Symmetrical Clock Synchronization with Time-Correlated Photon Pairs

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Abstract: We demonstrate a distance-independent clock synchronization protocol, using counter-propagating photons from spontaneous parametric down-conversion pair sources, secure against symmetric-delay attacks. With rates of 200 coincidences/s, we record a precision of 51 ps over 100 s.

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1. Introduction

Clock synchronization is crucial to the functioning of modern infrastructure. Despite its fundamental role, communication between clocks remain susceptible to disruption and manipulation [1, 2]. We present a distance-independent synchronization protocol based on a symmetric distribution of single-photons between remote clocks. Tight time correlations of the photon pairs generated by spontaneous parametric down-conversion (SPDC) enables precise synchronization. Similar to existing bi-directional protocols [3], the determination of the clock offsets is independent of the signal propagation times for a symmetrical communication channel. Our protocol, based on existing quantum communication techniques, provides a natural complement to Global Navigation Satellite Systems (GNSS) for quantum key distribution [4, 5], and is suited for synchronization between mobile stations where pair rates are typically low and propagation times are constantly changing. The single-photon regime allows, in principle, an additional security layer by distributing polarization entanglement and using a Bell measurement to verify the origin of the photons.

2. Experiment

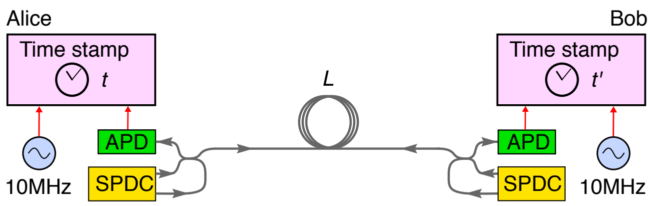

Fig. 1. Clock synchronization setup. Alice and Bob each have a source of time-correlated photon pairs produced from spontaneous parametric down-conversion (SPDC) and an avalanche photodetector (APD). One photon of the pair is detected locally, while the other photon is sent through a single mode fiber of length L to be detected on the remote side. Times of arrival for all detected photons are recorded at each side with respect to the local clock.

The experimental setup is shown in Fig. 1. Each of two parties, Alice and Bob, transmits photons from time-correlated photon pairs produced from SPDC to the other party through a shared optical channel. Each party time-stamps detection events according to a local clock and shares the time stamps over a classical channel. A histogram of the time difference between detection events at Alice and Bob shows two peaks centered at times τ_{AB} and τ_{BA}, from which it is possible to derive the time offset between the two clocks δ and a round-trip time for the photons ΔT

$$\delta = \frac{1}{2}(\tau_{AB} + \tau_{BA}) \quad \text{and} \quad \Delta T = \tau_{AB} - \tau_{BA} . \tag{1}$$

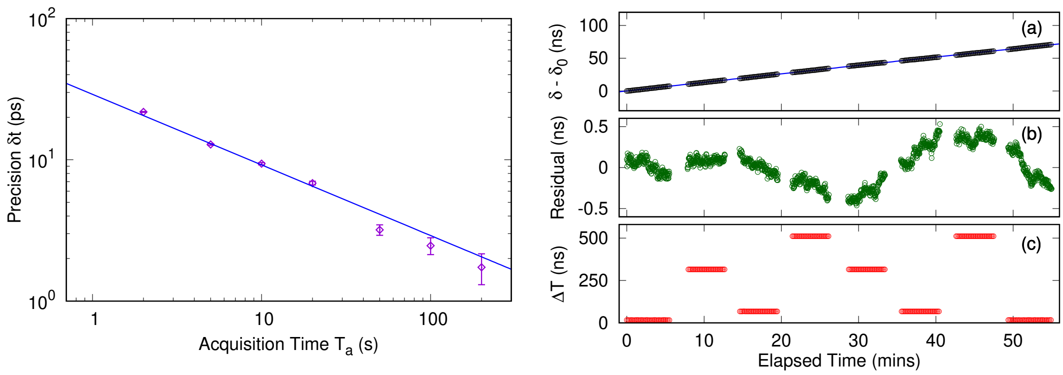

Fig. 2. Left: Standard deviation (precision δt) of the measured offset between two clocks, both locked to the same frequency reference. Solid line: Least-squares fit to a model where δt follows Poisson statistics and improves with acquisition time T_a. Right: (a) Measured offset δ between two clocks with independent frequency references, with respect to the initial measured offset δ_0. Each point corresponds to a 2 s acquisition time. Continuous blue line: fit used to extract the relative frequency accuracy ($\approx 4 \times 10^{-11}$) between the clocks. (b) Residual of the fit fluctuates due to the intrinsic instability of the individual frequency references. (c) The round trip time ΔT was changed using different fiber lengths.

3. Results

To demonstrate the independence of the synchronization from the propagation distance, we initially characterize the precision of the offset estimation δt when both parties share a rubidium frequency reference. The precision δt depends on detector time jitter and, for constant pair rate, scales with the total acquisition time, as in Fig. 2 (left).

For a more realistic synchronization scenario, each party uses an independent frequency reference, resulting in a clock offset that changes with time $\delta \to \delta(t)$. We simulate a symmetric-channel-delay attack by changing the propagation time between Alice and Bob every 5 mins using four fibers of different lengths. The measured offset $\delta(t)$, evaluated from time stamps collected every $T_a = 2$ s, tracks the drift between the two frequency references (Fig. 2 (right, a)). The clock drift is well approximated by a parabolic model that we estimate and subtract from the measured $\delta(t)$. The remaining fluctuation (Fig. 2 (right, b)), does not show any significant correlation with the estimated propagation time (Fig. 2 (right, c)), proving the resilience of the protocol against symmetric-channel-delay attacks. These fluctuations are mainly due to the intrinsic frequency instabilities of the frequency references, resulting in the slightly reduced synchronization precision of 51 ps in 100 s, comparable with the Allan deviation of our clocks ($< 2 \times 10^{-12}$).

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