True Counterfactual Communication with a Nanophotonic Processor

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In standard communication information is carried by particles. Counterintuitively, in counterfactual communication particles and information can travel in different directions. In counterfactual communication (CFC) the quantum Zeno effect allows Bob to transmit a message to Alice by encoding information in particles he never interacted with. The first suggested protocol[1], not only required thousands of ideal optical components, but also exhibited a so-called "weak trace" of the particles having travelled from Bob to Alice, calling the counterfactuality and scalability of previous proposals and experiments into question. In our work we overcome these challenges, implementing a new protocol[2] in a programmable nanophotonic processor[3].

In our protocol, one party (Alice) attempts to send particles to a second party (Bob), while Bob sends a message to Alice. The protocol uses a series of N beamsplitters with reflectivity $R = \cos^2(\pi/2N)$, which, together with mirrors, form a circuit of $N-1$ chained Mach-Zehnder interferometers (MZIs). One of the mirrors in each MZI sits in Bob's laboratory, and by choosing to remove (or not) these mirrors, he can control whether or not the photon returns to Alice's laboratory. Crucially, the photon only returns to Alice when Bob removes the mirrors, collapsing the part of the photon wavefunction that enters his laboratory. This means that there is no way for the photon to travel from Bob and back to Alice, ensuring that the communication is counterfactual.

We implement this protocol in a state-of-the-art silicon-on-insulator waveguide[3], operating at telecom wavelengths. The device consists of 88 MZIs each accompanied by a pair of thermo-optic phase shifters that facilitate full control over the internal and external phases of the MZIs. The fully tunable MZIs can be used to implement the mirror and beamsplitter operations used in the protocol. The single photons are generated using a spontaneous parametric down-conversion source operating at telecom wavelengths.

For finite N there is a small probability ($P_{err} = 1 - \cos(\pi/2N)^{2N}$) for a photon to exit the wrong port when Bob tries to send a logic 1. In the case of the logic 0 the communication can in principle succeed every time, but finite interferometric visibilities lead to cases in which the photon re-enters Alice's laboratory and she incorrectly records a logic 1. This leads to a counterfactual violation, as the wavefunction "leaks" from Bob's to Alice's laboratory. We overcome bit errors in the communication by encoding each logical bit into M single photons.

Experimental results for the case $N = 6$, the highest number of consecutive beamsplitters we can implement using our waveguide, are shown in Fig. 1. The high fidelity of the MZIs in our waveguide allow us to keep the average counterfactual violation probability at 1.3 % while repeating each bit enough times to overcome the losses in our system. This is the first demonstration of a counterfactual communication protocol that does not leave a weak trace.

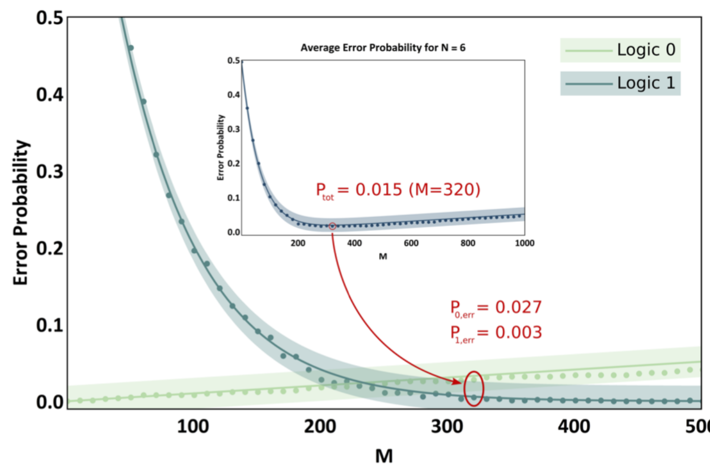

FIG. 1. **Success and CFC violation probability.** The curves are theoretical models of our experiment with no free parameters, and the points are experimental data. The figure shows the bit error probabilities for the two logical bits, while the inset shows the average bit error probability. The high interferometric visibility of the waveguide means that the error in the logic 0 only grows linearly even for quite large M, which allows us to reduce the average error while keeping the probability of a counterfactual violation low. In the $N = 6$ case, we achieve an average bit error rate of 1.5 % for $M = 320$, where the average CFC violation probability remains as low as 1.3 %.

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