Picosecond Clock Synchronization Across a 7-node Metropolitan Scale Quantum Network

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ABSTRACT

Quantum networking protocols relying on interference and precise time-of-flight measurements require high-precision clock synchronization. This study describes the design, implementation, and characterization of two optical time transfer methods in a metropolitan-scale quantum networking research testbed. The first technique called active electronic stabilization (ELSTAB), was able to achieve sub-picosecond time deviation (TDEV) at integration times between 1 s and 10^5s over multiple different fiber lengths of both underground and aerial deployed fiber. The second technique, White Rabbit-Precision Time Protocol (WR-PTP), was able to achieve 10-picosecond TDEV's over similar fiber lengths at comparable integration times. Environmental fluctuations affected the stability of clock synchronization over deployed fiber. These fluctuations resulted in path delay gradients, chromatic dispersion, polarization drift, and optical power variations. The results from this study will inform future work in the development of compensation methods essential for enabling experimental research in developing practical quantum networking protocols.

Keywords: quantum, quantum communication, quantum networking, time synchronization

1. INTRODUCTION

The potential benefits of quantum networks include theoretically secure quantum key distribution,[1] distributed quantum sensing[2] and computing,[3] and secure clock synchronization.[4,5] High-precision time and frequency synchronization enables fundamental quantum networking capabilities from measuring the indistinguishability[6] of sources to entanglement distribution[7–9] and swapping.[10–12] High-precision clock synchronization is sufficient to support near-term point-to-point quantum communications. As networks scale, the protocol requirements for high-accuracy time synchronization could evolve. Time transfer needs for quantum networking research include the ability to integrate into existing telecommunications infrastructure, co-propagation of quantum and classical signals,[13–16] scalability, resilience, and security. As single photon pulse durations can vary from nanoseconds to the femtosecond regime using ultrashort lasers, our initial goal is to achieve 10^{-11} s time deviation (TDEV) at one second integration time to enable delivery of entangled photons to distant nodes.[17,18] Optical two-way time and frequency transfer (OTWTFT) over fiber can achieve the initial testbed requirements,[19–23] including the standards-based White Rabbit–Precision Time Protocol (WR-PTP)[24–26] and the electronically stabilized (ELSTAB) OTWTFT[27–31]

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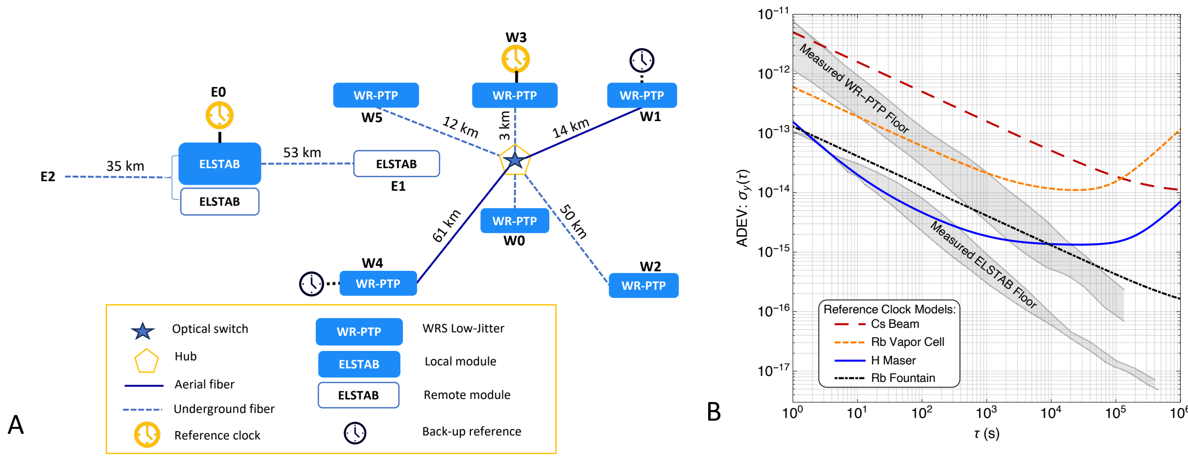

Figure 1. (A) The electronically stabilized (ELSTAB) and White Rabbit-Precision Time Protocol (WR-PTP) time and frequency transfer methods are deployed as two separate networks in the DC-QNet. E0 through E2 denote the locations of the ELSTAB modules. W0 through W5 denote the locations of the WR-PTP switches. WR-PTP communications pass through the optical switch (links are connected to a point on the star) or are directly connected (links start at a point on the pentagon) at the hub for the tests. (B) Fractional frequency instability models of atomic clocks and optical two-way time and frequency transfer (OTWTFT) methods in the DC-QNet with the measured noise range of the WR-PTP and ELSTAB devices included.

2. TIME SYNCHRONIZATION FOR DC-QNET 7 NODE NETWORK

Several groups are currently developing metropolitan-scale quantum networks.[23,32–36] As an emerging testbed to advance research in quantum network metrology and protocols, the Washington DC Metropolitan Quantum Network (DC-QNet) comprises seven locations with deployed underground and aerial optical fibers (Fig. 1A). Fig. 1B models the fractional frequency instability of the atomic clocks and the two OTWTFT methods integrated into the DC-QNet, each with their benefits and limitations. WR-PTP has been employed in various quantum network testbeds ranging from laboratory to metropolitan-scales.[13,33,37,38] Here, we configure White Rabbit Switches (WRS)[*] in a star topology where a centrally located reference clock (W3) synchronizes multiple WRS (Fig. 1A). For each of the links, WR-PTP was deployed over two separate fibers operating at identical optical wavelengths, using the dense wavelength division multiplexing (DWDM) either at wavelength 1539.77 nm or at 1541.35 nm. To design and demonstrate a communications network that can co-propagate with quantum signals in the low-loss C-band, we also implemented a single-fiber bi-directional synchronization architecture using coarse wavelength division multiplexing (CWDM) transceivers at 1270 nm and 1290 nm. Transceiver wavelength is chosen depending on the wavelength of the quantum source and noise that is generated from the interaction between classical light and fiber. For shorter distances, sources that operate in the telecommunication O-band are preferred due to the small amount of noise that leaks into that band.[39] However, at larger distances, losses are greater for O-band, so rather than accept those losses in the quantum channel, we choose the 1270 nm/1290 nm transceivers which produce small amounts of noise in the C-band.[15]

2.1 Sub-10ps Time Synchronization Over Deployed Fiber

One of the goals for this work was to achieve high stability time synchronization across all nodes of the network which is necessary for current quantum networking protocol research and development. Given that we want to accomplish this over optical fiber and we also want to coexist classical and quantum signals on the same fiber, that accuracy is 10 ps to 40 ps for distances from 10 km to 100 km.[14] The TDEV's reported in Fig.2 show that we are able to achieve this goal.

[*]Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, the Department of Defense, or the National Aeronautics and Space Administration, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

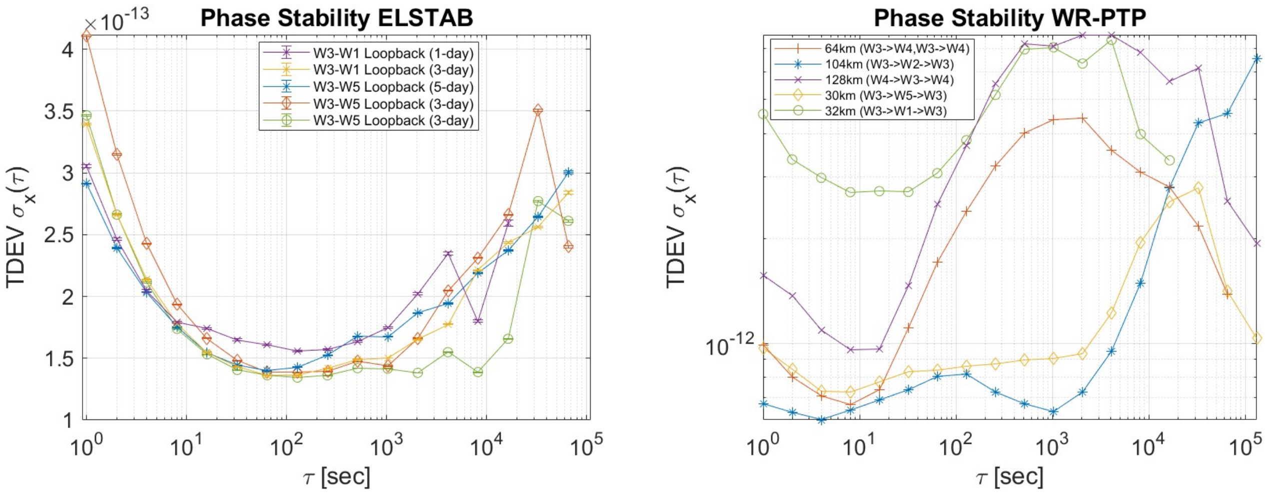

Figure 2. TDEV for various DC-QNet two-way time transfer deployments looking at both the ELSTAB and WR-PTP methodologies. (left) ELSTAB measurements were a simple loopback with the local and remote units located in the same lab where the time tagger was located. (right) WR-PTP measurements used an out and back technique, starting with one local device, connected to a remote device over deployed fiber, then routed back to a second local device over a second deployed fiber, in order to compare the two local devices with a time tagger. Each distribution technique is referenced to the same Cesium clock (measurements were not taken over the same time period).

Comparing the fiber paths as illustrated in Fig.1 to the resulting TDEV's in Fig.2 (left), we observed with active compensation, the phase stability remained similar for both underground, more environmentally stable, and aerial links. Additionally, this sub 10 picosecond accuracy was possible over large integrations times, up to 10,000 seconds on our noisiest fiber link. Although, for WR-PTP (Fig.2 (right)), phase stability varied much more between aerial (green) and underground links (blue), we still observed TDEV's less than or equal to 40 ps.

2.2 Environmental Effects On Phase Stability

Environmental conditions can have a large impact on the stability of each of the two methods of time transfer. We found that fibers that are exposed to the elements are significantly more susceptible to degradation in clock synchronization, as should be expected. This is most evident when you look at the TDEV of our fiber link with the most aerial fiber, the green line of Fig.2 (right). We can also see this more directly if we look at the path delay time between two nodes Fig.3. This path delay was calculated using WR-PTP and the air temperature is taken using the approximate GPS coordinates of the site within an area of about 500 m. This is almost a direct correlation between the two. We have also plotted the periods of time when cloud cover (gray) affected the path delay.

Path delay variation is largely due to temperature fluctuations causing the expansion and contraction of the fiber. This is the reason why aerial fibers have a greater tendency to vary. However, stretching fiber also results in greater polarization drift and optical power variation. We found that a combination of optical power fluctuations and temperature variations results in the largest clock synchronization error with regard to WR-PTP. Fortunately, if we wanted to correct for this error, temperature changes are relatively slow, so with the proper compensation scheme we should be able to make improvements.

3. CONCLUSION

Our goal was to achieve picosecond level time synchronization stability across all nodes of the DC-QNet and we were able to accomplish that goal. However, that level of synchronization is not sufficient for all use-cases (e.g. phase stabilization) and can still be improved. We are currently investigating machine learning models that use weather and clock error data for training sets. The hope is that these models can be used to predict sources of clock error that can be used to compensate path delay variations. Additionally, we will be investigating what

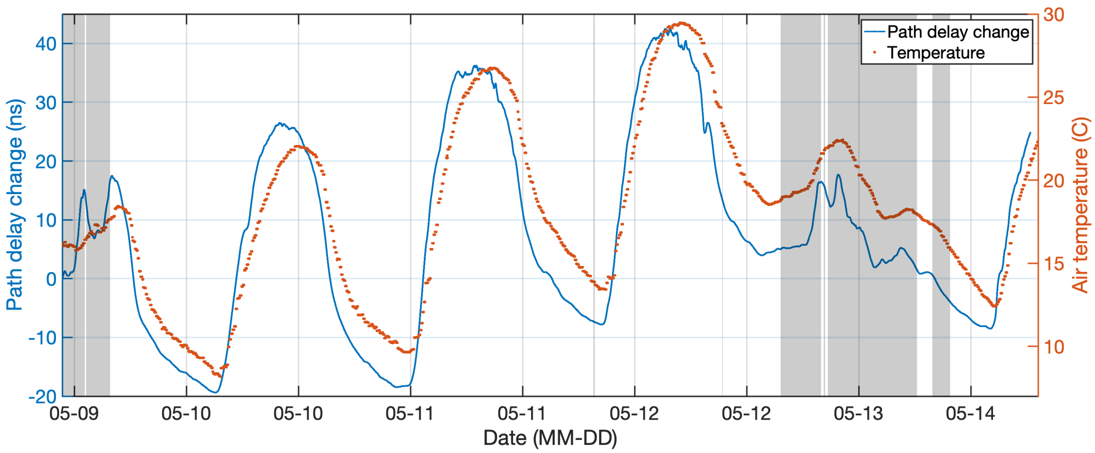

Figure 3. One-way path delay of the W4-W3 link (see Fig.1) with air temperature measured at a weather station located at W4. The shaded areas depict cloud cover.

combination of ELSTAB and WR-PTP is optimal for DC-QNet. ELSTAB is more stable, but it is point to point. Whereas WR-PTP can be dispersed from one reference clock to 18 different WR-PTP enabled devices, but is less stable. Improving stability and understanding the maximum range and flexibility these distinct time transfer technologies remains an active area of research.

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