Spectral Aggregation of Turbulence-Resilient FSO Links as Feeders for Capillary Access Networks

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***Abstract*—Free-space optical (FSO) communication provides fibre-grade connectivity even in fibre-scarce environments. As such, it is an ideal candidate to trunk capillary radio networks in the far-access segment. However, FSO links are prone to degradation due to misalignment and atmospheric effects. In response to this, we leverage optical antenna configurations with up to 91 elements as FSO air-interfaces that accomplish alignment-tolerant and turbulence-resilient coupling between two single-mode fibre ports. Despite exploiting the spectral domain to achieve a greatly simplified yet spectrally inefficient implementation for diversity reception, we prove that a total of up to eight FSO links at the access segment can be jointly and transparently fed over a single C-band aggregation link.**

I. Introduction

The increase in per-user data rates and the access to modern compute infrastructure call for fibre-grade capacities towards the network edge [1]. However, such connectivity is by no means guaranteed; Fibre-scarce fields face a bandwidth bottleneck unless fibre-grade alternatives are provided as a way to extend the bandwidth continuum. As one of these, free-space optical (FSO) links based on optical wireless communication can capitalize on license-free operation and the vast bandwidth of electro-optic signal converters [2]. Earlier works have demonstrated beyond-Tb/s capacities over FSO links [3-5], which if spanned between two single-mode fibre ports can build on mature fibre-optic technology. However, these fibre-in-the-air implementations require precise optical coupling and are prone to fading due to unfavourable atmospheric conditions [6]. Especially turbulence can lead to rapid signal fading, which despite available pointing, acquisition and tracking mechanisms requires additional diversity schemes for its mitigation [7, 8]. In an earlier work [9] we have shown that both, optical coupling over a fibre-wireless-fibre bridge and turbulence mitigation can be jointly facilitated through a simple fibre-optic beamformer.

In this work, we discuss the practical requirements for accomplishing optical turbulence mitigation through focal plane array (FPA) beamformers at both ends of a FSO link. We investigate the diversity gain when increasing the FPA size up to 91 optical antenna elements and analyse the optical spectral efficiency when mapping the diversity transmission to the wavelength domain. We find that up to eight FSO-based access links can be transparently and jointly fed from an aggregation node before the entire C-band spectrum of the feeder link is fully exhausted.

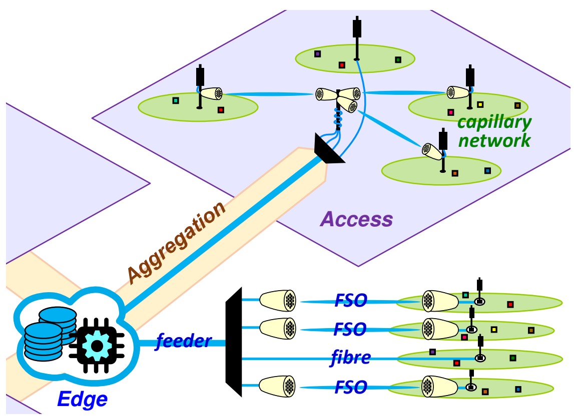

Fig. 1. FSO links providing a fibre-grade capacity continuum towards far-access networks that are located in fibre-scarce field environments.

II. FSO as an Access Modaliy for Capillary Networks

Access to edge computing has become a universal requirement. Ideally, a connection is made in a maximally transparent way and through provision of a communication pipe that offers a sufficiently high bandwidth. Towards that, fibre-optics, free-space optics or a mix thereof are an ideally suited solution. Figure 1 presents a deployment scenario where high-capacity fibre or FSO links in the access domain connect multiple RF-enabled capillary networks at the far-access side to the aggregation segment. The adoption of FSO as a wireless optical access technique supports radio deployments in fibre-scarce environments, where no high-bandwidth solution would be available through a wired backhaul solution to trunk local networks to the edge-computing infrastructure.

FSO systems have been intensively researched during the past decades. More recently, beamforming solutions have moved into focus in an attempt to assist fibre coupling and wide field-of-view coverage using pencil beams. Here, point-to-point FSO links will be considered for further investigation. While the feasibility of simplified alignment-tolerant point-to-point FSO links has been proven earlier [10], the concept that is employed in Section III to effectively mitigate optical turbulence will build on a reception diversity scheme that leverages on the optical wavelength domain. However, by extending the optical bandwidth

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required to accomplish an FSO-enabled access link, the spectral occupancy of the feeder link at the aggregation segment becomes a limiting factor. We will therefore investigate practical deployment challenges when collapsing multiple alignment-tolerant and turbulence-resilient FSO access links over a common feeder span.

III. Optical Air Interface and FSO Link

The arguably most important element of a FSO link are efficient air interfaces that provide low-loss coupling and, ideally, some sort of beamforming functionality. The optical air interface considered in this work is composed by fine-pitched single-mode fibre (SMF) cores of a photonic lantern, which are arranged over the focal plane of an optical lens, as shown in Fig. 2(a) which highlights the centre core through injection of red light. These cores therefore represent the antenna elements of a FPA beamformer, whose emitted pencil beam is steered by changing the offset of the launch core from the focal centre of the lens. In the experimental investigation that follows, a total of up to 91 hexagonally arranged antenna elements have been used with a core-to-core pitch of 35 µm. Together with the focal length of 100 mm for the 2” lens optics, which leads to a beam diameter of 28 mm, this enables a field-of-view of 0.22° for the point-to-point FSO link, whereas the beamsteering through the FPA will be used to optimize the fibre-to-fibre coupling efficiency over the air. Moreover, the control of the FPA beamformer can be accomplished through simple core switching rather than complex phase calibration, as it would apply for optical phased array implementations.

The overall FSO link is presented in Fig. 2(b). Each of the two air interfaces of this point-to-point link employs a FPA beamformer. Two beamformer architectures are considered, building on either an exclusively space-switch FPA beamforming network, or a mix of space- and wavelength-switched network. The difference among these resides in the supported optical bandwidth: The colourless beamforming network of a space-switched architecture trades against the accomplishment of centralized beamforming control when adopting a hybridly switched beamforming scheme. This is highlighted in Fig. 2(b) for which the coloured configuration features passive control of the tail-end side beamformer since the routing for the wavelength-determined FPA can be simply facilitated by a centralized beamforming control located at the head-end of the FSO link. The architectural peculiarity of the FPA-based air interface further motivates a dedicated use of these colourless and coloured FSO links in aggregation- and access-centric deployments with fibre-grade capacity, as will be discussed in Section IV.

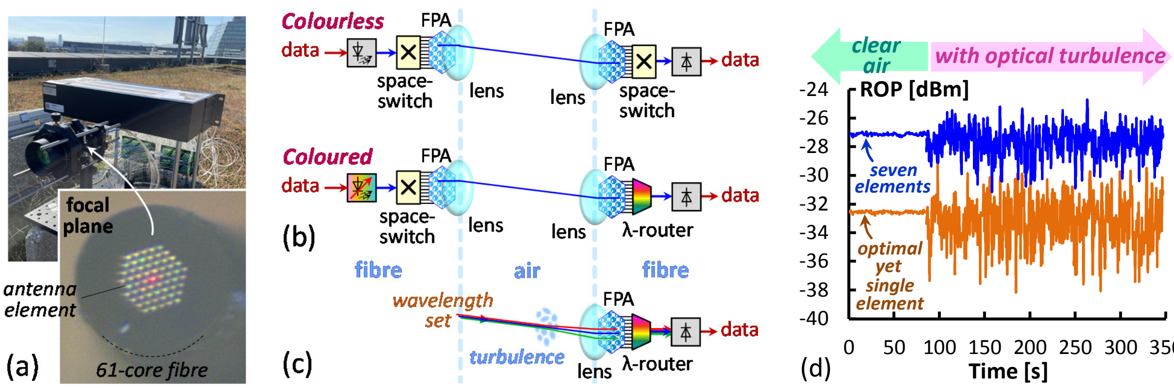

Fig. 2. (a) Fibre-based FPA beamformer and photograph of the FPA plane resembling the cross-section of a photonic lantern. (b) FSO link layouts with space- and hybridly space-/λ-switched FPA configurations. (c) Diversity reception through wavelength-set signal coding. (d) Diversity gain in presence of turbulence.

Given the capability to optimize the optical coupling, the air interfaces not only enhance the fibre-coupled power after FSO transmission with coarse initial installation of the FSO terminals; The architecture of these air interfaces further enables the mitigation of optical turbulence [9] by means of diversity reception, as it is schematically introduced in Fig. 2(c). Scintillation leads to fast beam wander and therefore a spread of transmitted signal power over multiple antenna elements. Given that many of the antenna elements can be multiplexed, such as it inherently applies to the wavelength-routed beamforming network that can be, for example, implemented on a 50-GHz WDM grid, optical turbulence can be simply mitigated by encoding the air-side data stream on multiple wavelengths that coincide with the antenna element allocations covered by the beam wander. Figure 2(d) reports the coupled power at the output of the FPA beamformer when transmitting data on a single wavelength allocated to the most optimal antenna element of the wavelength-routed FPA architecture, in presence of optical turbulence introduced by a heat gun positioned at the head-end side of a lab-scale FSO link. This case of single-wavelength data transmission is compared against data encoded on a wavelength-set of seven channels, which corresponds to the optimal antenna element and its six surrounding elements. Besides an enhancement in the aggregated power, which evidences that the turbulence leads to a significant power spread, the variance in the received power is greatly reduced, as discussed shortly.

IV. Aggregation of Wavelength-Set Coded Turbulence-Resilient FSO Links

Figure 3 shows the experimental coupling of light from a space-switched FPA beamformer at the FSO transmitter (TX) to a wavelength-routed FPA at the receiving (RX) site, where each of the FPAs has 91 antenna elements. The results reported have been accomplished over a 63-m out-door link. The receiver-side antenna element ρ with the highest coupled power, coded in red colour in Fig. 3, depends on the antenna element τ over which the FSO signal is launched. Several of these optimal pairs are available, whereas the receiving antenna element is linked to a certain wavelength channel Λ. For the shown launch conditions at the centre element $\tau = 46$ and within its vicinity $\tau \in \{35, 36, 45, 47, 56, 57\}$, the coupled power varies from -13.5 to -18.1 dBm.

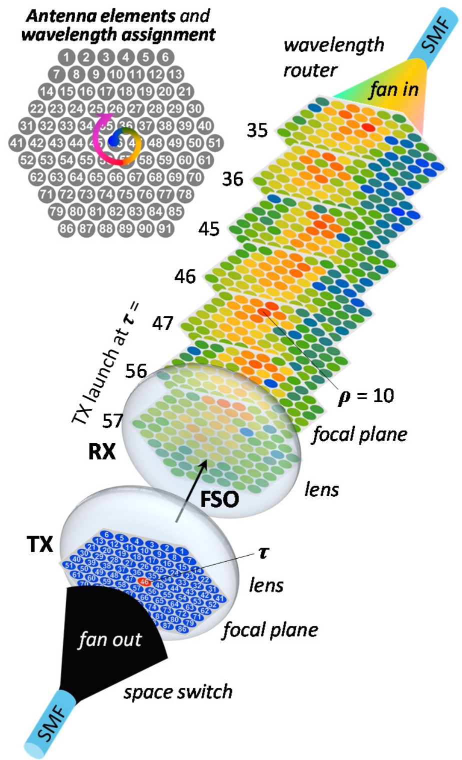

Fig. 3. Coupled light at the focal plane of the FSO receiver when varying the launch antenna element τ at the head-end FSO terminal.

A more detailed analysis on the coupled power is reported in Figs. 4(a) and (b) for FPA configurations with 91 and 61 elements, respectively. The markers (+) indicate the TX-RX pairs that lead to an optical coupling which falls within a margin of 3 dB with respect to the global maximum in coupled optical power. For the 91-element FPA setting, a total of 24 τ-ρ pairs are available. The black line in Fig. 4(a) is caused by a damaged port at Λ = 1542.54 nm, while the areas blacked out in Fig. 4(b) result from the omission of the outermost antenna elements due to the reduced FPA dimension. This reduction leads to a smaller number of 16 antenna element pair for the same power margin. The availability of such coupling pairs is summarized in the bar diagram of Fig. 5(a). Results are shown as a function of the power margin for three FPA configurations that feature 91, 61 and 37 antenna elements arranged within their hexagonal focal plane. For the largest FPA dimension, 24 (93) pairs are available at a margin of 3 (6) dB.

The availability of many τ-ρ pairs translates into multiple options to implement the wavelength-routing at the receiver-side FPA beamformer. The realization of diversity reception through incoherent signal combining for mitigating power spread due to optical turbulence requires a set of seven wavelengths to be encoded – as given through the optimal antenna element and the six surrounding elements in its vicinity [9]. Figure 5(b) presents the reduction in spread of received optical power (ROP) under turbulence when adopting diversity reception where all neighbouring antenna elements contribute to signal reception after incoherent combining, equivalent to signal transmission at seven wavelength channels. The 95% interval in which the ROP is found reduces from 6.8 to 4.2 dB when mitigating turbulence, while the average ROP level is increased by 5.5 dB. However, this improvement comes at a spectral burden since the same signal needs to be transmitted at multiple wavelengths Λ_i. The increased availability of spectral channels is therefore crucial as it enables a non-overlapping wavelength assignment for multiple air interfaces until the C-band spectrum of a common feeder for these air interfaces is exhausted.

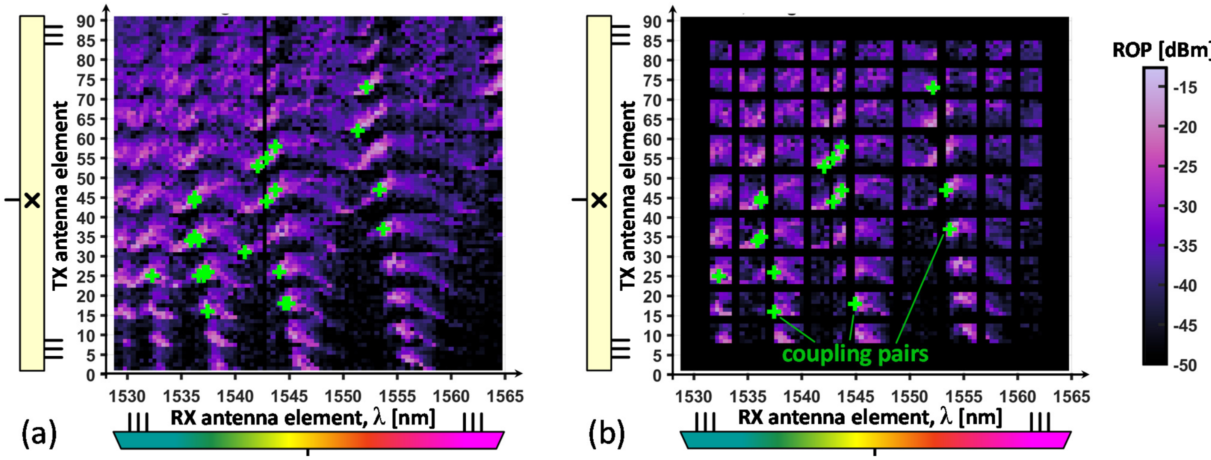

Fig. 4. Coupled power between various antenna elements for air interfaces that are comprised of (a) 91-element and (b) 61-element FPA beamformers.

Figure 6 shows such a wavelength-set assignment for the 24 τ-ρ pairs of the 91-element FPA configuration and a power margin of 3 dB. Two points shall be noted: First, not all elements ρ that fall within the margin conditions feature a complete array of 6 neighbouring elements. This is because they might be located at the edge of the focal plane. This reduces the number of sets to 22. Second, the wavelength sets overlap greatly towards the lower C-band. This is due to the chosen wavelength assignment, which follows a spiral-shaped inwards-out allocation over the focal plane (Fig. 3), originating from the element ρ = 46 at Λ = 1528.76 nm and terminating at ρ = 1 at Λ = 1564.74 nm. Since the inner antenna elements of the FPA naturally show a higher probability in overlap for their neighbours, the allocation is forced towards lower wavelengths at the centre of the FPA. When eliminating spectrally overlapping wavelength sets (corresponding to turbulence-mitigated FSO channels) according to a first-come, first-serve allocation, a total of four wavelength sets remain for simultaneous and non-blocking operation. This number could be increased by additionally exploring the L-band by virtue of the cyclic nature of the AWG. However, this adjacent waveband is reserved for the purpose of simultaneous channel sounding [10].

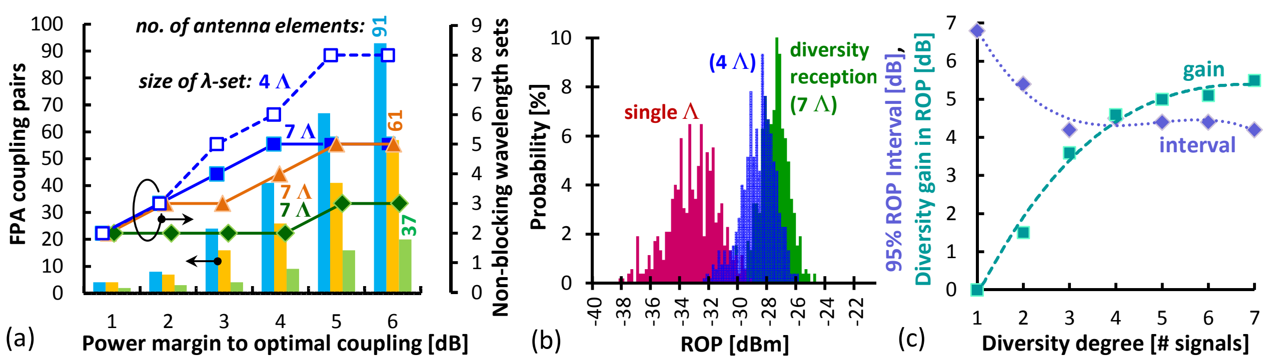

Fig. 5. (a) Available antenna element pairs as function of the tolerable FSO power margin. (b) Spread in ROP under optical turbulence when adoption diversity reception and (c) obtained diversity gain as function of the depth of the wavelength-set used for data encoding.

Figure 5(a) includes the number of wavelength sets that can be accommodated for FPA beamformers with 91 (■), 61 (▲) and 37 (◆) antenna elements. For a set size of seven wavelengths, four (five) set can be allocated for a 91-element FPA. The results also show that coupling towards the border of the focal plane leads to a reduction of the number of wavelength sets that can be provisioned, as it is more likely the case for the 37-element FPA (◆) where turbulence mitigation becomes more challenging to implement.

The rapid blocking of new spectral diversity channels in Fig. 6 poses the question whether the wavelength set can be compressed to less than seven wavelength channels while still obtaining a significant improvement. Towards that, Fig. 5(c) shows the impact of the diversity degree, expressed as the number of wavelengths (i.e., signals) that contribute to the launched wavelength set, on the reduction in ROP spread. Further shown is the accomplished optical diversity gain concerning the average ROP level in presence of turbulence. The results indicate that the wavelength set does not have to be fully expanded but can be effectively reduced to four constituent channels, which results in a penalty of 0.9 dB in diversity gain with respect to the fully populated set. Figure 5(b) evidences the good performance for this case of a reduced wavelength set through the proximity of the ROP histogram to the fully expanded set. Considering this case for wavelength allocation at the feeder link (Fig. 5(a)), the number of non-blocking sets can then be increased up to eight simultaneously trunked sets at the common feeder span when accepting a power margin of 6 dB (□) for signal reception at the access-side FSO link.

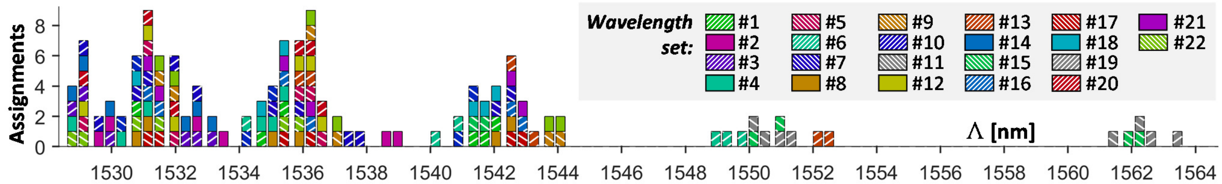

Fig. 6. Wavelength-set allocation when accommodating multiple turbulence-resilient FSO links in the access segment over a common aggregation link.

V. Conclusions

We have evaluated the aggregation of multiple alignment-tolerant FSO access links that employ diversity reception in combination with 91-element optical antenna configurations to harden the resilience of free-space communication against optical turbulence. Based on experimental findings that prove an effective mitigation of optical turbulence for transmission of data over a wavelength-set comprised of four 50-GHz channels, a total of 5 (or 8) access links can be jointly fed over a common C-band aggregation link when accepting a power margin of 3 (or 6) dB for the FSO links. This enables a fully transparent optical connection between the edge infrastructure and multiple capillary radio networks at the far-access segment.

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