Delivering 10 Gb/s optical data with picosecond timing accuracy over 75 km distance

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The transfer of very accurate time information over long distances has numerous applications in modern society. Satellite-based links have typically been used so far, but fiber-optical signals can transfer time with increased precision. In this paper, a novel method suited for time transfer employing conventional optical data signals is demonstrated; specifically, transmission of 10 Gb/s signals for up to 75 km over an amplified bidirectional link enabling time transfer with 4 ps accuracy is shown. The very high accuracy achieved and compatibility with existing optical links may allow reliable synchronization of vital infrastructure, and positioning systems with mm-level precision.

Introduction

The dissemination of precise time information and clock synchronization is of fundamental value in modern society. Navigation systems for vehicles and ships, telecommunication networks, systems that handle financial transactions, they all depend on the availability of an accurate timing signal, with more applications being developed [1]. Global Navigation Satellite Systems (GNSS) are arguably the most successful example of a time-dissemination network, providing positioning and timing services across the globe. However, due to its satellite-based nature, GNSS has a number of vulnerabilities (*e.g.* susceptibility to jamming or disruptions due to space weather) that may necessitate a back-up system for critical applications [1]. Moreover, the accuracy achieved by satellite systems is limited to around 1 ns if bidirectional transmission is used [2] and can be as low as tens of ns for commercial receivers.

Fiber-based timing dissemination systems can provide a back-up solution for GNSS that is virtually free from interference (natural or man-made), and at the same time considerably increase the timing accuracy. Optical frequency transfer over 1840 km of fiber [3] and time transfer with offsets as low as 35 ps over 480 km [4] has been demonstrated. However, such methods use either ‘dark’ fiber (a dedicated fiber link for time/frequency transfer) or a ‘dark’ channel (a dedicated wavelength), which means that significant capacity is being lost for data transfer. It would be preferable and more cost-effective to implement simultaneous data and time transfer. The most sophisticated approach in this respect is the White Rabbit Ethernet project, which combines 1 Gb/s data transfer with a precision below 1 ns for links up to 10 km [5].

In this paper, a novel method of determining delay times in optical links (the key step to implementing time transfer between clocks) using typical optical data signals that is scalable in both bit rate and link length is proposed and demonstrated for 10 Gb/s signals and 25, 50 and 75 km links, achieving 4 ps accuracy over only 1 ms of data.

Proposed Method and Experimental Approach

In order to synchronize two clocks that are situated at different locations, typically electromagnetic signals are exchanged between the clocks, the process being known as Two-Way Time Transfer (TWTT). To ensure accurate synchronization, the signal delay between the two locations needs to be known with high precision. A powerful method for estimating time delays between signals is cross-correlation; similar to the technique used in GNSS, we estimate the signal delay in the link by cross-correlating Pseudo-Random Binary Sequences (PRBSs) transmitted using optical signals.

To validate the concept of such a delay-determination method, an experimental set-up was designed and built, shown in Fig. 1. A rubidium (Rb) atomic clock serves as the reference time base. A Bit Pattern Generator (BPG) creates a 10 Gb/s bit stream, a PRBS of 2^{23}-1, which is amplified and used to modulate an optical carrier at 1550.52 nm through on-off keying modulation. Part of the signal at point A (Fig. 1) is fed into a Digital Phosphor Oscilloscope (DPO), which samples the reference, non-delayed electrical signal. The optical data signal is then launched into a fiber spool (25 km long) through an ITU grid wavelength multiplexer. An optical amplification stage is located after the fiber spool; two Semiconductor Optical Amplifiers (SOAs) amplify the downstream and upstream channels, which are separated by demultiplexers. Optical isolators ensure that no back-reflected light enters the amplifiers. After the amplification stage, a short patchcord, a 25 km or a 50 km fiber spool is inserted, enabling measurements over 25, 50 or 75 km links. In the remote end, a receiver consisting of photodiode, a transimpedance amplifier and a limiting amplifier convert the optical signal to the electrical domain. The signal of one of the two outputs of the receiver is sampled by the DPO (point B in Fig. 1), while the second output signal is amplified and modulates an optical carrier at a different wavelength than the downstream channel. The return channel is then launched into the link and is received at point C, where it is also sampled by the DPO.

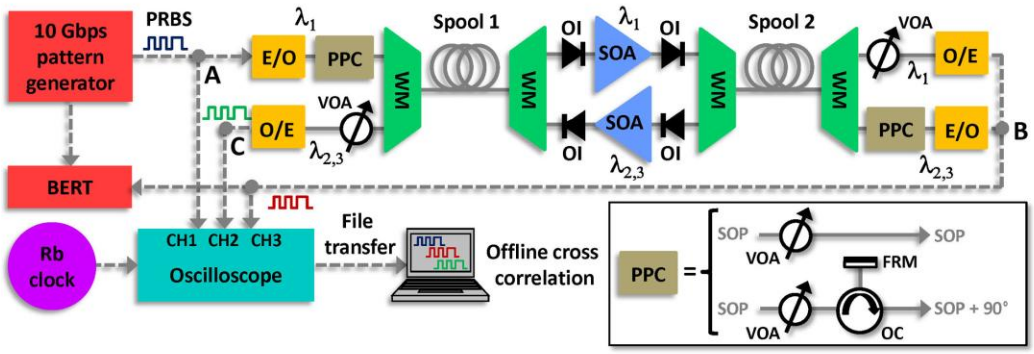

Fig. 1 Experimental set-up

In order to synchronize two clocks located at each end of the optical link, the One-Way Delay (OWD) delay t_{AB} needs to be determined. Since the clock at point B would not be initially synchronized, the OWD has to be estimated using the Round-Trip Delay (RTD) t_{AC}, which can be directly measured. Ideally, the OWD would be the half of the RTD: $t_{AB}=t_{AC}/2$. However, a number of asymmetries are present in the link, which will

introduce a delay asymmetry Δ so that $t_{AB}=(t_{AC}-\Delta)/2$. The delay asymmetry can be further subdivided into the instrument asymmetry, Δ_I, and the link asymmetry, Δ_L. The instrument asymmetry arises from unequal path lengths, electrical or optical, for the downstream and upstream signals in the transceivers and the optical amplification stage. The link asymmetry is a result of the difference in propagation time between the downstream and upstream signals over the common fiber link; the two signals are transmitted over different wavelengths, which results into different propagation speeds due to Chromatic and Polarization-Mode Dispersion (CD and PMD, respectively).
The combined effect of Δ_I and Δ_L can amount to several ns, which means that in order to achieve ps-level precision, the delay asymmetries need to be carefully accounted for. To estimate Δ_I, the fiber spools are removed and the instrument delays, denoted t'_{AB}, t'_{AC} are directly measured. Then, the instrument asymmetry is calculated as $\Delta_I= t'_{AC}- 2t'_{AB}$. The link delay asymmetry, on the other hand, is not so straightforward to calculate. The asymmetry due to CD can be estimated by measuring the dispersion parameters of the fiber. However, the uncertainty in the measurement of the dispersion parameters translates to a total delay uncertainty higher than 10 ps. Moreover, as these parameters change over time due to environmental conditions, the measurements should be repeated periodically. A more accurate method of estimating the delay asymmetry due to CD is to use two different wavelengths for the upstream channel. By combining the delay measurements performed with the two possible wavelength pairs, a very accurate estimate of Δ_L is obtained. The details of the method and the dispersion model used here will be presented in a longer manuscript. The asymmetry caused by PMD, which is statistical in nature, is estimated by performing a second set of measurements where the input State Of Polarization (SOP) of the optical signals is rotated by 90^0. This is accomplished by inserting a circulator and a Faraday mirror in the set-up, as is shown in Fig. 1. The full PMD analysis is also to be expanded on in a longer manuscript.

Results and Discussion

By propagating the uncertainty introduced by all the parameters involved in the estimate of the OWD of the link, with the most important ones being the uncertainty in Δ_I, the time base stability of the DPO, the error in determining the peak of the correlation spectrum and the estimation of PMD, the total time uncertainty of the system can be calculated. The error propagation described above yields a system-level uncertainty of 4 ps. To assess the performance of the delay estimation method, the estimated OWD, θ_{AB}, is compared with the directly measured t_{AB} for different link lengths, with the results (including the uncertainty) shown in Fig. 2b-d. It is observed that all 24 estimates are within ±5 ps of the measured delay, while 20 of them are within ±4 ps, confirming the very high precision allowed by the method. Moreover, there is no sign of increasing errors as the link becomes longer, indicating scalability of the method to link lengths longer than 75 km. In addition, the Bit Error Rate (BER) of the downstream data signal is measured and is shown in Fig. 2a. It can be seen that error-free transmission ($BER<10^{-9}$) is possible for the 25 and 50 km links. For the 75 km link, a BER of 10^{-9} can be achieved if slightly higher signal powers are used, or if compensation for the accumulated dispersion is implemented (or a better receiver is used).
The very high precision in the estimation of delay, in combination with the compatibility of the proposed system with existing optical networks and the fast acquisition time (only 1 ms of data are captured to produce each measurement) indicate the potential of the

method to provide a fiber-optical back-up for GNSS timing, to supply a time reference for cutting-edge scientific research, and to enable novel applications. For example, the positioning accuracy of a system with 4 ps resolution would be $c \times 4\ \text{ps} \times \sqrt{4} = 2.4\ \text{mm}$. Other potential applications could take advantage of the availability of very precise timestamps to offer more secure transactions over communication networks and synchronize wireless base stations to achieve faster mobile communication links.

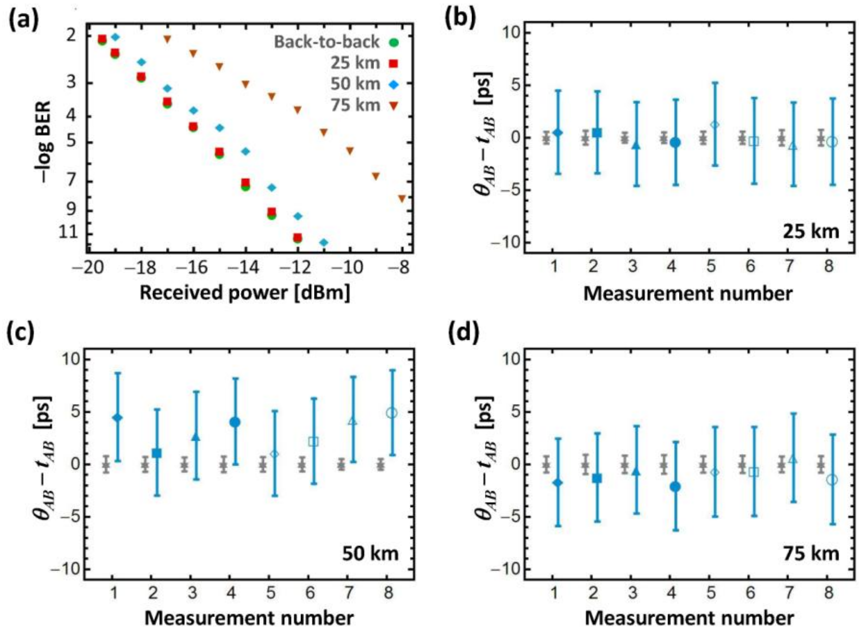

Fig. 2 Experimental results: BER curves (a) Delay errors (b) 25 km (c) 50 km (d) 75 km

Conclusion

A novel method of estimating the propagation delay of optical data transmitted through fiber-optical links with unprecedented accuracy is described and its key functionality is demonstrated over 75 km employing 10 Gb/s signals. The proposed system can enable ubiquitous availability of ps-range timing signals, providing GNSS back-up for critical infrastructure and supporting novel applications such as mm-level positioning and new techniques for fast and secure communications.

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