaptive optics. (b) Generalized mutual information of received signal at fixed Baud rate of 60 Gbaud. (c) Normalized generalized mutual information of the channel as a function of time under turbulence with variable interleaving (d) Rate vs interleaver size with varying code rates of standard FECs

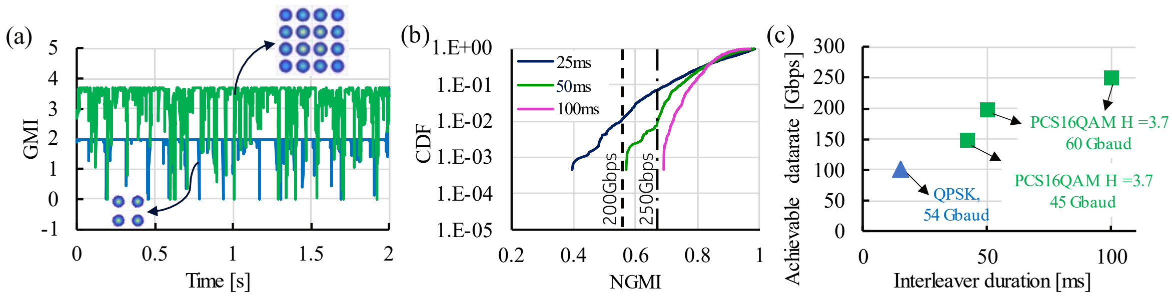

Fig. 3: (a) GMI as a function of time for QPSK and PCS-16QAM (H=3.7). (b) The CDF of the NGMI for different interleaver durations along with the target rate of 200 and 250 Gbps. (c) The achievable data rate as a function of different interleaver durations for QPSK and PCS-16QAM.

3. Experimental results

Now, we interface our testbed with our offline coherent receiver for performance measurements at symbol level. We use the optimal mix of format found in Fig. 2d i.e., PDM-PCS-16QAM (H = 3.7), with Nyquist shaping of 0.1 rolloff, and 1% pilot tones. We tested three different symbol rates 45, 54, 60 Gbaud. The NGMI is estimated as a function of time at each instant in time using 2.10^6 received symbols. We performed measurements over several seconds (at least 3000 measurements) for each configuration. We estimated the channel performance by triggering the oscilloscope to acquire data at sequential instants in time. We replicate the effect of an interleaver by measuring the mean NGMI over varying sliding windows up to 100 ms. In Fig.3a, we show the GMI for the case of strong turbulence for PCS16QAM and for comparison we show also for QPSK. In Fig. 3b, we estimate the cumulative distribution function of the NGMI for different interleaver durations between 25 and 100 ms. For PCS-16QAM, one could transmit up to 200 Gbps with interleaver of 50ms, 250 ms with an interleaver of 100 ms. We indicate the FEC limit corresponding to 200 Gbps (coderate 0.5) and 250Gbps (coderate 0.6) for PCS-16QAM 60 Gbaud. In Fig.3c, we show the experimentally achievable data rate as a function of interleaver. The measurements with QPSK show that is better to decrease the symbol rate (54 Gbaud) to transmit at least 100 Gbps with latency of 20 ms. By moving to PCS-16QAM, it is preferable to further reduce the symbol rate to 45 Gbaud to transmit 150 Gbps with interleaver of 40 ms. The results show that we need at least 30, 50 and 100 ms to transmit 150, 200, 250 Gbps respectively.

Conclusion

In this paper we demonstrated high capacity optical link under strong turbulence with up of 250 Gbps using probabilistically shaped 16 QAM modulation format. We reviewed the multiple transmission modes that constellation shaping offers, where 2.5x throughput increase can be traded for 5x latency reduction, depending on service level agreement. The modulation scheme, the coding rate and the interleaver time could be adjusted differently for real-time communication or data download.

4. References

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