Unscrambling entanglement through a complex medium

[Valencia, N. H., Goel, S., McCutcheon, W., Defienne, H., & Malik, M. (2020). Unscrambling Entanglement through a Complex Medium. *Nature Physics*. https://doi.org/10.1038/s41567-020-0970-1.]

Quantum properties of light enable unconditionally secure optical communications. In this respect, high-dimensional entangled states offer a way of exceeding the limitations of current approaches to quantum communication (e.g. larger information capacity and increased noise resilience). For example, the orbital angular momentum of photons was first used to establish high-dimensional quantum key distribution (HD-QKD) protocols in free-space, but with a limited range due to diffraction and the presence of atmospheric turbulence. Alternatively, multimode optical fibres (MMF) can be used to transport information encoded in parallel across many modes over large distances, and with almost no loss. However, the complex mode mixing process occurring during light propagation through the fibre "scrambles" the encoded information, making it unusable by the receiver. In their work, N. H. Valencia and co-workers demonstrate the transport of six-dimensional spatial-mode entanglement through a 2-m-long commercial MMF, by compensating the random mode mixing effect using a transmission matrix based wavefront-shaping technique (Figure 1) [0]. Such an ability to certify the presence of high-dimensional entanglement between two parties (Alice and Bob) is an essential step towards the implementation of practical HD-QKD protocols in optical fibres.

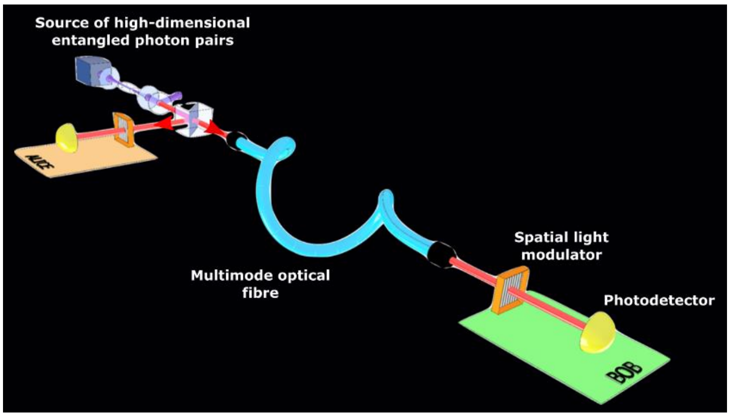

Figure 1. High-dimensional spatially entangled photon pairs are produced by spontaneous parametric down conversion in a non-linear crystal. One photon of the pair is sent towards Bob using a 2-m-long commercial MMF, while its twin photon is detected by Alice. Combinations of spatial light modulators (SLM) and single-pixel photodetectors measure coincidences between spatial modes of photons (i.e. single-outcome projective coincidence measurements). Alice's SLM is also used to compensate for the complex mode mixing process occurring in the fibre at Bob's end using the transmission matrix of the system previously measured by the entanglement itself.

In classical optics, the problem of optical information mixing as it propagates through an MMF has been extensively studied for imaging (endoscopy) and classical optical communication applications. Recently, measuring the transmission matrix of an MMF has enabled to carefully shape the light entering the fiber using a spatial light modulator (SLM) to preserve its spatial information content [1,2]. Inspired by this technique, N.H. Valencia and coworkers used it to "unscramble" high-dimensional entanglement propagating through the fiber, with two essential differences compared to the classical case: (a) the transmission matrix is directly measured using the entanglement between photons and (b) wavefront-shaping is applied to the photon that does not propagate through the fiber.

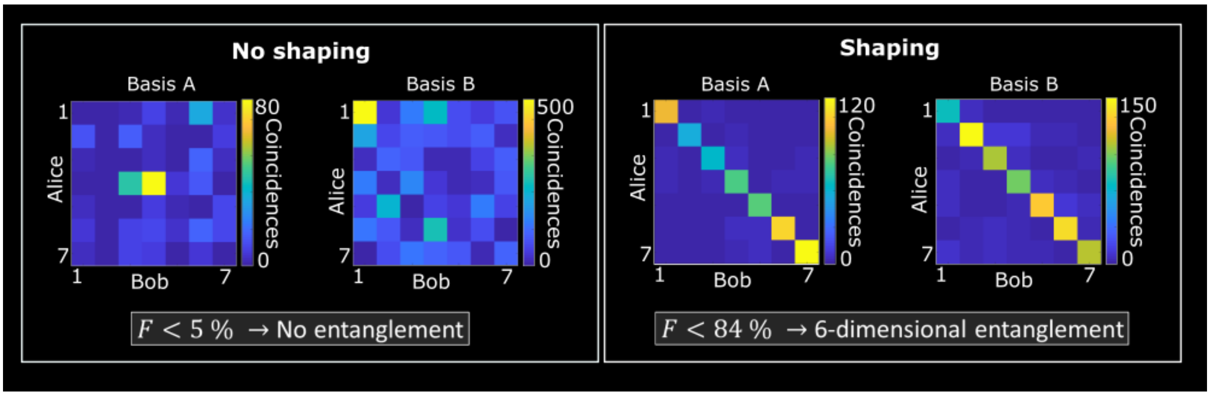

Figure 2. Coincidence measurements performed by Alice and Bob between 7 spatial modes of photons selected from two different basis (A and B). Without shaping, coincidence values are not sufficient to certify the presence of entanglement. Under shaping, significan correlations are observed between spatial modes of photons allowing the certification of 6-dimensional entanglement.

To certify the presence of entanglement, Alice and Bob perform coincidence measurements between spatial modes of photons from two different bases (A and B) [3]. As shown in Figure 2 ("No shaping"), the measured coincidence values do not reveal significant correlations and the resulting fidelity F is not sufficient to certify the presence of entanglement. However, these measurements - that seem to be "noise" - still enable to reconstruct the transmission matrix of the MMF (together with other additional measurements). Once the matrix is measured, Alice uses it to program her SLM accordingly for compensating the mode-mixing process induced by the fibre. Photon coincidence measurements performed under shaping show strong correlations between spatial modes of the photons in both bases (Figure 2 – "Shaping") and a resulting fidelity value that is sufficient to certify the presence of 6-dimensional entanglement.

Figure 3. Certification: Alice and Bob certify entanglement by measuring correlated spatial modes of photons (illustrated here by two identical smiley images). Multimode fiber: In the presence of a multimode fiber, the spatial information content of one photon gets mixed and is no longer correlated with that carried by its twin (smiley becomes a speckle). Scrambling: By carrefully scrambling spatial information carried by Alice's photon, it is possible to recover the correlations between spatial information carried by each photon without directly unscrambling the scrambled image (speckles are correlated, but they are not smileys anymore).

In essence, the entanglement itself holds the key to its own preservation: entanglement is first used to measure the matrix of the fibre, that is subsequently employed to certify its presence and dimensionality. Even more intriguing, the spatial correlations - and thus entanglement – are preserved through the MMF by carefully "scrambling" the photon that does not directly experience the mode mixing, instead of "unscrambling" the photon that propagates through it (Figure 3).

The work of N.H. Valencia and co-workers unlocked the potential of multi-mode fibers as a practical communication platform for implementing high-dimensional quantum key distribution and paves the way towards the use of wavefront shaping techniques - initially developed and extensively used with classical light - to manipulate optical quantum states for quantum information processing and communication.

References:

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