White Rabbit-assisted quantum network node synchronization with quantum channel coexistence

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Abstract: We show that the Ethernet-based time transfer protocol 'White Rabbit' can synchronize two distant quantum-networked nodes to within 4 ps, enabling HOM interference at >90 % visibility using 17.6 ps FWHM single-photons coexisting with White Rabbit.

1. Introduction

The Hong-Ou-Mandel (HOM) interference effect lies at the heart of future quantum networking protocols such as entanglement swapping and teleportation. For these protocols to entangle two distant quantum network nodes, a photon from each node must arrive at a third node within a fraction of their coherence time. Both nodes, which may be kilometers apart, therefore need to be synchronized such that their path length differences to the measurement plane are known and compensated for. Photon coherence times vary depending on the physical implementation of the qubit system from several nanoseconds (ns) in certain quantum memories to picoseconds (ps) or even femtoseconds (fs) using spontaneous parametric down-conversion (SPDC) sources. While matching path lengths to ps is easily achievable in laboratory demonstrations, long-distance fiber network synchronization to ps is a challenging task. Here, we show how Ethernet-based time transfer protocols such as White Rabbit (WR) can be used to synchronize two distant quantum-networked nodes to below 4 ps, sufficient to observe HOM interference with greater than 90 % visibility using SPDC photons with 17.6 ps FWHM coherence times. We also show and demonstrate that, in principle, low-noise quantum channels exist such that the optical WR signal can coexist with the weak quantum signals for synchronization of the actual (rather than adjacent) fiber path lengths to the measurement location.

2. White Rabbit

Developed at CERN, WR provides time and frequency transfer by augmenting the Precision Time Protocol with physical layer frequency syntonization using synchronous Ethernet [1]. Current state-of-the-art commercial WR systems have timing precision (timing jitter) of a few ps [2] and synchronization accuracy (clock offset) of < 1 ns. It is worth noting that a clock offset can be independently measured and compensated by appropriately modifying the path length between the two photon sources or by manually trimming the phase of a local oscillator. Therefore, we are mainly interested in the short-term (~ 1 s) variability, *i.e.* the timing jitter between the leader and follower. Also, in order to compensate for path length changes in the fiber quantum channel during operation, it is ideal to use the WR on the same fiber. Figure 1a shows the measurement setup used to determine the clock offset and timing jitter of two WR synchronized nodes arranged in a leader-follower pair. The leader is phase aligned and driven by a stable rubidium (Rb) oscillator at 10 MHz. The follower in turn employs WR to establish a local 10 MHz pulse train that is phase synchronized to the leader. Both 10 MHz outputs are connected to a low-jitter (1.5 ps RMS) time-tagger with time tags recorded every 100 ns. Figure 1b shows our verification of quantum/WR coexistence.

3. Results

Coexistence: To assess the coexistence of quantum and WR signals in the same fiber, we use the setup shown in Fig. 1b. A CWDM mux/demux isolates one of the WRs from the C-band, and a 1547.72 nm (C37) channel is the designated quantum channel while the other WR is isolated from C37 with a much narrower fiber Bragg grating. A 50:50 fiber beamsplitter (FBS) probes noise without disrupting the WR protocol. Channel C37 is selected by a dual-pass DWDM and a 1 nm volume Bragg grating to ensure $>10^{12}$ suppression of background light at other wavelengths. In a direct configuration, the WR leader is behind the CWDM (Fig. 1b), and in a reverse configuration the WR follower is behind the CWDM (Fig. 1b right inset). With two WRs separated by a short fiber we observe <10000 photons/s of background. When a long spool of fiber is inserted before the FBS the amount of noise significantly increases and is directly proportional to distance (Fig. 1b left inset). We acquired initial experimental evidence that in both configurations this noise is mainly due to Raman scattering of the WR pulses at 1490 nm and can be addressed by choosing a pair of lower wavelengths for WR communications. The complete WR synchronized network with coexisting quantum channels will require symmetric CWDM mux/demux filtering as shown in Fig. 1b at both WR nodes where quantum channels are added/dropped to a CWDM 1550 channel.

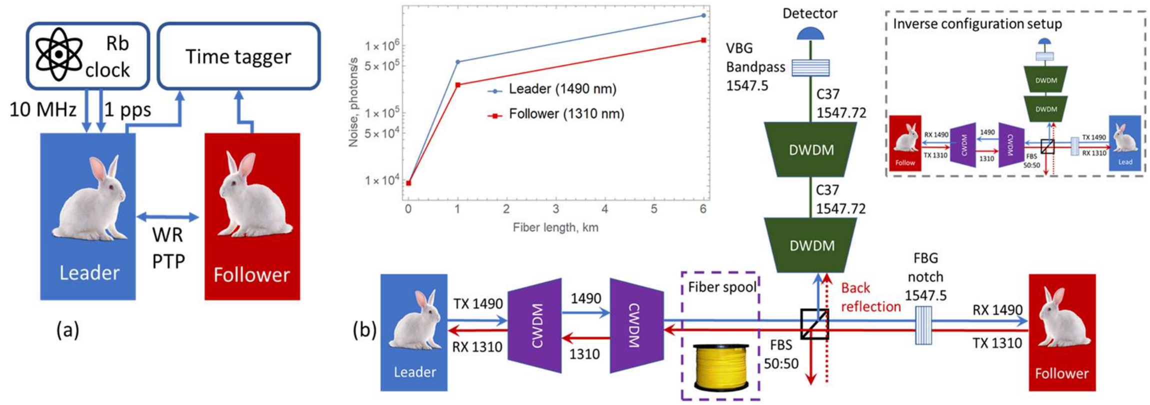

Figure 1. (a) White Rabbit leader-follower scheme. (b) Noise measurements setup and results in a quantum channel at 1547.5 nm, coexisting with the WR synchronization signals at 1310 nm and 1490 nm in the same fiber. Right Inset: The same setup, reversed. Left Inset: Background photons vs fiber length. Measured number of photons is adjusted for nominal loss in optical components.

Synchronization: The synchronization measurements were repeated for both a leader-follower pair of 'low-jitter' and 'standard-jitter' WR nodes. The time deviation (TDEV) is plotted as a function of averaging time in Fig. 2a, including when the coexistence setup was integrated. The standard WR system shows a minimum shot-to-shot precision at around 10 ms averaging time (TDEV = 9 ps), while the low-jitter WR system shows a shot-to-shot TDEV of about 3 ps at 10 ms averaging time. However, the minimum precision of the low-jitter system is less than 4 ps at about 1 ms averaging time. Figure 2(b) shows the simulated HOM interference between two photons with timing uncertainty based on the raw time-tag data for the standard WR without background noise (black line) and with added background noise as established from the 1 km coexistence study (red line). The dashed black line shows the optimal HOM interference without noise or timing jitter. We assumed a 17.6 ps coherence time photon pair with a center wavelength around 1550 nm generated via SPDC. The choice of the 17.6 ps coherence time is related to the standard ITU channel bandwidth of 50 GHz. The apparent HOM visibility is higher than 90 % for the standard-jitter WR system. Note that the coherence time can be longer and still pass through the DWDM, therefore possibly reaching even higher HOM visibility.

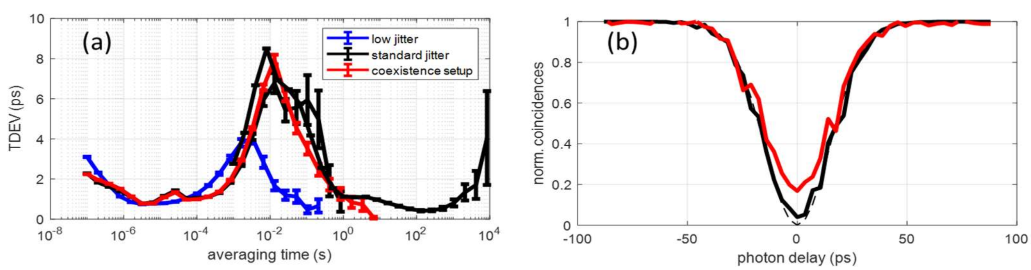

Figure 2. (a) White Rabbit TDEV vs. averaging time for the low-jitter (blue), the standard-jitter system (black) and the integrated coexistence setup (black), respectively. (b) simulated HOM interference for the standard White Rabbit system with/without background noise (red/black line) and without jitter or noise (black dashed line)

We have demonstrated two distant nodes synchronized to <10 ps with a coexisting quantum link and have measured the noise induced by the classical signals. Coexisting propagation of classical and quantum signals in the same fiber may enable observation of HOM between remote sources with high visibility and can be used to preserve coherence between faint quantum signals by phase drift tracking and compensation.

4. References

[1] Lipiński, M., Włostowski, T., Serrano, J., & Alvarez, P. (2011, September). White rabbit: A PTP application for robust sub-nanosecond synchronization. In 2011 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control and Communication (pp. 25-30). IEEE.

[2] Rizzi, M., Lipinski, M., Ferrari, P., Rinaldi, S., & Flammini, A. (2018). White rabbit clock synchronization: Ultimate limits on close-in phase noise and short-term stability due to FPGA implementation. IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 65(9), 1726-1737.