Recent Developments Towards High-Capacity Free Space Optical Communication Systems

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Abstract *We review recent Tbit/s class optical free space transmission experiments*

Introduction

Even though the first proposal for free space optical communications was 60 years ago [1], the practical use of optical communication is a recent innovation, and only "in-flight" for space applications this century [2]. Recent plans to introduce basic terrestrial technologies such as optical amplification offer significant size, weight and power advantages over radio frequency communications [3]. As shown in Fig. 1 satellite capacity is on an exponential growth trend (tracking the growth of transatlantic cable capacity, but with a lag of around 21 years). Similar trends are well known in Ground to Ground (G2G) applications, with rapid deployment 2.5 and 10 Gbit/s links available and current commercial capacities in the region of 20 Gbit/s and offers great prospects for deployment in challenging environments [4]. The capacity lag is partly due to user demand, but a significant reticence occurs due to the impact of turbulence and scintillation, which are more significant for G2G applications.

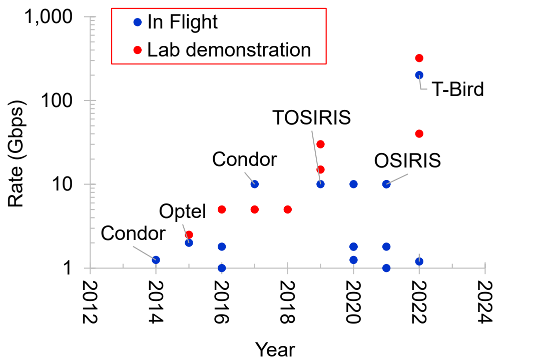

Fig. 1: Data rates for satellite communications showing lab-based (red) and in-flight (blue) reports.

In this paper, we will discuss the summarise progress towards the next milestone in free space optical communications, 1Tbit/s, for both satellite and terrestrial applications.

Fibre versus Free space channels

Widespread commercial deployment of single-mode fibre was initially prompted by the need to avoid modal noise, giving almost time invariant channels and system with high availability. Whilst the cost advantages of multi-mode fibre dominated short reach systems, and mode-group division multiplexing offered modest capacity gains, coherent detection enabled the detection of the full optical field distribution. In the absence of mode-dependent loss, the time varying speckle pattern contains all the light, if all modes are collected, then no information is lost. The channel is said to be "unitary" and high-capacity transmission over few-mode [5] and multi-mode fibre [6] is possible.

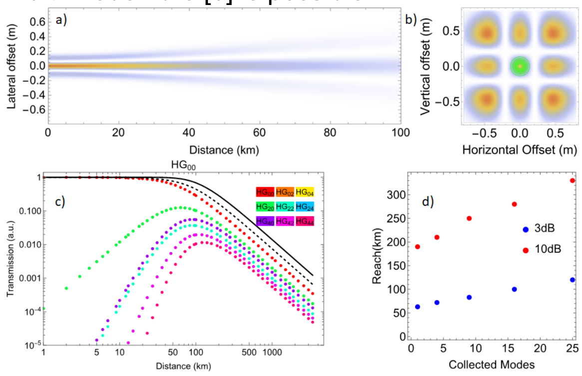

Fig. 2: a) Evolution of HG_{22} mode over 100km, b) mode profile of HG_{22} mode after 100km (shading) and mode profile of HG_{00} mode at 100m (green), c) power transmission from HG_{00} mode to higher order modes (coloured dots) and total collected power (black) for 25 collected modes (fixed magnification), (d) Maximum reach for 3dB (blue) and 10dB (red) HG_{00} diffraction loss as a function of the number of collected modes.

For a free space channel, diffraction typically dominates, with misalignment adding to power loss and turbulence all of which may be modelled as modal scattering, as in fibres, although an infinite number of modes are available, and not all will be collectable in a finite size receiver. This is shown in Fig 2 for a perfectly aligned turbulence-free system based on a simple overlap integral between the diffracted transmitted mode and the receiver mode. This illustrates how diffraction can allow an increase in detected power in a different mode to that originally transmitted. Understanding of this mode conversion may be used to optimise the system design, either by adjusting the receiver design to maximise the collected power using, for example, adaptive optics [7] improving the signal-to-noise (SNR) ratio, or by decomposing the modes and detecting them independently [8,9] giving the potential for enhanced capacity through multi-input multi-output (MIMO) transmission, or using multiple apertures [10].

Capacity Limits of FSO Systems

Whilst Fig.2 illustrates that there is always a SNR advantage associated with awareness of the modal structure of the received signal, the potential for mode-multiplexing depends on the extent to which the detectable modes are orthogonal. This has been shown to be limited by the product of the Fresnel numbers of the transmit and receive antennas [11] and is illustrated in Fig. 3 for 6-, 12- and 24-inch diameter apertures.

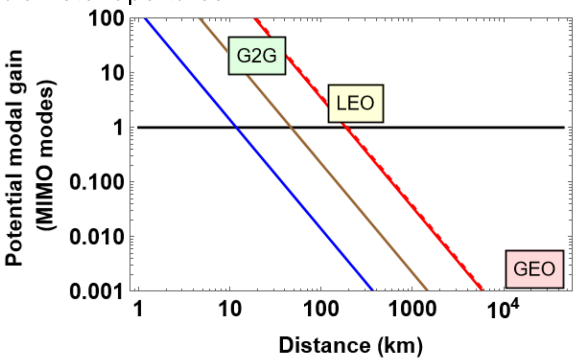

Fig. 3: Estimates for potential modal gain for free space communication systems at 1560nm with 6" (blue), 12" (brown) and 24" (red, also showing 1530nm as dotted line) apertures.

Whilst potential modal gain is clearly dependant on aperture size, even for particularly large antenna (⅔m), meaningful modal gain for satellite applications appears difficult, whilst substantial gains are possible for terrestrial applications, with apertures as small as 15cm for short reach systems. However, for such systems, the impact of turbulence can be severe (Fig. 4). Even with selection of the optimum subset of all practical modes to minimise the impact, it has been estimated that the impact of turbulence is more severe for large diameter aperture, reducing the maximum reach by between 5 (10cm aperture) and 20 (40cm) fold for a single-input single-output (SISO) system in strong turbulence [11]. However, this may be reduced using MIMO signal processing to between 2 and 5-fold respectively, benefiting from the scatter of transmitted modes into other detected modes, with the MIMO benefit increasing with the number of usefully detectable modes (Fig 2c and Fig.3).

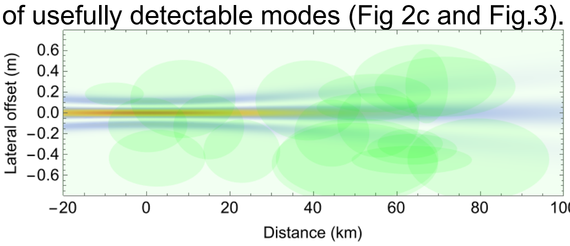

Fig. 4: Illustration of HG_{22} beam (orange-blue colour grade) through a turbulent atmosphere (green).

Typical received power distributions are shown in Fig.5, representing a practical link with strong turbulence and pointing jitter.

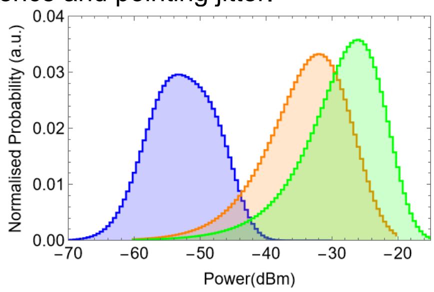

Fig. 5: Received power distribution for a system with random pointing errors (blue), tip-tilt correction (orange) and optical turbulence correction (green). Inspired by [7].

Record Capacity SISO Systems

Tbit/s class transmission SISO systems have been recently reported for both long [7] and short [12-13] transmission distances. Targeting hybrid fibre-free space links for front-haul applications, [12] exploits 96 channel wavelength division multiplexing to multiply the capacity of a high sensitivity QPSK signal (-23dBm at 80Gbit/s *line rate*) achieving a turbulence-free free-space transmission distance of 102m.

The impact of realistic turbulence was recently investigated for a wavelength division multiplexed system over 10km [14] and a single channel Tbit/s class link over a 56km free-space path [7]. In [7] high-power optical amplification (to 500mW per channel) and large aperture (up to 35cm) telescopes were used to maximise the optical SNR, enabling 84 Gbaud 64 QAM signals to be used. Degradations due to pointing jitter and atmospheric turbulence were addressed using a deformable mirror running at 1.5kHz, comfortably exceeding typical Greenwood frequencies of less than 200Hz.

However, as shown in Fig. 2, even in the absence of turbulence, light is scattered into many modes (defined in the basis of the receiver), and residual turbulence is inevitable. The resultant power fluctuations suggest three strategies.

1. Operate at a sufficiently low bit rate to tolerate the lowest expected received power.
2. Operate at a bit rate more suitable for the most likely received power, and retransmit lost packets, benefiting from a significantly increased rate between outage events.
3. Adapt the transmitter (symbol rate, modulation format or launch profile), to the current channel conditions. Only practical for systems where the round-trip time is lower than the inverse of the Greenwood frequency (distances < 750km for 200Hz).

Relative throughputs (normalised to the achievable rate at the mode of the received power distribution) for three turbulence conditions are shown in Fig.6. Here we plot the net throughput (averaged over the full Gamma-Gamma distribution) (GGd), normalised to the achievable transceiver rate at the peak of the GGd against the maximum rate of the transceiver itself, also normalised to the rate at the peak of the GGd. For two strategies. For short links, the symbol rate is adjusted in proportion to the received optical power (adaptive transmission – blue), whilst for longer links we assume packet retransmission at the maximum transceiver rate, giving a throughput proportional to the availability [15] (retransmit – red). This shows a clear and consistent advantage for symbol rate adaptive transmission, and we note that further (SNR dependent) improvement is possible for adaptive modulation formats [8, 16].

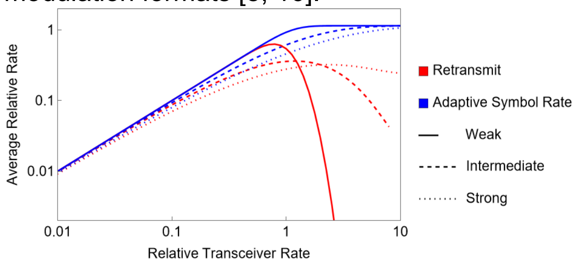

Fig. 6: Predicted throughput rate for short links (adaptive transmission), and long links (retransmit strategy) as a function of maximum transceiver rate for weak (solid), intermediate (dashed) and strong (dotted) turbulence.

In addition to adaptive optics, spatially diverse information (mode or path) may be equally effectively digitally combined to enhance performance and turbulence resiliency [9,10].

Record Capacity MIMO Systems

As beneficial as aperture size and launch power are to increasing the SNR, and this availability and/or capacity of a free space link, in common with all communication systems, these resources are even more efficiently utilised through wavelength [12,14] and space division multiplexing either using modes [8,17,18], or multiple paths. [19]. For a MIMO system, and orthogonal mode basis is selected to transmit each mode, and either the modes are simply optically demultiplexed, detected and individually demodulated [17,18], or full MIMO signal processing, typically implemented with DSP [8], is used to maximise the available information. In the former case, if the lowest order modes of a so called complete set are used, power scattered from one mode is not only lost from that mode, but appears as coherent crosstalk on "neighbouring" modes. This penalty may be reduced to simple power loss from each mode by selecting a partial set of modes, such that the coupling between the selected modes is minimised, one such set being the Orbital Angular Momentum modal basis [17,`18].

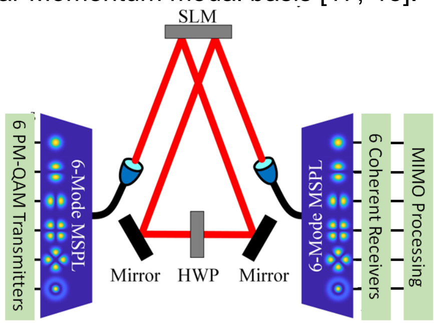

Fig. 7: Schematic diagram of a 12x12 MIMO system based on the LP mode basis.

Penalties from turbulence, and other causes of mode coupling such as diffraction and pointing errors, are further reduced by MIMO signal processing, in principle eliminating all crosstalk between detected modes [8]. A typical MIMO system comprising a number of independent transmitters, a pair of mode multiplexers, and independent coherent receivers is shown in Fig.7. Even with MIMO signal processing, penalties still remain resulting from light entering the receiver aperture but scattered into modes which are not detected, and from light scattered beyond the receiver aperture.

Conclusions

In this paper we have highlighted some key differentiating features between fibre and free space optical communication systems. We have shown how an understanding of these can lead to Tbit/s class free space transmission systems, and the promise of Pbit/s class systems, combining these innovations, is clear.

Acknowledgements

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