1 Reviewer 1

In this manuscript, the authors demonstrate a point-to-point clock synchronization system based on SPDC photon source which has fewer single photon detectors and SPDC sources. The authors realize the implementation of clock synchronization with independent clocks over 10km fiber, and analyze the performance and security of the system. The performance analysis is comprehensive and seems correct to me. However, this manuscript lacks comprehensive theoretical derivation and simulation, and the security analysis is unclear, which makes me confused about which physics to study. Specifically, there are several points that I do not understand. The followings are my questions and comments on the paper.

1. The manuscript uses fibers of different lengths to simulate symmetric channel delay attack. However, the potential symmetric channel delay attack may change the length of fiber rapidly. Is that means this clock synchronization system cannot defend all kinds of symmetric channel delay attack? How to analyze this problem theoretically?

Ans: The symmetric delay attacks demonstrated in our paper focused on attacks that introduced different, but largely stationary symmetric delays at various intervals. A similar focus can be found in Ref. 7.

An analysis on an attack where the symmetric channel delay changes rapidly with speed v involves considering the associated change to the autocorrelation peak position τ_{AA},

$$\Delta\tau_{AA} = 2vT/u, \tag{1}$$

where T is the measurement time required to achieve a desired precision

$$p = \frac{\sigma}{\sqrt{RT}}, \tag{2}$$

where R is the rate of autocorrelation events detected at Alice, σ is the standard deviation of the autocorrelation distribution, and u is the propagation speed of the photon in the fibre.

To remain in the pseudo-stationary regime, we require that the overall peak drift $\Delta\tau_{AA}$, due to changing delays and the relative frequency inaccuracy between the clocks d, is much smaller compared to the peak width:

$$2vT/u + dT < \sigma. \tag{3}$$

This inequality sets the maximum detectable speed v for accurately measuring τ_{AA}. A full analysis involves a similar treatment for measuring the single-trip time τ_{AB}.

We note that, beyond the context of a symmetric delay attack, the value of a distance independent clock synchronization scheme is also valuable in contexts where the distance is practically stationary, since it removes the requirement of obtaining the physical seperation between the clocks with an independent measurement scheme.

2. The manuscript mentions that the synchronization channel must not be asymmetrically manipulated, which seems easy to be realized, such as using an optical circulator.

Compared to classical clock synchronization system, what are the advantages (or potential advantages) of this quantum clock synchronization system?

Ans: One main disadvantage that a classical clock synchronization scheme has yet to solve is that of authenticating whether the synchronzation signal was delayed during an intercept, delay and resend attack. The resent signal can have the same cryptographic characteristics as that of the genuine signal, the only difference being that it is received with a (possibly small) additional delay, then classical synchronization techniques are unable to detect this attack [1,2]. However, such an attack will not work in this quantum clock synchronization scheme as intercepting, delaying and resending the photon will degrade the entanglement between distributed photon pairs.

While we have highlighted that this quantum clock synchronization scheme remains vulnerable to an attack that does not alter the quantum state of the photons, such as an asymmetric delay attack using polarization-independent optical circulators, the scheme is nonetheless more secure against intecept, delay and resend attacks, compared to classical schemes.

3. In figure 3, the solid lines are generated by 'heuristic model' or 'empirical model'. How does the model work?

Ans: The solid lines are obtained by interpolating the datapoints of the photodetection time-difference histograms, associated with the single-trip and round-trip propagating photons, as described in line 80-81. The model is used to fit subsequent histograms in order to extract their peak positions.

For example, the autocorrelation peak $R(\tau)$ associated with the round-trip photons can be modeled by $R(\tau) = a_0 + a_1 r(\tau - \tau_{AA})$, where a_0 is the background coincidence, a_1 is an amplitude related to the total number of self-correlation events registered at Alice's detector, and τ_{AA} the peak position. The heuristic model $r(\tau)$ is centered at $\tau_{AA} = 0$.

For each autocorrelation peak obtained by histogramming the photodetection time differences at Alice's detector, a least-squares fitting algorithm is used to fit the data to the model in order to extract τ_{AA}. A similar process is used to determine the peak position for the cross correlation peak. We note that the fitting process is similar to that used in Ref. 6 where it is described in detail.

4. Compared to other existing quantum clock synchronization systems, does this system has a higher theoretical or experimental performance?

Ans: The system in this work, which used one time-correlated pair source, has a comparable experimental performance to the two-way clock synchronization scheme performed in Ref 6. using two time-correlated pair sources. In both experiments, the synchronization precision over 100 s is limited by the intrinsic instability of the Rubidium frequency references used.

2 Reviewer 2

The authors demonstrate a technique based on the measurement of correlated photons for the synchronization of clocks. The presented idea is interesting and the model is easy to understand. However, the article has some points that haven't been interpreted clearly, here I have addressed my comments as follows.

1. The author motivates their work by pointing out that only one entangled source is required and the protocol is a distance-independent synchronization of remote clocks. While the results of the manuscript show that the clock offset has a dependence on the distance by a factor of 4×10^{-4}, which is a little confused: in two-way time transfer protocol where the wavelengths of the travel lights in the two directions is slightly detuned, there is an extra time bias caused by the wavelength difference; in this article, it is the same path of photons which experience the round trip and single trip travel, and the propagation time of half the roundtrip and the whole single trip could therefore be eliminated in the clock offset measurement, is it related to polarization-dependent delay?

Ans: We highlight that 4×10^{-4} is the ratio between the additional single-trip delay due to an additional 10 m of fibre (48.3 ns), and the residual mean offset measured between the clocks (19 ps).

We do not observe a correlation between the residual mean offset and single-trip delay, as was suggested by the reviewer. This is evident from the mean offsets $\bar{\delta} - 24(17)$ ps, and $\bar{\delta} + 20(20)$ ps measured when $L = L_0 + 1$ m and $L_0 + 10$ m, respectively (line 113). Moreover, we observed a continuous, gradual change in the offset measurement even when L changed abruptly during the the symmetric delay attack (Fig. 5).

Given the evidence so far, and given that both timestamp units were disciplined to the same Rubidium oscillator over the entire measurement duration in Fig. 5, it is plausible that the remaining continuous offset drift can be attributed to the long-term instability of the timestamp units. e.g. fluctuating timestamp unit accuracy due to the non-uniformity of implementing timestamping bin-widths, varying as a function of operation time and temperature.

2. line 130, the author declares that with two independent Rb clocks, the continuous trend of the measured $\sigma(t)$ indicates the delay attacks were ineffective. This result is also not obvious, the fluctuation of the independent clocks is much larger than that caused by the distance variations of several tens of picoseconds, as shown in Fig. 5. The author should investigate and clarify this, as the security capacity against symmetric channel delay attacks is one of the major contents in the article.

Ans: We believe that the reviewer made an incorrect observation: In Fig. 5a, the measured offset between the independent clocks has a standard deviation (fluctuation) of 26 ps (line 114), whereas in Fig. 5b, the round-trip time changed by much more than a nanosecond., which is much larger than the fluctuation.

3. line 138, with two independent Rb clocks, the time deviation =88 ps in 100s has been reported, the author contributes the result to the clock instabilities, however, in Ref. 6, the author also reported time deviation =45 ps in 100 s with two independent Rb clocks,

the reason of almost doubled deterioration should be given, maybe it is related to the few photons of the round trip? as from Fig. 4 the results with common clocks are also at the level of ten picoseconds?

Ans: We attribute the difference to the fact that the Rubidium clocks used between the two papers were not the same pair of clocks – both experiments were performed two years apart with different pairs of clocks, albeit the same model. The relative frequency intability between two pairs of clocks of the same model will differ, but will be within manufacturer's specifications.

2.1 Minor issues

1. The transmission media should be pointed out in the title ".....over 10 km" for clarity.

Ans: We have updated the title to include the transmission media.

2. line 32, Ref. 9 synchronize two independent clocks of H maser and Rb clock, not two Rb clocks.

Ans: We have made the necessary corrections in the text "With independent hydrogen-maser and rubidium clocks as references...".

3. line 86, the authors state '100 s of timestamp data', however, in the caption of Fig. 3, they extract the timestamps over 90 s, it is confused which one is used in the experiment.

Ans: We thank the reviewer for pointing out the typological error. The timestamp data was recorded for 100 s. We have made the appropriate change to the caption in Fig. 3.

3 Summary of changes

1. Title was changed from "Absolute clock synchronization with a single time-correlated photon pair source over 10 km" to "Absolute clock synchronization with a single time-correlated photon pair source over a 10 km optical fibre"

2. line 32-33: "With two independent Rubidium (Rb) clocks as reference" was changed to "With independent hydrogen-maser and rubidium clocks as references"

3. Fig. 3. caption: "timestamps acquired over 90 s" to "timestamps acquired over 100 s".

References

[1] Narula, Lakshay, and Todd E. Humphreys. "Requirements for secure clock synchronization." IEEE Journal of Selected Topics in Signal Processing 12, no. 4 (2018): 749-762.

[2] Dai, Hui, Qi Shen, Chao-Ze Wang, Shuang-Lin Li, Wei-Yue Liu, Wen-Qi Cai, Sheng-Kai Liao et al. "Towards satellite-based quantum-secure time transfer." Nature Physics 16, no. 8 (2020): 848-852.