400G+ Wireless Transmission via Free-Space Optics

Fernando P. Guiomar*, Marco A. Fernandes, José L. Nascimento, and Paulo P. Monteiro

Instituto de Telecomunicações and University of Aveiro, Campus Universitário de Santiago, 3810-193, Portugal.
*E-mail: guiomar@av.it.pt

Abstract *High-capacity wireless transmission is a key requirement for next-generation communication systems. In this paper, we review some of the most recent achievements on the convergence between coherent fiber communications and free-space optics systems, enabling data rates in the range of 400 Gbps to 1 Tbps.*

Introduction

Although traditional fiber-based networks have ever proved their extraordinary capacity, reliability and competitive cost-per-bit[1], the last access point of the network typically requires a viable wireless solution for portability, ubiquity and ease of access. Typically, the convergence between fiber and wireless systems has been efficiently provided by radio-over-fiber technologies[2]. However, with the ever-increasing bandwidth demand, the spectrum made available by legacy radio-frequency solutions is quickly becoming exhausted. Fostered by a plethora of novel bandwidth hungry applications, such as 5G and beyond access[3] and datacenter interconnects (DCI)[4],[5], novel high capacity wireless solution must be developed and perfected in order to avoid a capacity disruption between the wired and wireless sections of the network. In particular, it is important to develop wireless transmission solutions that might be able to cope with the data-rate provided by the last generation of coherent optical pluggables, which already provide commercial support to bit-rates above 400 Gbps[6].

While a great a deal of effort is currently being put in the development of THz-wave transmission[7], resorting to carrier frequencies above 300 GHz, the cost and complexity associated with this technology seems to be prohibitive for a near future deployment. In order to avoid the intricate practical issues associated with such extremely-high frequency RF solutions, free-space optics (FSO) has been progressively gaining momentum in the research community[8]. As opposed to other RF alternatives, FSO enables to keep the wireless signal in the optical domain, thereby simplifying the convergence with the backbone fiber-based network. Resorting to this concept, we have recently demonstrated practical FSO transmission systems supporting per-channel bit-rates in the range of 200 Gbps up to 1 Tbps[9]–[12]. Furthermore, FSO systems provide an outstanding scalability for wavelength-division multiplexing (WDM) applications, with a recent record demonstration of 35-WDM channel 14 Tbps transmission over 220 m[13].

In this paper, we will review our recent progress on the development of high-capacity FSO systems with advanced modulation and full compatibility with fiber-based coherent optical transceivers. Special attention will be provided to the impact and mitigation of atmospheric turbulence and pointing errors, resorting to the use of adaptive probabilistic constellation shaping (PCS) modulation[11],[14].

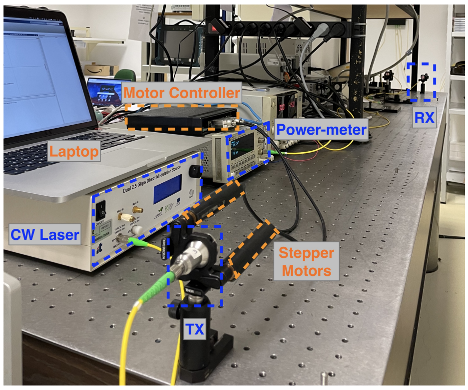

Fig. 1: Experimental setup with automatic beam alignment apparatus.

Impact of Pointing Errors

Figure 1 shows the experimental setup utilized to study the impact of pointing errors on an FSO link with seamless air-to-fiber optical beam reception, using a commercial fiber collimator – Thorlabs F810APC-1550 – with 24 mm lens diameter, 0.24 numerical aperture and 0.0017° divergence angle. In order to align the optical beam between the transmitter and receiver fiber collimators, we utilize a pair of high-precision stepper motors – Thorlabs ZST200 – that control the tip and tilt of the Tx collimator, thus providing two axes for beam alignment. The stepper motors are controlled by a processing unit that is connected to a laptop where the alignment scripts are implemented in MATLAB. In its simplest form, i.e. when the setup is utilized to characterize the power budget of the FSO link, the optical source is a simple continuous-wave (CW) laser and the receiver is a remotely operated power-meter. Instead, when performing actual communication over the FSO link, the Tx and Rx units are replaced by a full-fledged coherent optical transmitter and receiver. Note that, thanks to the seamless air-to-fiber convergence enabled by the optical fiber collimators,

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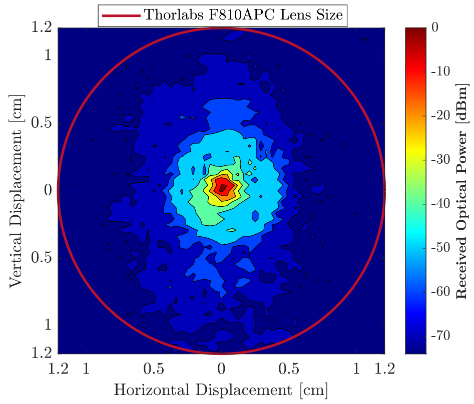

Fig. 2: Characterization of pointing error tolerance of Thorlabs F810APC fiber collimator.

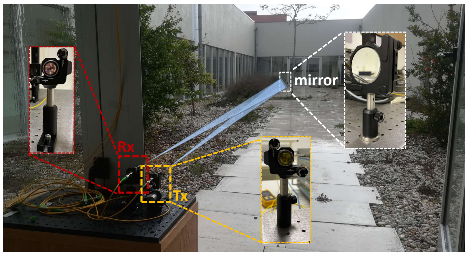

Fig. 3: Outdoor FSO link for 400G+ transmission enabled by adaptive modulation.

the actual FSO section of the setup is independent of the technology employed in the Tx / Rx pair. This opens up the opportunity to promote the convergence between FSO transmission and state-of-the-art coherent pluggable technologies supporting 400G and above, which are progressively conquering the access market.

In Fig. 2 we show an example of received optical power characterization using the stepper motors to sweep the position of the incoming beam on the full 2D axis of the Rx fiber collimator. It can be seen that the alignment of the FSO link is extremely sensitive to the impact of pointing errors: a mere 1 mm displacement from the optimal focusing point leads to approximately 10 dB power loss on the fiber-collimated optical signal.

Impact of Atmospheric Turbulence

In order to study the impact of atmospheric turbulence and weather conditions on power budget of FSO links, we have deployed the experimental setup shown in Fig. 3 in an outdoor environment exposed to the changes of weather conditions, including raining periods. The Tx and Rx collimators are separated by approximately 55 m, with a concave mirror place halfway in the link.

Using this outdoor FSO link, we have acquired a series of long-term optical power measurements under different weather conditions, leading to the results shown in Fig. 4. Besides the clear impact of rain on the higher variance of the received optical power shown in Fig. 4a, we also highlight the strong time correlation that characterizes the FSO system, mainly when it is subject to slowly varying weather conditions, as it is the case of the rain weather dataset in Fig. 4b, where

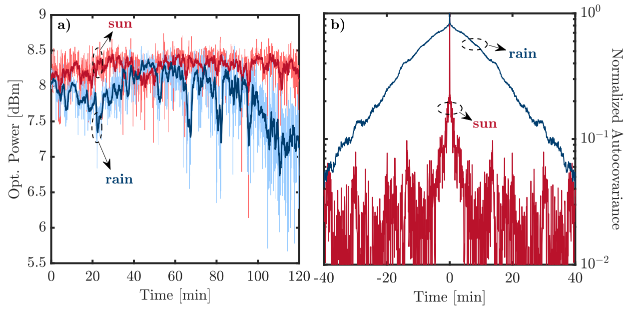

Fig. 4: Impact of atmospheric turbulence and weather phenomena on FSO power budget. a) received optical power over time with sun and rain conditions; b) normalized autocovariance unveiling the presence of time correlation.

the autocovariance of the signal shows correlation times of several minutes.

Adaptive PCS Modulation

Taking advantage of the observed time correlation on the FSO link, and resorting to the concept of probabilistic constellation shaping, it is possible to adapt the delivered bit-rate to the actual channel condition, thereby allowing to maximize the channel capacity and also minimize the out-of-service periods due to the impact of scintillation on the received optical power. In few steps, and summarizing the work presented in[11], the PCS-based adaptive modulation concept can be implemented as follows:

1. Estimate the SNR for the next time instant,

$$\overline{\mathrm{SNR}}(n+1) = \frac{1}{N_{\mathrm{taps}}} \sum_{n-N_{\mathrm{taps}}+1}^{n} \mathrm{SNR}(n), \quad (1)$$

   where $\mathrm{SNR}(n)$ is the measured SNR at time instant n and $\overline{\mathrm{SNR}}(n+1)$ is the estimated SNR for the subsequent $n+1$ time instant, which is obtained from a moving average estimator of length N_{taps};

2. Add some SNR margin, $\Delta\mathrm{SNR}_{\mathrm{dB}}$, to account for the error in the SNR estimation;

$$\overline{\mathrm{SNR}}_{\mathrm{dB}} \Leftarrow \overline{\mathrm{SNR}}_{\mathrm{dB}} - \Delta\mathrm{SNR}_{\mathrm{dB}}, \quad (2)$$

3. Determine the entropy to be loaded into the PCS constellation, resorting to a pre-stored look-up table (LUT) implementing the following nonlinear function:

$$H_{\mathrm{PCS}} = f(\overline{\mathrm{SNR}}_{\mathrm{dB}}, \mathrm{NGMI}_{\mathrm{th}}, M), \quad (3)$$

   where M is the constellation order and $\mathrm{NGMI}_{\mathrm{th}}$ represents the threshold normalized generalized mutual information (NGMI) required for error-free operation after FEC[15].

4. Evaluate the achievable information rate (AIR) in bits-per-channel-use (bpcu) as

$$\mathrm{AIR} = H_{\mathrm{PCS}} - (1 - R_{\mathrm{FEC}}) \log_2(M), \quad (4)$$

   where R_{FEC} is the FEC rate.

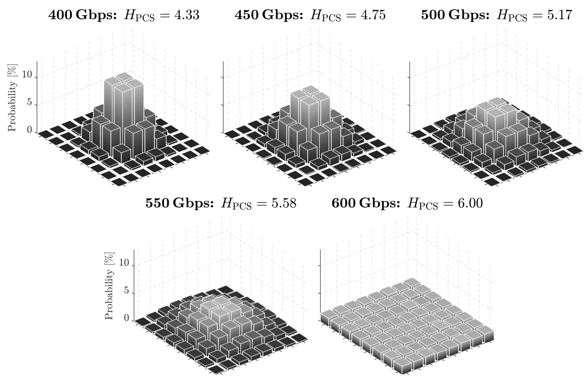

Fig. 5: PCS-64QAM configurations to deliver net bit-rates in the range of 400–600 Gbps for a fixed symbol-rate of 60 Gbaud, $R_{\mathrm{FEC}} = 5/6$ and $R_{\mathrm{pil}} = 1$.

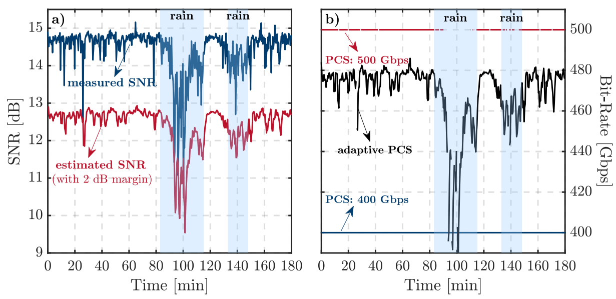

Fig. 6: Experimental demonstration of outdoor 400G+ FSO transmission with adaptive PCS modulation. a) measured and estimated SNR over time; b) bit-rate over time with fixed and adaptive PCS solutions.

5. The transmitted net bit-rate is automatically set by the AIR as

$$R_b = 2R_sR_{\mathrm{pil}}\mathrm{AIR}, \tag{5}$$

where R_s is the symbol-rate and R_{pil} is the rate of DSP pilot symbols.

400G+ Outdoor FSO Demonstration

Employing the aforementioned recipe for PCS-based adaptive modulation, in[10],[11] we have demonstrated the practical application of this concept to the outdoor FSO link of Fig. 3, enabling transmission at data-rates in the range of 400–600 Gbps. An illustration of the bit-rate adaptability provided by PCS is shown in Fig. 5, depicting the distribution of symbol probabilities for a set of discrete bit-rates. The measured and estimated SNRs, as well as the corresponding optimized bit-rates are shown in Fig. 6, where the merit of the adaptive PCS-based modulation concept becomes clear: while fixed 400/500 Gbps solutions become either too pessimistic or optimistic depending on the time-varying link condition, the adaptive PCS technique provides a bit-rate that adapts in real-time to the changing conditions of the link, thereby maximizing the capacity and reliability of the system.

Terabit Intra-Datacenter FSO Demonstration

Utilizing a setup similar to the one depicted in Fig. 1, but replacing the CW laser source and

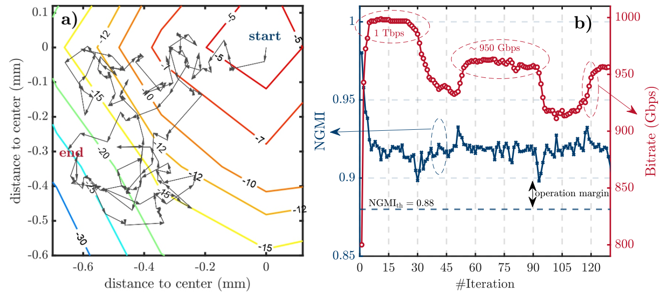

Fig. 7: Experimental demonstration of Terabit-capable FSO transmission for intra-DC transmission. a) emulated impact of pointing errors; b) adapted bit-rate and NGMI over time.

power-meter by wideband (> 70 GHz) coherent transmitter and receiver instrumentation, in[12] we have demonstrated an indoor 3 m Terabit-capable FSO transmission targeted to intra-datacenter applications. Due to the required beam steering between datacenter racks, pointing errors represent a major hurdle for FSO communications at the intra-datacenter level. In Fig. 7a we show the pointing errors incurred into the systems, which were emulated through the application of a random walk over the 2D position of the stepper motors. The system departs from an ideal alignment position and after roughly 130 iterations it reaches an end point that is displaced by 3 and 6 mm in the vertical and horizontal axes, respectively.

By employing the adaptive PCS technique, Fig. 7b shows the progression of bit-rate over time, once again showing the notable capability of real-time and system-aware data-rate adaptation with rather stabilized NGMI performance, while including a small operating margin to guarantee 100% reliability. In the best channel condition, this FSO link is shown to support up to 1 Tpbs, while in the worst case scenario the data-rate is always kept above 900 Gbps.

Conclusions

Free-space optics provides an ultra-high-capacity solution for the wireless access of next-generation networks, including key applications such as 5G/6G fronthaul/backhaul, datacenter interconnects, last-mile access and temporary backup links for disrupted fiber-based networks. Despite the important challenges that are still ahead, mainly associated with atmospheric turbulence and pointing errors on the reliability of FSO systems, several recent works have demonstrated that the use of FSO transmission supporting more than 400 Gbps per channel might become a viable practical solution in the near future.

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