Quantum-compatible Phase Stabilization of a 120 km Network Link

M.V. Jabir[1], D. H. Ahn[1], N. F. R. Annafianto[1], I.A. Burenkov[1,2], M. Merzouki[1], P. Kuo[1], T. Gerrits[1], A. Battou[1] and S.V. Polyakov[1,3]

[1]*National Institute of Standards and Technology, Gaithersburg, MD 20899, USA*
[2]*Joint Quantum Institute & University of Maryland, College Park, MD 20742, USA*
[3]*Department of Physics, University of Maryland, College Park, MD 20742, USA*

Stabilization of the optical phase in fiber links is required for efficient telecommunication. There exist many quantum protocols that are sensitive to optical phase, including those enabling long-distance communication through quantum repeaters, which have been considered out of reach for deployed networks due to the insurmountable challenge of tight phase control. Long fiber links are susceptible to severe phase instabilities due to environmental factors. Until now, a strong classical optical phase reference signal would be required to stabilize long optical fiber links, which, at the same time, would introduce broadband noise into quantum channels, incompatible with quantum signals. Here, we demonstrate two distinct approaches to phase-stabilize a metropolitan-network-scale link: time-division multiplexed (TDM) phase stabilization with a displacement receiver, and using just 650,000 photons per second in a probe state that reaches the receiving detector [1], and wave-division multiplexed (WDM) phase stabilization with picowatt-level signals, which allow for a dark quantum payload channel with photonic noise of just 500 photons s^{-1} [2]. These schemes achieve long-term stabilization over a metropolitan-scale fiber link, providing a scalable platform for future quantum networks.

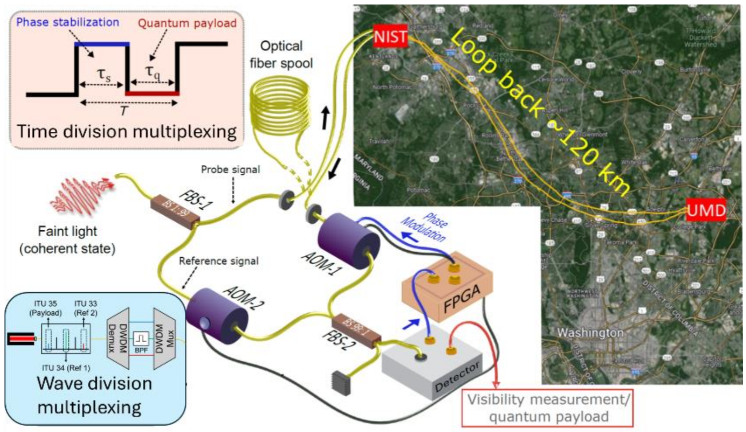

Fig. 1 The experimental setup for phase stabilization. *An attenuated ultra-stable reference laser is time multiplexed or combined with an electro-optic phase modulator to produce a frequency comb (three wavelengths* $\lambda_{payload}, \lambda_{Ref1}, \lambda_{Ref2}$ *are selected using dense wavelength-division-multiplexing) and then sent into an unbalanced MZI. One arm of the interferometer carries the signal through a long optical fiber spool or a deployed fiber loop, while the other arm uses a short fiber. AOMs are used to modulate phase and frequency in both arms. Inset in the top left: Time division multiplexing used in this work. Inset in the bottom left: Wave division multiplexing used in this work. AOM: Acousto-optic modulator, PD: Photo diodes, FBS: Fiber beam splitter, FPGA: Field Programmable Gate Array. Imagery ©2024 TerraMetrics. Map data ©2024 Google.*

The experimental setup is shown in Fig. 1. We use faint coherent light from an ultra-narrowband laser at 1550 nm to stabilize the optical fiber loop spanning over 120 km between NIST in Gaithersburg and UMD in College Park. TDM with a single-photon level reference signal offers background-free phase stabilization at the cost of a 50 % duty cycle, while WDM keeps the quantum channel dark with a minimal background of just 500 photons s^{-1}. We measure the integrated phase noise (from 1 Hz to 50 kHz) of ≈0.1 rad for the deployed fiber, corresponding to a RMS timing jitter of ≈0.1 fs. In other words, a 120 km link is stabilized to within approximately 4 nm, or to a fraction of approximately 3×10^{-13}!

[1] M.V. Jabir et. al., Optica 12, 570–576 (2025) https://doi.org/10.1364/OPTICA.540759
[2] D. Ahn et al., Optica, (accepted, 2026) https://doi.org/10.1364/OPTICA.586649