Unscrambling Entanglement through a Complex Medium

Natalia Herrera Valencia[1], Suraj Goel[1,2], Will McCutcheon[1], Hugo Defienne[3] and Mehul Malik[1,4]

[1] *Institute of Photonics and Quantum Sciences (IPAQS), Heriot-Watt University, Edinburgh, UK.*
[2] *Indian Institute of Technology Delhi, New Delhi, India.*
[3] *School of Physics and Astronomy, University of Glasgow, Glasgow, UK.*
[4] *Institute for Quantum Optics and Quantum Information, Vienna, Austria.*

Abstract. We achieve the transport of high-dimensional entanglement through a multi-mode fibre. Exploiting the parallelism of entanglement, we propose a new method for imprinting the information of the transmission matrix of a complex medium onto a two-photon quantum state entangled in the spatial degree of freedom. In this manner, we are able to revert the effects of scattering on entanglement by only manipulating the photon that did not enter the medium, thus recovering 6-dimensional entanglement in a 7-dimensional subspace after propagation through a 2-meter multi-mode fiber.

Keywords: high-dimensional entanglement, complex media, channel-state duality.

The transfer of quantum information through a noisy environment is a central challenge in the fields of quantum communication, imaging, and nanophotonics. In particular, high-dimensional quantum states of light [1,2] enable quantum networks with significantly higher information capacities and noise-robustness as compared with qubits [3]. However, while qubit-entanglement has been distributed over large distances through free-space and fibre, the transport of high-dimensional entanglement is hindered by the complexity of the channel, where effects such as free-space turbulence or mode-mixing in multi-mode waveguides involve the intricate interplay of hundreds to millions of modes, and effects of scattering must be overcome in a manner that preserves higher order quantum coherence between the modes of interest. Here we demonstrate the transport of six-dimensional spatial-mode entanglement through a two-metre long, commercial multi-mode fibre with 84.43% fidelity [4]. We show how the entanglement can itself be used to measure the transmission matrix of the complex medium, allowing the recovery of quantum correlations that were initially lost. In contrast to the classical technique of measuring a response function one state at a time, our method exploits the idea of channel-state duality to map the entire transmission matrix of a complex, multi-mode scattering channel onto a single high-dimensional entangled state. Using a unique property of entangled states, the medium is rendered transparent to entanglement by carefully "scrambling" the photon that did not enter it, rather than unscrambling the photon that did. This results directly from the invariance of maximally entangled states under operations of the form $(U \otimes U^*)$ for any unitary operator U. Our results overcome a primary challenge in the fields of quantum communication and imaging, opening a new pathway towards the control of complex scattering processes in the quantum regime.

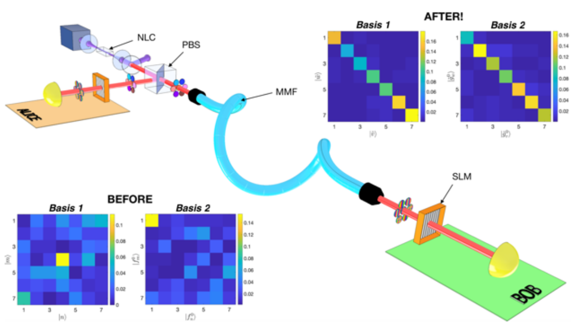

Figure 1 One photon from a maximally-entangled pair is sent through a multi-mode fiber (MMF), which completely scrambles its spatial correlations ("before" picture showing measured correlations in two mutually unbiased bases, 1 and 2). While the scrambled correlations do not exhibit any entanglement, they contain information about the transmission matrix of the fiber. Along with additional measurements, knowledge of the transmission matrix allows us to regain entanglement ("after" picture) by carefully transforming the photon that did not enter the medium.

References

[1] J. Bavaresco, N. H. Valencia, C. Klöckl, M. Pivoluska, P. Erker, N. Friis, M. Malik, and M. Huber, *"Measurements in two bases are sufficient for certifying high-dimensional entanglement,"* **Nature Physics 14**, 1032 (2018), doi: 10.1038/s41567-018-0203-z, Preprint: arXiv:1709.07344

[2] N. Herrera Valencia, V. Srivastav, M. Pivoluska, M. Huber, N. Friis, W. McCutcheon, and M. Malik, *"High-Dimensional Pixel Entanglement: Efficient Generation and Certification,"* **arXiv:2004.04994** (2020), arXiv:2004.04994.

[3] S. Ecker, F. Bouchard, L. Bulla, F. Brandt, O. Kohout, F. Steinlechner, R. Fickler, M. Malik, Y. Guryanova, R. Ursin, and M. Huber, *"Overcoming Noise in Entanglement Distribution,"* **Phys. Rev. X 9**, 041042 (2019), doi: 10.1103/PhysRevX.9.041042, Preprint: arXiv:1904.01552.

[4] N. H. Valencia, S. Goel, W. McCutcheon, H. Defienne, and M. Malik, *"Unscrambling Entanglement through a Complex Medium,"* **Nature Physics AOP** (2020), doi: 10.1038/s41567-020-0970-1, Preprint: arXiv:1910.04490.