

A Robust Basis for Multi-Bit Optical Communication with Vectorial Light

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Increasing the information capacity of communication channels is a pressing need, driven by growing data demands and the consequent impending data crunch with existing modulation schemes. In this regard, mode division multiplexing (MDM), where spatial modes of light form the encoding basis, has enormous potential but is impeded by noise due to imperfect channels. Here, this challenge is overcome by breaking the existing MDM paradigm of using the modes themselves as a discrete basis and instead exploiting the polarization inhomogeneity (vectoriness) of vectorial light as the information carrier. It is shown that this vectoriness communication basis is completely impervious to channel noise, which is verified by near perfect data fidelity maintained in multi-bit information transfer through atmospheric turbulence, with negligible changes on the order of 1%. This allows for demonstration of a new state-of-the-art of 50 vectorial modes in a communications channel with little cross-talk. This approach replaces conventional amplitude modulation with a novel modal alternative for potentially orders of magnitude channel information enhancement, offering a new paradigm to exploiting the spatial mode basis for optical communication.

1. Introduction

Optical communication has been an integral part of human society since recorded time, initially visual and thus free-space based, with wire-based solutions only emerging 200 years ago, from copper wire to modern day fiber optics. Today, our optical communication solutions are rapidly reaching their capacity limit,^[1,2] requiring new degrees of freedom for packing information into light. Here, so-called structured light comes to the fore,^[3] where light's spatial degree of freedom is used in space division multiplexing (SDM)^[4] and mode division multiplexing (MDM),^[5] for more channels and more capacity per channel, with significant advances over recent years.^[6,7] Topical among the multiplexing techniques is the use of orbital angular momentum (OAM)

modes, with excellent reviews available on the topic.^[8–10] For instance, in free-space reaching petabits-per-second data rates in the laboratory^[11] and 80 gigabits per second over 260 m^[12] while advances in optical fiber have shown 1.6 Tbit s⁻¹ OAM communication over kilometer lengths with a custom ring core fiber.^[13] In both these channels, modal cross-talk is a limiting factor.

Atmospheric turbulence induced modal scattering in free-space links is a particularly severe example,^[14–22] impeding classical and quantum communication links with structured light to only hundreds of meters.^[12] To mitigate this, there has been active research in searching for robust states of structured light in turbulence, including Bessel–Gaussian,^[23–34] Hermite–Gaussian,^[35–38] Laguerre–Gaussian,^[39–43] and Ince–Gaussian^[44] beams, but none have been shown to be robust in

laboratory and real-world experiments. This can be explained best from the perspective of OAM: The atmosphere itself can transfer OAM to and from the beam, so that all beams will be affected equivalently regardless of their initial structure.^[45] A recent development has been the creation of vectorial combinations of OAM, for vector vortex light^[46,47] with inhomogeneous polarization patterns, and these too have found applications in optical communication, both classical^[48,49] and quantum.^[50–53] Unfortunately, they have been found not to be resilient in turbulence,^[54–58] a fact that has been generalized to many different channels, revealing that the vectorial nature of such light remains invariant even as the spatial pattern itself alters.^[59] It is this “altering” or distorting of the pattern that impedes MDM, since its very premise is to “recognize” the original pattern in its undistorted form.

Here, we present a novel approach to MDM in optical communication, foregoing the discrete modal basis of MDM and instead exploiting the polarization inhomogeneity (vectoriness) of vectorial light as an encoding basis in a manner that does not require the mode itself to be recognized: a modal basis without the penalty of a modal detection. Similar to amplitude, it spans 0 (scalar light) to 1 (fully vectorial) but with the pertinent benefit that the full range can be used as a high-dimensional alphabet, rather than the 2D amplitude alphabet of conventional on-off keying (OOK). Since the vectoriness is measured using relative powers of polarization projections, global power fluctuations which hinder pulse-amplitude modulation (PAM) from effectively using the complete 0 to 1 range^[60] have little to no effect.

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Encoding information using vectorness can be seen as a modal form of quadrature amplitude modulation (QAM),^[61] with the added advantage that vectorness is measured independently of the chosen polarization basis. Because the vectorness is an invariant quantity, it remains intact even in the presence of aberrations, where all parties will receive the same information regardless of their particular channel conditions. This implies the potential for optical communication free of channel noise without the need for adaptive optics or digital corrective procedures. We demonstrate our encoding scheme on a highly aberrated channel of dynamically changing atmospheric turbulence, chosen as an extreme example of a noisy channel, showing correction-free data transmission under a wide range of conditions, with the dimensionality of the encoding primarily limited by detector noise. Our approach replaces conventional amplitude modulation with a modal alternative for potentially orders of magnitude channel information enhancement, offering a new approach to exploiting structured light for optical communication.

2. A New Encoding Scheme

Our technique involves exploiting the spatial mode basis using vector fields of the form

$$|\Psi\rangle = \sqrt{a}|\psi_+\rangle|H\rangle + \sqrt{1-a}|\psi_-\rangle|V\rangle \quad (1)$$

where $|\psi_\pm\rangle$ represents any pair of orthogonal spatial modes, $|H(V)\rangle$ are the horizontal(vertical) linear polarization Jones vectors, and the real amplitude determined by a ensures that the total power in the field remains constant for $a \in [0, 1]$. Such beams are ubiquitous, and in particular are the natural modes of both optical fiber and free space when $|\psi_\pm\rangle$ is chosen appropriately.^[47] It has been shown that fields of this type have a degree of non-separability in their spatial and polarization degrees-of-freedom (DoFs) which can be quantified using a quantum inspired metric (the concurrence), termed the vector quality factor,^[62,63] and which we will refer to as the vectorness for short. The concurrence, C , for the field in Equation (1) is given by ref. [64]

$$C = 2\sqrt{|\langle\psi_+|\psi_+\rangle\langle\psi_-|\psi_-\rangle| - |\langle\psi_+|\psi_-\rangle|^2} \quad (2)$$

which reduces to $C = 2|\sqrt{a(1-a)}|$. We see that the weighting parameter a allows C to be varied monotonically from a minimum value of $C = 0$, which represents completely scalar fields (homogeneously polarized), to a maximum of $C = 1$ which represents fields with maximally non-separable spatial and polarization DoFs (inhomogeneously polarized), with the required amplitude modulation trivially found from

$$a = \frac{1}{2} \left(1 \pm \sqrt{1 - C^2} \right) \quad (3)$$

Note that both C and a span from 0 to 1, but the invariance of C allows us to use it as a multi-bit encoding basis. This is because all measures of C will agree on the value regardless of the detector type (and we will show, regardless of the channel conditions), a property inherited from its quantum origin. This is in stark contrast to a measurement of the amplitude, a , directly, where

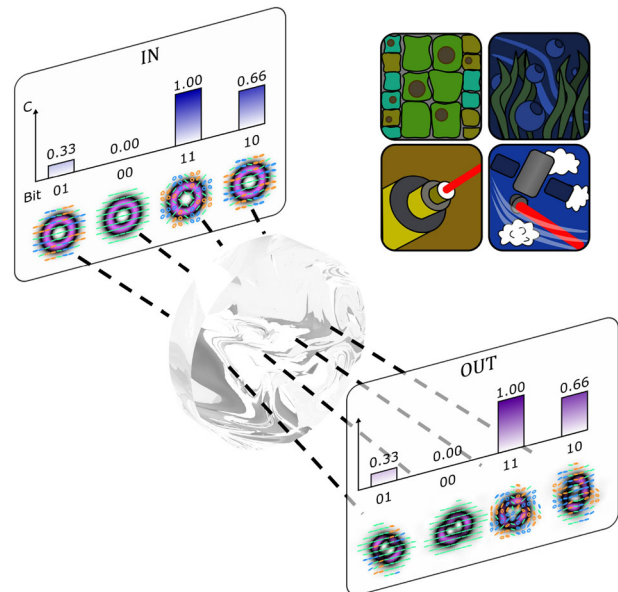


Figure 1. Modal vectorness for multi-bit encoding. Conceptual visualization of a sequence of vector beams with tuneable vectorness (denoted as C). Each C value is binned into the user-defined basis allowing for the received C to map to a bit-string of length determined by the basis choice. After propagating through an aberrating channel (e.g., atmospheric turbulence, underwater, single-mode fiber, or even transparent cellular material), the intensity and polarization profiles of the beams are distorted, however, the C is left unaffected.

disparate detector efficiencies and channel noise/loss mean no universal agreement on a , thus reducing the full multi-bit bandwidth spanning 0 through to 1, to just 0 or 1 (one bit) for light or no light. To use the vectorness as measured by C as an encoding basis we can assign unique information to values separated by ΔC , for $N \approx 1/\Delta C$ as the number of elements in the basis (we will return later to how small ΔC can be). This allows us to transmit $d = \log_2 N$ bits per on/off pulse, rather than the one bit with the traditional non-modal amplitude approach. We illustrate this concept in **Figure 1**, where initial modes (IN) are passed through an aberrating channel and emerge distorted (OUT). Although the spatial mode structure appears scrambled and would have high modal cross-talk, the vectorness remains intact with no cross-talk and can therefore be used as a multi-bit encoding basis. Here, concurrence values of $C = \{0, 0.33, 0.66, 1\}$ are used with $N = 4$ as an example. Although in the remainder of this paper we will use turbulence as our example channel, it could be optical fiber, underwater, or cellular media too, as illustrated in **Figure 1**.

3. Invariance of the Basis to Turbulence

Now that we have defined how we construct a communication basis from the concurrence of classical vector beams, we can investigate how this basis responds to propagation through the atmosphere where spatially varying air densities due to both pressure and temperature variations induce a spatially varying refractive index according to the Gladstone–Dale law. We select turbulence as an example only, chosen because it represents a particularly dynamic and extreme distorting medium. We can

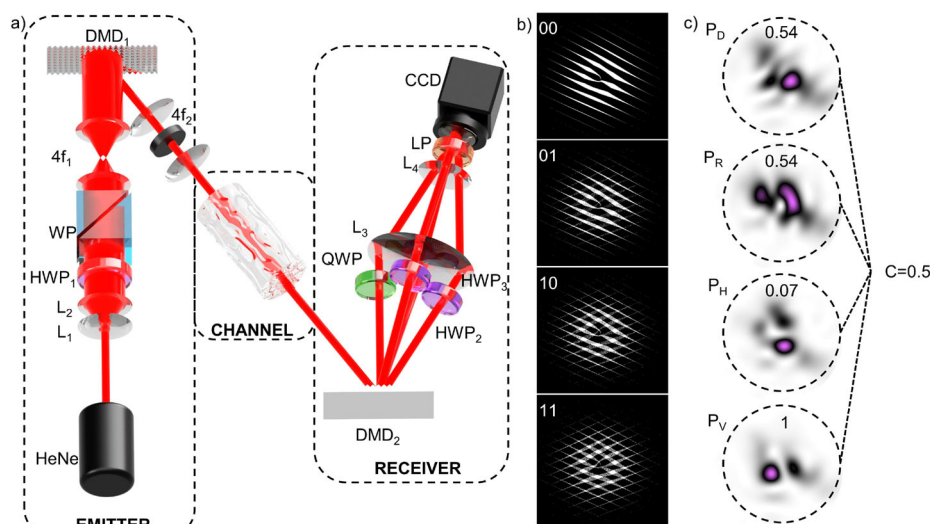


Figure 2. Experimental demonstration. a) Diagram showing the setup used to generate vector fields with tune-able concurrence (EMITTER) and measure the concurrence (RECEIVER) after propagating through heated air (CHANNEL)—(L_i, lens; HWP_i, half-wave plate; WP, Wollaston prism; DMD_i, digital micro-mirror device; LP, linear polarizer; CCD, charge-coupled device). b) Exemplar multiplexed binary amplitude holograms used to holographically control the concurrence of generated beams via weighting parameter a ; associated bit strings are displayed. c) Exemplar Stokes intensities which are integrated over the dashed circles in order to calculate the concurrence C (P_H , horizontal; P_V , horizontal; P_D , diagonal; P_R , right-circular polarization integrated powers).

express the total phase change, $\Phi(\vec{r}_T)$, through a width of turbulent medium using the thin screen approximation.^[65] This phase acts only on the spatial DoF via the operator in the position basis $\hat{P}_\Phi = \int e^{i\Phi(\vec{r}_T)} |\vec{r}_T\rangle \langle \vec{r}_T| d\vec{r}_T$. We also choose to allow propagation to the far-field for phase-only distortions to become phase and intensity fluctuations, modeled by using a Fourier transform operator $\mathcal{F}$. We thus express our field after propagating into the far-field through turbulence as

$$|\phi_\pm\rangle = \mathcal{F} \hat{P}_\Phi |\psi_\pm\rangle \quad (4)$$

We can now take note of an important property of this transformation, namely, that it is unitary and therefore preserves inner products such that $\langle \phi_\pm | \phi_\pm \rangle = \langle \psi_\pm | \psi_\pm \rangle$ and $\langle \phi_+ | \phi_- \rangle = \langle \psi_+ | \psi_- \rangle$. From Equation (2), we see immediately that this implies the invariance of the vectorness (concurrence) to this channel, and obviously extended to other similar transformations. The result of this is illustrated in Figure 1, where the vectorness and the bit-strings they are mapped to are unchanged through the channel, even though the intensity and polarization profiles are severely distorted. A more detailed derivation of this theory is given in Supporting Information. This theoretical concept reveals the potential of vectorness as a robust multi-bit information carrier. It is worth noting that transformations which are non-unitary, such as polarization-dependent coupling in optical fiber or excessive Rayleigh scattering in the atmosphere, will result in $\langle \phi_\pm | \phi_\pm \rangle \neq \langle \psi_\pm | \psi_\pm \rangle$ effecting a change of vectorness. In systems where this non-unitary effect is static, compensating calibration can be utilized to mitigate this effect.

4. Practical Demonstration

In order to verify the effectiveness of the suggested encoding scheme, we utilized the experimental setup seen in Figure 2,

with a more detailed breakdown given in the Experimental Section. The vector beams were generated using an interferometer consisting of a Wollaston prism (WP), an imaging system, and a digital-micromirror device (DMD₁), where the independent complex modulation of horizontally and vertically polarized components of a diagonally polarized (approximate) plane wave was facilitated by two multiplexed binary amplitude holograms.^[66] In order to control C , the relative efficiencies of the holograms were tuned according to Equation (3) by varying the amplitude, a , with exemplar multiplexed holograms for a $N = 4$ vectorness basis shown in Figure 2b. The vectorial beam was passed through a dynamically aberrated channel created by a heater set to a steady state temperature of $T \approx 185^\circ\text{C}$ to induce turbulence in the air along ≈ 200 mm of beam path. The resulting beam was then passed to the detection system, a custom built single shot Stokes polarimetry arrangement, composed of a second DMD₂ encoded with multiplexed binary gratings which diffracted four copies of the vector field into the ± 1 diffraction orders. The beams were allowed to propagate to the far field for the phase distortion to manifest as both amplitude and phase distortion. The four copies were then imaged onto the sensor of a CCD camera—initially, a low-cost FLIR Chameleon was used and later replaced by a higher quality FLIR Grasshopper to highlight the role of detector sensitivity. Prior to the CCD, each of the four copies were passed through different combinations of quarter-wave and half-wave plates and a common linear polarizer in order to capture horizontally (I_H), vertically (I_V), diagonally (I_D), and right-circularly (I_R) polarized Stokes intensity measurements from which the concurrence was calculated. Furthermore, the Stokes measurements form an over-complete set of polarization projections, making our decoding step independent of the polarization basis that the modes were prepared in, that is, the sender or the channel can alter the polarization basis without any effect on the outcome.

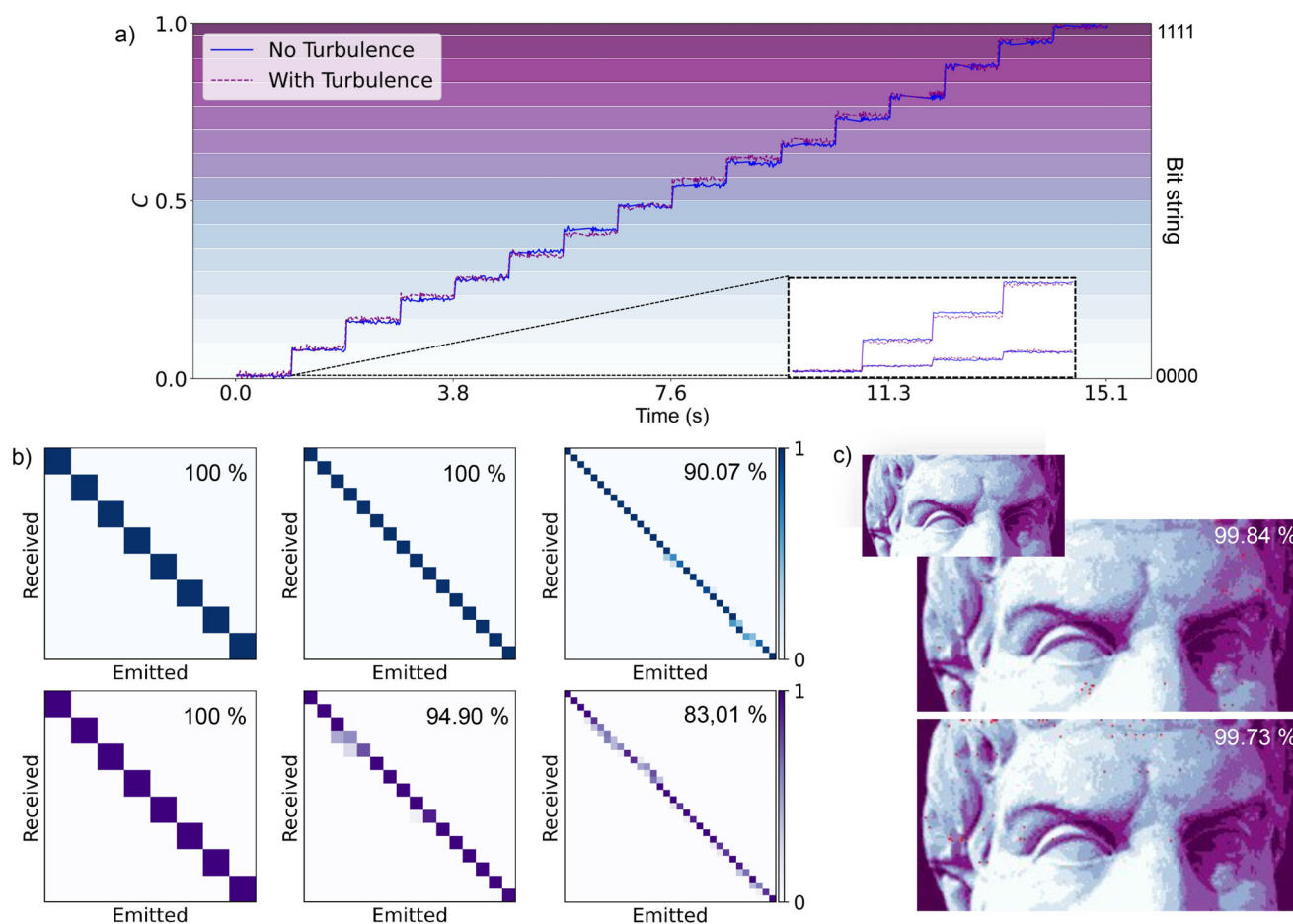


Figure 3. Discretized bases, crosstalk and multi-bit information transfer. a) Received concurrence of an input value varied in 16 discrete steps (insets show partial results for 8 and 32 steps) through still (solid line) and turbulent (dashed line) air. b) Crosstalk matrices (with associated fidelity) for the emitted and received concurrence through still (top) and turbulent (bottom) air for bases with $N = 8, 16$ and 32 (left to right). c) 3 Bit (8 level) image transmitted through still (top) and turbulent (bottom) air - red pixels highlight errors (inset shows the ground truth image) while the values report the image fidelity.

Figure 2c shows exemplar Stokes intensities integrated over the dashed region to obtain associated powers $P_{H,V,D,R}$, from which the concurrence could be determined (see Experimental Section).

5. Multi-Bit Encoding

The key to our proposed technique is that C does not change due to beam distortions, so that the full range from 0 to 1 can be used in a user-defined number of steps (N) independent of how perturbing the channel is. This sub-division of the available encoding space is shown in Figure 3a for $N = 16$ (with $N = \{8, 32\}$ included as an inset). To indicate the low cross-talk, the transmitted vector beam was allowed to “idle” at each basis element (delineated into bins shown as shaded bars) while repeated measurements were taken, confirming only small dynamic changes in still and turbulent air alike. The robust nature of the encoding is quantified by the cross-talk matrices in Figure 3b for up to $N = 32$, corresponding to 32 vectorial modes, yet with low levels of cross-talk. Finally, we use the system to transmit information over this dynamically changing turbulent channel with no ad-

justment to the received data signal, resulting in the high fidelity images shown in Figure 3c for still (top) and turbulent (bottom) air using $N = 8$. The consistency of the results under different channel conditions validates the concept. The notable feature of this approach is that the number of modes used can be tailored up to a maximum $N_{\max} = 1/\delta C$, where δC is the inherent noise in the system—calculated as the standard deviation of repeated measurements at a given C . Next, we take a closer look at this to estimate the potential of the approach and show that, as expected, δC is limited primarily by detector noise and not the condition of the channel itself.

6. Noise and Information Capacity

We see from the “idling” results of Figure 3a that the noise of the still and turbulent air are comparable, suggesting that detector noise is the primary cause of the statistical variation of a given vectoriness about the target, as anticipated by theory. This results in only very small errors between what was emitted and what was received, as illustrated in Figure 4a, for $N = 16$ as an example,

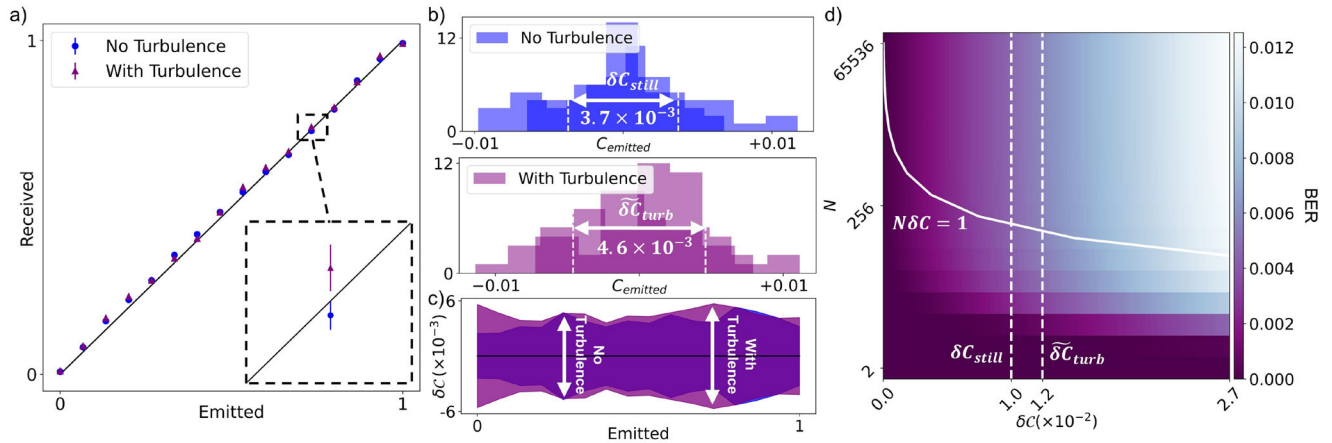


Figure 4. Noise, statistical variation, and bit-errors. a) Mean received concurrence (over 50 points) per element in the $N = 16$ basis in both still (circles) and turbulent (triangles) air; error bars are visible in the inset. b) Distribution of received C values about their target (C_{emitted}) for two example basis elements both without (top) and with (bottom) turbulence—values report the mean deviations across the $N = 16$ basis. c) Measured standard deviation for each element in the $N = 16$ basis through still and turbulent air, where the large overlap illustrates the turbulence invariance. d) Theoretically predicted BER as a function of the statistical spread δC and basis choice N ; the white solid line represents the points where $N\delta C = 1$ and white dashed lines represent the deviations of our receiver under different channel conditions - δC_{still} and δC_{turb} .

with the small scale of the deviation shown in the enlarged inset. A statistical analysis of the experimental noise, shown graphically in Figure 4b, reveals that $\delta C_{\text{still}} \approx 3.7 \times 10^{-3}$ in still air (no turbulence), which we take to represent the inherent noise of the detection system. When instantaneous turbulent channel conditions are introduced, we observe only a slight increase in noise to $\delta C_{\text{turb}} \approx 4.6 \times 10^{-3}$, which we attribute to the signal-to-noise limit of our detector, that is, defocusing aberrations in turbulence leading to a signal below the noise threshold of the detector (see Supporting Information). It is notable that a spread in the received C due to detector noise is akin to the spectral spread observed in OAM due to channel aberrations. We confirm too that the noise is not mode specific, as shown by the small difference in variance with and without turbulence in Figure 4c. This validates the claim that the minimum subdivision of the encoding space, or maximum number of modes (or bits), is limited primarily by detector noise and not channel conditions, contrary to traditional MDM schemes.

To probe the potential of this approach, we consider how a given detector noise limit (δC) and subdivision choice (N) affect the resulting bit-error-rate (BER), using our turbulence channel as an example. The BER is the ratio of incorrectly received bits to total transmitted bits and represents how crosstalk in the scheme affects the information transfer. The results of this are illustrated graphically in Figure 4d. In order to quantify the relationship between the cross-talk inducing δC and the system fidelity, we can analytically inspect the overlap of neighboring basis elements to reveal the BER for a given choice of basis (i.e., N) and δC

$$\text{BER}(N, \delta C) = \bar{E}(N) \frac{\delta C}{2} \sqrt{\frac{\pi}{2}} e^{-\frac{N^2}{2\delta C}} \text{erf}\left(\sqrt{\frac{2}{\delta C}}\right) \quad (5)$$

where $\text{erf}()$ represents the error function and $\bar{E}(N)$ is the mean bit-error per erroneously binned measurement for a given basis choice (see Supporting Information). If we inspect the BER for

different channel conditions and basis choices, as shown in Figure 4d, we notice how reducing δC allows for the use of denser choice of basis while maintaining a low BER. The white curve in Figure 4d indicates the special cases of $N\delta C = 1$, with the associated line acting as a limit for the basis size under a given channel condition. It is however notable that this overlap is significantly lower than the modal overlap experienced by MDM systems as we shall demonstrate. This is because MDM is reliant on projecting into the spatial mode basis where the broken orthogonality (i.e., $\langle \psi_i | \phi_j \rangle \neq \delta_{ij}$, where δ_{ij} is the Kronecker delta) results in high error rates. The increase in error occurs since a received mode $|\phi_i\rangle$ overlaps with multiple modes $|\psi_i\rangle$ of the emission basis. Our results indicate that, with a suitable detector, acceptable telecommunications BERs on the order of 10^{-9} are plausible.^[67] A more suitable detector would take the form of high signal-to-noise photodiodes which would facilitate faster measurements and a lower δC . These results indicate that the effectiveness of the technique for high-dimensional information transfer places the burden only on the signal-to-noise ratio of the detector system. The notably poor diffraction efficiency offered by DMDs^[68] and the limited dynamic range of CCDs means that our particular system suffers from a lower signal-to-noise ratio (SNR) than alternatives, such as the sensitive photodiodes used in free-space communication links. The white dashed lines in Figure 4d indicate the mean measured δC for our system with and without turbulence. The associated $\text{BER}(N = 8) \approx 2 \times 10^{-3}$ also agrees well with the fidelities reported in Figure 3c and is below the forward-error correction limit of 3.8×10^{-3} .^[69–71]

7. Comparative Performance

The highlight of the proposed vector-based encoding scheme is that its invariance to the channel conditions makes it a more robust choice in comparison to direct modal encoding schemes. To illustrate this point, we will use the OAM basis as a comparative example. Additionally, we changed the CCD detector from

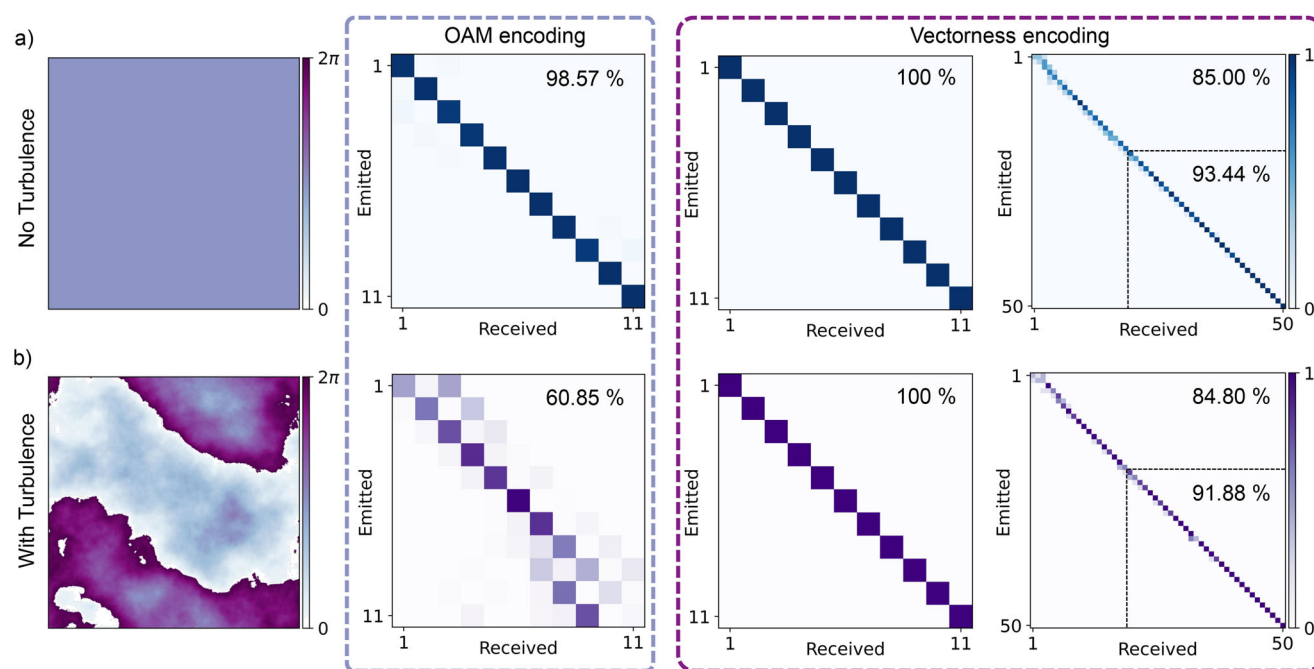


Figure 5. Channel invariance comparison to OAM encoding. Crosstalk matrices through a) ideal and b) aberrated channels using both OAM (with $N = 11$) and vectoriness (with $N = 11$ and $N = 50$) encoding schemes. The turbulence phase screen used to aberrate the beams is shown in the left panel of (b). A truncated 32 mode subset of the $N = 50$ basis is highlighted showing improved fidelity.

a 58.81 to a 60.62 dB dynamic range model to further highlight the role of detector choice and to allow a larger basis to be explored (more subdivisions). The setup of Figure 2 (using DMD₂) allowed us to generate and perform spatial mode projections on scalar Laguerre–Gaussian beams (LG_{*p*}^{*l*}) of azimuthal order *l* and radial order *p*. The results in Figure 5a show the baseline case with no turbulence for direct OAM encoding and indirect OAM encoding using the vectoriness. In the direct OAM case, we utilized an 11 mode basis spanning the range of $l \in [-5, 5]$ with $p = 0$. Here, the size of the OAM basis was constrained by the system aperture, as increasing mode order results in ever larger beams. Our modal vectoriness scheme can be executed with low order modes for the same size across all bit-levels, and so does not suffer from this limitation. The detector noise limit in the vectoriness scheme allowed us to probe a $N = 50$ basis, far larger than OAM encoding approaches which typically range from $N = 4$ to $N = 34$.^[49,72] To the best of our knowledge, $N = 50$ is the largest number of vectorial modes used in a communication link experiment. The fidelities in Figure 5a are indicative of experimental limitations (detector noise) and can be taken as the baseline values.

Since we are interested in the effect of the channel, we replaced our dynamic channel aberrations with a static turbulence phase screen with a fixed Fried parameter of $r_0 = 1.5$ mm as displayed in the left panel of Figure 5b (see Experimental Section for the generation technique). The static screen allowed for a controlled comparison of how the crosstalk in each of the schemes changes when the channel perturbations are introduced. The 37.72% decrease in fidelity using OAM encoding is in stark contrast to the 0% change observed using vectoriness encoding at the same basis size ($N = 11$). When pushing the dimensionality of the new

encoding scheme further, the channel-induced crosstalk only increases marginally, in the order of 1%.

There are two important observations one can make from the vectoriness data in Figure 5. First, the baseline (no turbulence) indicates how the detector choice limits the maximum subdivision number by its noise, setting a limit on how small δC can be. For our detector at $N = 50$, the baseline fidelity is 85%, but can be improved to 93% by using a smaller number of modes ($N < N_{\max}$) in the available space—while also maintaining the modal density. With better detector technology, the maximum number of modes can be significant, or the impact of noise made small by using a smaller encoding alphabet. Second, a comparison of the baseline (no turbulence) to the baseline with channel noise (with turbulence) makes crystal clear that the channel noise is negligible in the new scheme, validating our central claim. In no other modal approach is the channel noise so inconsequential, here contributing in the $\approx 1\%$ range.

8. Discussion and Conclusion

The proposed scheme and the results of our demonstration reveal its potential for multi-bit encoding using a new modal version of amplitude modulation, enabling a *d*-fold increase in information density using existing amplitude modulation technology for superior data transmission rates. Unlike MDM systems, our source of noise is primarily detector based, while being almost completely invariant to channel noise, negating the need for adaptive error-correction, which we showed using atmospheric turbulence as an extreme example. This is illustrated by using 50 spatial modes in a turbulent channel with a cross-talk that is comparable to the no-turbulence case, differing by less than 2%. For

comparison, our crosstalk observed between 11 OAM modes was 37.72% but zero for the vectorness approach, while other studies with four orthogonal vector OAM modes have reported $\approx 20\%$ crosstalk even in weak turbulence conditions,^[73] while crosstalk between seven neighboring scalar OAM modes reached 13.2% even with corrective measures.^[74] Our observed BER using eight modes, on the order of 2×10^{-3} , is comparable to that achieved in error-corrected MDM systems,^[72] even though we have deployed only a proof-of-principle version of the experiment with rudimentary detectors. Our direct comparison to OAM encoding revealed the superior channel invariance while also demonstrating how a larger basis (e.g., up to 50) can be achieved with the same system aperture which constrained the OAM basis to 11 modes—this is since the increase of basis size in OAM encoding requires larger mode orders which require larger apertures, while our approach can scale the number of modes up to the noise floor of the detector.

We point out that while the particular vector beams we used were composed of OAM-endowed LG_p^l modes, the core feature of our scheme is the utilization of vector beams (our modal basis) in a manner that does not require the spatial modes nor orthogonal polarization components to be detected or recognized. Instead, only their vectorness is detected, an invariant quantity that is found by an integrated modal signal. It is a modal approach without the penalty of detecting modes. In this regard, while our proof-of-principle experiment used a CCD camera for detection, fast and sensitive photo-detectors are all that is required for a real-world implementation. Because our channel-invariant basis is derived from spatial modes without actually detecting them and is independent of the polarization basis that they were prepared in, it brings with it some significant benefits over traditional MDM schemes that use the modes themselves as the basis. For instance, i) system misalignment is mitigated since the integrated detection (a power) is spatially invariant, ii) the modes can be selected with low order to reduce divergence^[75] (since more information does not require higher mode numbers), iii) like amplitude modulation, our scheme does not prohibit other enhancement schemes such as wavelength division multiplexing (WDM) to further improve information density, including even MDM if modal correction is applied, and further, iv) unlike alternative vectorial techniques,^[48,49] the nature of our detection scheme is over-complete even in the polarization basis and, therefore, means that the sender and receiver do not have to agree on the measurement basis, allowing the scheme to work even in polarization scrambling media such as stressed optical fiber. These benefits are provided by the vectorness, a physical quantity which displays resilience to transformations which generally hinder modal communication systems. The trade-off lies in the scaling of our scheme; in order to increase d by 1, N has to double. This places the burden of performance on the power and amplitude modulation resolution of the emitter and the SNR of the receiver, all factors which already receive considerable attention in free space optical communication systems.

To conclude, we have presented how the vectorness of vectorial light can be used as a new modal version of amplitude modulation, exploiting spatial modes in a manner that makes them effectively immune to channel noise, with the number of modes used limited primarily by the sensitivity of the detectors used. We have demonstrated high fidelity, correction-free, multi-bit infor-

mation transfer to verify our technique, even through dynamic turbulence, an extreme example of a communications channel. Our approach can be extended to other channels too, such as optical fiber and under-water, since the invariance property will hold in all such channels. We believe this approach will open up a new avenue for high-bandwidth optical communication, with the immediate benefits of MDM but without the modal cross-talk challenges. The vectorness presents a new scheme for information encoding, which if coupled with other communication techniques such as WDM and SDM, can be used to push the boundaries of optical communication.

9. Experimental Section

Experimental Details: In order to demonstrate the effective high-dimensional information transfer using concurrence as the communication basis, the setup as shown in Figure 2a was utilized. A Gaussian beam produced by a HeNe laser (wavelength 633 nm) was expanded and collimated using lenses L_1 and L_2 , respectively. The plane of polarization was converted to 45° using a half-wave plate (HWP₁) before passing through a Wollaston prism (WP) which separated the horizontally and vertically polarized components of the expanded beam at an angle of $\approx 1^\circ$. The plane at the WP was imaged onto the screen of a digital micro-mirror device (DMD₁) using a $4f_1$ imaging system. DMD₁ was addressed using two multiplexed binary holograms of the form

$$H_{A/B}(\vec{r}) = \frac{1}{2} + \frac{1}{2} \text{sign} \left[\cos \left(\varphi_{A/B}(\vec{r}_T) + 2\pi \left(\vec{g}_T^{A/B} \cdot \vec{r}_T \right) - \cos \left(\arcsin \left(A_{A/B}(\vec{r}_T) \right) \right) \right] \quad (6)$$

facilitating the modulation of the complex field $U_{A/B} = A_{A/B} e^{i\varphi_{A/B}}$, where $\vec{g}_T^{A/B} = (g_x^{A/B}, g_y^{A/B})$ are grating frequencies.^[76] In order to control the relative amplitudes of the resulting beams, complimentary weighted random matrices were multiplied to $H_{A/B}$ according to the method outlined in ref. [77]. Examples of the multiplexed gratings corresponding the different concurrence values are shown in Figure 2b. By selecting $\vec{g}_T^{A/B}$ appropriately, the $+1$ diffraction orders of independently modulated, orthogonally polarized components were spatially overlapped creating this vector beam $|\Psi\rangle$.^[66] For this case, $|\psi_\pm\rangle \equiv LG_0^\pm$ were chosen, where LG_p^l is the Laguerre–Gaussian mode with azimuthal (radial) index $l(p)$. The combined diffraction order was isolated using an aperture placed at the focal plane of a $4f_2$ imaging system, which imaged $|\Psi\rangle$ onto a second DMD₂. DMD₂ was addressed by simple binary diffraction gratings which were multiplexed in order to produce four copies of $|\Psi\rangle$; these copies were allowed to propagate into the far field through a 200 mm length of air, heated by a plate at 185°C . Additionally, three of the four paths were each passed through a HWP_{2,3} (fast axes at 45° and 22.5° , respectively) or a quarter-wave plate (QWP - fast axis at 45°). Lenses L_3 and L_4 were used to demagnify the four beams onto a CCD camera, while filtering using a linear polarizer (LP—transmission axis at 0°). The intensities projected onto the CCD correspond to the horizontal, vertical, diagonal, and right-circular polarized components, which allowed for the determination of C .^[78] Simulated examples of the far field Stokes intensities showing the region of integration (dashed circles) are given in Figure 2c.

Concurrence Measurement: The Stokes measurements were used to calculate C according to ref. [79]

$$C = \sqrt{1 - \frac{(P_H - P_V)^2 + (2P_D - P_H - P_V)^2 + (2P_R - P_H - P_V)^2}{(P_H + P_V)^2}} \quad (7)$$

where $P_i = \int \int I_i d\mathbf{r}_T$ represent the powers obtained from the transversely integrated Stokes intensities; the dashed circle in Figure 2c indicates the necessary region of integration. The entirety of the experiments, from the control of the emitted vectorness via the DMD's weighted multiplexed binary amplitude holograms to the integration of the measured CCD intensities and the calculation and binning of the received vectorness values, was automated using Matlab.

Static Turbulence Screens: In order to probe the performance of our encoding scheme along with alternatives under controllable conditions, a static turbulence phase screen was implemented, $\Phi(\vec{r}_T)$ which was used to modulate the phase of our beams during their generation (i.e., on DMD₁). The screen was generated using a fast-Fourier transform technique according to the following expression:

$$\Phi(\vec{r}_T) = \Re\left(\mathcal{F}^{-1}(M_{rand}\sqrt{\theta})\right) \quad (8)$$

where $\Re$ is the real-part, M_{rand} is a complex Gaussian random matrix centered at 0 with unit deviation, and θ is the Kolmogorov–Weiner spectrum conventionally determined (in pixel coordinates (i, j)) by the following expression:

$$\theta(i, j) = 0.023 \left(\frac{2D}{r_0}\right)^{\frac{5}{3}} (i^2 + j^2)^{-\frac{11}{3}} \quad (9)$$

where D is the hard aperture of the screen and r_0 is the Fried parameter (diameter over which the root-mean-squared wavefront aberration is 1 radian).^[80] It has been found that Equation (9) does not accurately model the statistics in the low spatial frequency region (which is notably dominant in the Kolmogorov regime). In order to accurately model this region of the spectrum, we employed additional subharmonic sampling according to the method outlined in ref. [81], when calculating our spectrum. In our experiment, we set $r_0 = 1.5$ mm.

Modal Projection Measurements: To facilitate a comparison to OAM based encoding, scalar $U_{emitted} = LG_p^l$ modes were generated by setting $a = 0$ on DMD₁. For simplicity, only the OAM associated azimuthal index l was varied on the interval $[-5, 5]$ to form the communication basis - while setting $p = 0$. To determine crosstalk between basis elements, correlation filters encoded on the second DMD₂ were utilized along with the far-field propagation to perform inner product measurements with each of the basis elements. The correlation filters were implemented according to Equation (6) with $U_A = (LG_0^l)^*$, resulting in the following intensity profile, to be captured in the far-field by the CCD

$$I_{FF} = \left| \int U_{emitted}(LG_0^l)^* e^{i2\pi\vec{k}_T \cdot \vec{r}_T} d\vec{r}_T \right|^2 \quad (10)$$

where it is clear that measuring the on axis intensity in the far-field (i.e., where $\vec{k}_T = 0$) results in the absolute-squared inner product between the emitted field and the given basis element. This allows us to project the received spatial mode $|\phi_i\rangle = \mathcal{F}\hat{P}_\Phi|\psi_i\rangle$, which has passed through the channel, into the emission basis which in this case is formed by $LG_0^l(\vec{r}_T) = \langle\vec{r}_T|\psi_i\rangle$ modes. The projection is done through inner product measurements of the form $c_{ij} = \langle\psi_i|\phi_j\rangle$, where c_{ij} are the elements of the resulting crosstalk matrix. This procedure is referred to as modal decomposition and a thorough tutorial is available in ref. [82].

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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