Hyper-Entanglement Distillation in Shared Communication Networks

Domenico Ribezzo[1], Giulia Guarda [1], Alessandro Zavatta[2], Davide Bacco[1]

[1]*Department of Physics and Astronomy, University of Florence, 50125, Florence, Italy*
[2]*National Institute of Optics (CNR-INO), 50125, Florence, Italy*

Co-propagating quantum and classical signals in shared optical fibers is essential for scalable networks, but hindered by Raman scattering [1]. High-dimensional (HD) QKD offers intrinsic noise resilience [2], but remains experimentally demanding. Here, we exploit HD states without a full HD protocol. Projecting a 4D hyper-entangled state onto a 2D subspace, we filter Raman noise in the remaining dimensions, restoring high visibility without substantially reducing detection rates.

A CW-pumped PPLN waveguide generates photon pairs at 1560.48 nm (DWDM 21), routed into two borosilicate-glass PIC imbalanced Mach-Zehnder interferometers (iMZIs) (Franson configuration) [3]. Outputs are discretized into two 100 GHz DWDM channels per side (Alice: 19, 20; Bob: 23, 22), achieving both energy-time and frequency hyper-entanglement:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|EE\rangle + e^{i\phi_t}|LL\rangle) \otimes \frac{1}{\sqrt{2}} \sum_{k=1}^{2} |k\rangle_A |-k\rangle_B \,. \tag{1}$$

Before the iMZI, Bob's photons traverse a 25 km fiber spool, where DWDM channel 17 is populated by a lased emulating classical traffic, which generates Raman noise. Our single-copy distillation scheme extracts the 2D energy-time entangled states using the DWDM filter acting as a quantum CNOT gate. Here the frequency mode is the control qubit: valid correlations preserve the energy-time target state, while uncorrelated Raman noise fails the energy conservation condition and is discarded. A single broadband filter spanning N channels yields accidental coincidences scaling as N^2. By demultiplexing into N narrow bins and post-selecting only energy-conserved pairs ($k_A = -k_B$), accidental coincidences are restricted to N diagonal terms. This suppresses broadband noise by a factor $\propto 1/N$. With respect to previous single-copy distillation schemes, we totally bypass active phase-locking necessity, and we moreover demonstrate resilience against genuine co-propagating telecom traffic in place of simulated laboratory noise [4].

Fig. 1 compares individual DWDM pair visibilities against a combined virtual broadband channel. The gap between 100 GHz pairs stems from the iMZIs' wavelength-dependent thermal response. Crucially, the wideband channel yields consistently lower visibility than the individual narrow pairs. For secure QKD (requiring QBER $\leq 11\%$, i.e. visibility $\geq 78\%$), our method enables key generation alongside a -6.5 dBm classical channel over 200 GHz bandwidth, impossible in a standard 200 GHz filter. Therefore DWDMs are not only simple multiplexers for key rate improvements, but real quantum gates unlocking secure QKD in traffic-heavy networks.

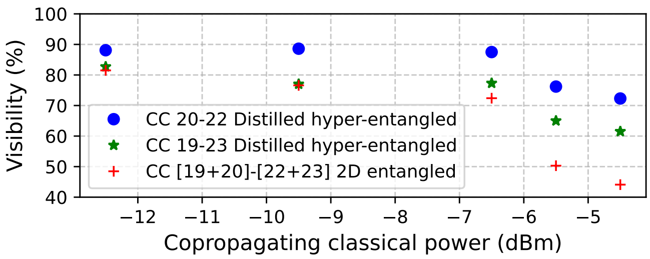

Figure 1: Visibilities extracted via thermal phase sweeping and sinusoidal fitting. After distillation (blue, green), and for the original 2D energy-time state.

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References

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