Long-distance measurements for quantum communication

Picosecond-accurate stable measurement of correlated signals with two Time Taggers over a distance of 13 kilometers

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In quantum key distribution, quantum teleportation and superdense coding, entangled photon pairs are usually detected at locations that can be separated by several kilometers. For quantum key distribution, in particular, this places high requirements on the accuracy of the time-of-arrival-measurement of the correlated photons. To ensure a low error rate of the generated key, arrival times on both sides must be measured with very high relative accuracy and without temporal drift over long stretches of time. Here, we show how this can be achieved with our Time Taggers by distributing a common clock signal alongside the correlated photons. With this, we demonstrate time-of-arrival measurements with a relative timing uncertainty of just a few picoseconds over a distance of 13 kilometers. We also show that stable operation can be achieved over several hours without the need for intermediate resynchronization.

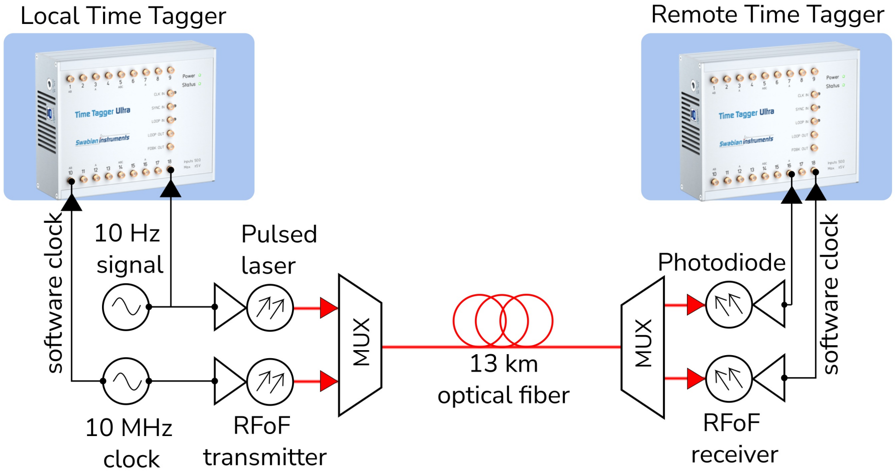

Figure 1. Setup for measurements with two Time Taggers separated by 13 km of optical fiber.

MEASUREMENT SETUP

Fig. 1 shows the setup for time-of-arrival measurements with two Time Tagger Ultra, that are separated by a 13 km long single mode optical fiber. Both Time Taggers are operated in the high-resolution mode (HighResB) and individually have a per-channel timing resolution of 4 ps (RMS jitter). To achieve a common stable time base, a 10 MHz clock signal is shared between the two Time Taggers. The clock signal is generated by a Rubidium clock (Stanford Research Systems FS725) and connected to the input ports of both Time Taggers. By using the Time Tagger's software clock feature, the 10 MHz signal is used as the time base for both devices. To transmit the clock signal to the remote Time Tagger, an RF-over-Fiber (RFoF) converter (RFOptic Programmable 2.5GHz RFoF) is used that transforms the clock signal into an optical signal and sends it through the optical fiber. On the remote site, the optical signal is transformed back into an electrical signal. Transmitter and receiver of the RFoF converter operate at an optical frequency of 1310 nm. The time-of-arrival measurements are performed with a separate 10 Hz signal that is generated by a laser driver. This signal is used to modulate the output of a pulsed laser (LDH-P-F-N-1550) operating at a wavelength of 1550 nm. For the local Time Tagger, the 10 Hz signal is fed from the laser driver's sync output to the Time Tagger's input port. For the remote Time Tagger, the modulated optical signal is injected into the single mode fiber. On the remote site, the signal is separated from the clock signal by a wavelength division multiplexer (MUX), detected with a photodiode and connected to the Time Tagger.

RESULTS

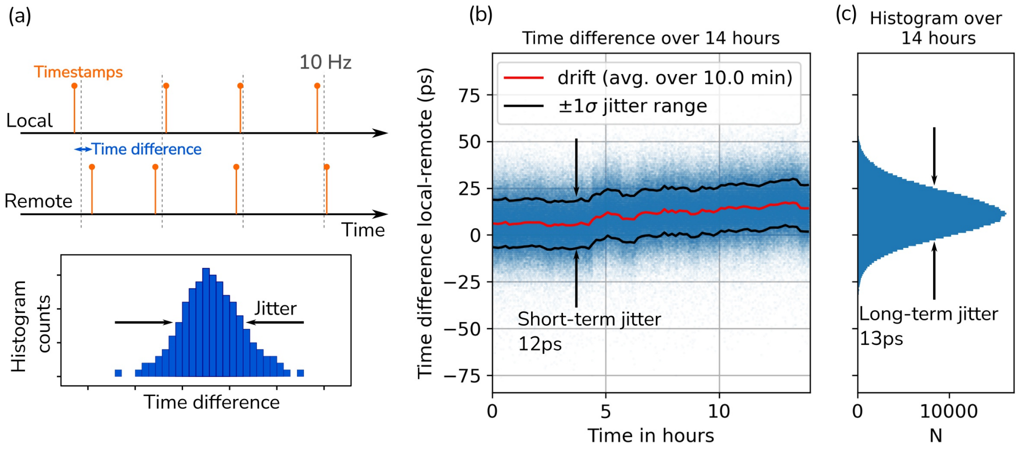

Figure 2. Measurement of relative timing accuracy over 14 hours of operation.

Fig. 2a shows a sketch of the time-of-arrival measurement and the determination of the relative timing accuracy. On the local and the remote Time Tagger, timestamps are created from corresponding pairs of rising edges of the shared 10 Hz signal, where noise and drift introduce timing jitter. For each pair of timestamps, the resulting time difference between both sides is measured. From a histogram of these time differences, the average relative timing accuracy is then determined, where the RMS jitter denotes the standard deviation of the distribution. Fig. 2b shows all timing differences over a measurement duration of 14 hours. We analyze the short-term jitter over time windows of 10 minutes as well as the long-term drift. The short-term jitter is 12 ps and the average time difference drifts by a maximum of 12 ps during the measurement. Fig. 2c shows the corresponding histogram of the time differences over the entire 14-hour time window. Compared to the short-term jitter, the drift causes an additional widening of the distribution with a long-term jitter of 13 ps.

	Single Time Tagger	**2 Time Tagger with 2m optical fiber**	**2 Time Tagger with 13 km optical fiber**
Short-term RMS jitter	*5 ps*	*8 ps*	*12 ps*

Figure 3. Relative timing accuracy for different measurement configurations.

To understand how the long distance between both Time Taggers influences the timing resolution, we compare the short-term jitter between different measurement configurations in Fig. 3. When measuring the time differences with a single Time Tagger, the short-term RMS jitter is 5 ps, which corresponds to the two-channel time resolution of the Time Tagger Ultra. When measuring the timing jitter between two Time Taggers with 2 m of optical fiber in between, the short-term RMS jitter increases to 8 ps. This reflects the additional noise of the RFoF converter as well as the jitter between two Time Taggers. When increasing the length of the fiber to 13 km, the additional attenuation and thermal fiber instabilities increase the jitter by just 4 ps, hence demonstrating that the picosecond timing precision of the Time Tagger can be maintained even over long distances.

The distribution of a stable clock signal with an RFoF converter combined with the Time Tagger's software clock feature and its inherent low jitter thus makes the Time Tagger an ideal tool for quantum communication, as well as other applications requiring long-distance correlation measurements.