EVALUATION OF OUTPUT PHASE STABILITY IN A FIBER-OPTIC TWO-WAY FREQUENCY DISTRIBUTION SYSTEM

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Abstract

The assembly of a real-time actively controlled fiber-optic frequency transfer link based on additions to an existing static solution is proposed and evaluated. The dynamic variations of transmission delays, caused mainly by temperature dependence of the fiber, is continuously measured and used to adjust a delay at the transmitter for net cancellation of the effect. The resulting link shows no visible temperature dependence; however, the feedback induces added noise at short integration times.

INTRODUCTION

Frequency distribution from one master oscillator to different users within a local area can be easily implemented using commercial, often optical multimode, equipment. The distribution channel can be either wireless or wired, and the latter could be electrical cable or optical fiber. An electrical cable system will heavily suffer from surrounding interference and attenuation, while a fiber system will be more resilient to interference and attenuation for local area ranges. However, both cable and fiber will suffer from temperature-dependent delays which can be significant at transmission distances on the order of hundreds of meters, which is a reasonable distance in local area frequency distribution. These variations are slow and their influence on the output frequency stability is small. When the output phase stability is an important factor, the variations will nevertheless be significant, and several solutions address this issue through two-way solutions with datalogging and recalculation of phase data in retrospect **[1]**. For a real-time solution, dynamic compensation of the transmitted phase will therefore be desirable, and a previously presented solution includes data transmission for delay adjustment at the receiving site **[2]**, delay adjustment of transmitted and received signal in two synchronized electrical delays **[3]**, or through two-way transfer through a single-mode fiber stretcher **[4]**. The setup presented in this paper has some similarities with the later solution; however, it is based on multimode fiber, which is a more affordable choice on sub km distance. Furthermore, we use a free-space tuneable delay, which has a lower inherent delay with respect to its tuning range, in comparison to a fiber stretcher.

BACKGROUND

A commercial fiber-optic frequency distribution system was evaluated with respect to output phase stability. The system was fed by a 10 MHz signal from a Cs-clock traceable to UTC (SP), and transmitted through 200 m of multimode fiber, where approx. 100 m was located outdoors. The phase of the received 10 MHz signal was measured with reference to UTC (SP) and, since the perturbations are slow, averaging is used to minimize influence of measurement noise. The aim is to quantify the variations of output electrical phase through the system, and construct the desirable compensation. The measurements shown in the graph in Figure 1 were performed in December and January, and the delay of the output phase through one-way transfer (solid line) was strongly correlated with the outdoor temperature (dashed line). From these measurements, the effective temperature coefficient was estimated to be 60 ps/°C.

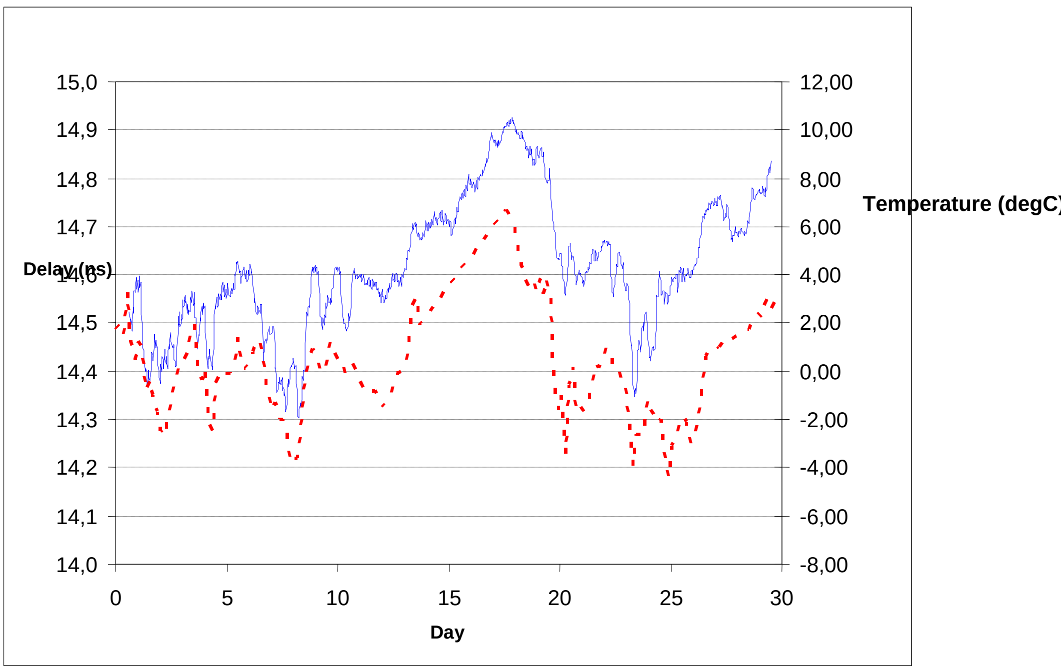

Figure 1. Delay of output phase from 10 MHz signal (solid) and the outdoor temperature (dashed). The left scale has an offset of 1 μs.

In order to receive a stable reference frequency, traceable to UTC (SP), within a campus area, some kind of dynamic compensation must be inserted. The possibility to keep a stable phase in a frequency distribution system based on multimode fiber in a local area with outdoor transmission distances below 1 km will be evaluated.

THEORY

The phase change of a frequency, transferred over a link, $\Delta\varphi_{transfer}$, can be described by:

$$\Delta\varphi_{transfer} = 2\pi f\left(t_{dist} - t_0\right) = 2\pi f t_{lag} \quad (1)$$

where t_0 is the time corresponding to the reference phase at the master oscillator, t_{dist} is the time corresponding to the same phase at the distant location, and t_{lag} is the transmission time in the link. If t_{lag} is constant, it can be measured once and then compensated for statically at the receiving site. Unfortunately, if the transmission distance is long, and especially if it includes temperature variations, this is not a valid assumption for a static link. The time lag of the signal must then be elaborated to

$$t_{lag} = t_{lag0} + \Delta t_{lag} \qquad (2)$$

where t_{lag0} is the time lag at the time of calibration and Δt_{lag} is the lag difference due to variations in transmission delay. In the setup, the main contribution to Δt_{lag} is presumed to be delay variations in the fiber transmission (including variations in the repeater at the distant site). To compensate for this, a tunable delay is inserted at the master site, which will induce a delay equally influencing both the uplink and the downlink. This tunable delay adds both a constant and a variable parameter to the equation, and the time transfer can now be described as

$$t_{dist} = t_0 + t_{tun} + \Delta t_{tun} + t_{link} + \Delta t_{link} \qquad (3)$$

where t_{tun} and t_{link} are the tunable delay and delay of the transmission link, respectively. The objective is to continuously adjust the delay, such that:

$$\Delta t_{tun} = -\Delta t_{link} \qquad (4)$$

thereby enabling increased real time phase stability in a frequency transfer.

The proposed solution is based on two-way transfer in the fiber link, requiring a second fiber parallel to the first. This fiber must be as identical as possible, since any discrepancies will reduce the phase stability quality.

The signal transmitted from the master site to the distant site and back is described by:

$$t_{return} = t_0 + 2\left(t_{tun} + \Delta t_{tun} + t_{link} + \Delta t_{link}\right) + t_{TxRx} \qquad (5)$$

where T_{TxRx} is any delay induced in the transceiver of the distant site. The system must now compare the returned time, t_{return}, with the transmitted, t_0, and adjust Δt_{tun} such that this difference is constant. This will only occur when $\Delta t_{tun} = -\Delta t_{link}$ which is the desired relation.

INFLUENCE OF ASYMMETRY

If there is an asymmetry in the duplex fiber length, i.e. the effective length of the transmission fiber between the master and the slave oscillators differs from the effective length of the analysis fiber returning the signal, the compensation will not have the full effect.

If an asymmetry of Δt_{asymm} is taken into account, equation (3) becomes

$$t_{dist} = t_0 + t_{tun} + \Delta t_{tun} + \left(t_{link} + \Delta t_{asymm}\right)\left(1 + \frac{\Delta t_{link}}{t_{link}}\right) \qquad (6)$$

And after active compensation, the residual temperature dependence is

$$\Delta t_{res} = \Delta t_{asymm} \frac{\Delta t_{link}}{t_{link}} \qquad (7)$$

This indicates that the influence of the asymmetry is proportional to the asymmetry length of the fiber affected by temperature variations. When the system is applied in on-campus frequency transfer, asymmetries less than 1 dm are assumed, which would correspond to a residual temperature dependence below 4 ps for outdoor temperature between -20 and +40°C. The influence of asymmetry will therefore be neglected in future analysis.

EXPERIMENT AND RESULTS

EXPERIMENTAL SETUP

This experiment has used an H-maser as frequency source, which is steered to UTC (SP) by an AOG. After conversion from 5 MHz to 10 MHz, the signal was inserted into a frequency distribution unit which also fed the measurement system, as can be seen in Figure 2. The next step in the link includes driving the light source from the frequency distribution. The output of the light source is connected to the adjustable delay unit, and from that the light is launched into the transmission fiber. This is a 625-m duplex multimode G62.5/125 fiber with specified attenuation: ≤ 3,5/1,0 dB/km (850/1300 nm). For detection of the light at the distant site, a photo-detector is used in connection with a distribution amplifier for further distributing and returning frequency, measurement, and delay-compensating steering. This fiber-optic transmission is performed at a wavelength of 850 nm (infrared light), determined by the frequency transfer equipment. Approximately 575 m of the fiber is located outdoors wound on spools.

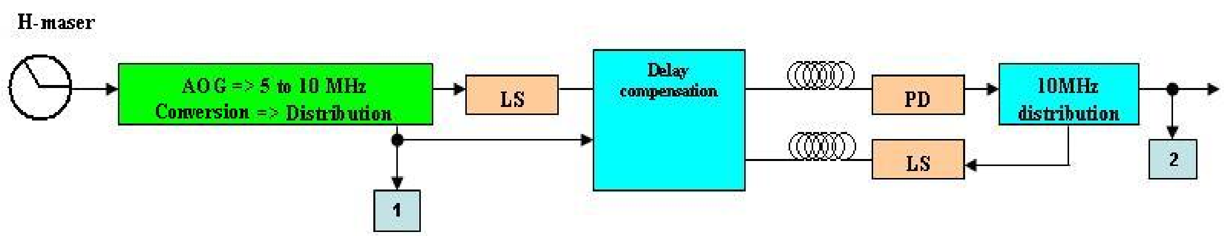

Figure 2. Schematical experimental setup, with 5 MHz source (H-maser), distributions, light sources (LS), photo-detections (PD), and delay compensation. The numbered boxes indicate measurement points.

The realization of the delay-compensating equipment is shown in more detail in Figure 3, where the thin solid lines correspond to optical fibers, the thick solid lines correspond to electrical coax cables, and the dashed lines are optical-free-space light beams. The lens tubes forms a collimated light beam of the light from the input fiber, and reversely focus the light back into the fiber at the other end. The photo-detector (PD) detects the modulated light, and transfers the signal into an electrical 10-MHz signal, which is connected to the RF input of a mixer. With a 10-Hz signal from the master clock at the LO input, the IF output will contain a DC voltage corresponding to the phase difference of the two input signals. This phase difference is measured by a high resolution DC voltmeter, and through a computerized control of the stepper motor, the retroreflector is moved until IF voltage equals zero. The adjustment of the reflector is performed continuously, with a repetition rate of approx. 1 Hz, to compensate for any variations in the transmission delay, causing a phase change at the RF input.

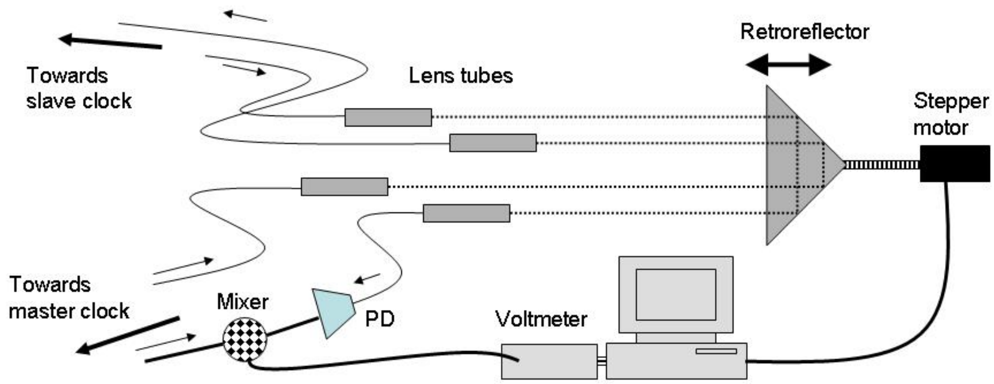

Figure 3. Shows a schematic of the optical tunable delay. The setup includes transmission in optical fibers (thin solid lines), free-space optics (dashed lines), and electrical coax-cables (thick solid lines). The conversion from optical to electrical signal is achieved in a photo-detector (PD).

RESULTS AFTER PROPAGATION IN FIBER WITHOUT COMPENSATION

Figure 4 shows the results after propagation in 625 m of fiber for a time period of 5 days, without active delay compensation. The delay is measured between measurement point 1 and 2 in Figure 2. This measurement was performed in order to receive a reference frame for the specific fiber. The measurement shows a correlation between the outdoor temperature presented by the blue line and the fiber delay of the output phase through one-way transfer. Since the perturbations are slow, averaging is used to minimize the influence of measurement noise, and the temperature dependence is estimated to be 100 ps/°C for this link.

RESULTS AFTER PROPAGATION IN FIBER WITH ACTIVE COMPENSATION

The results after propagating the signal through the fiber with added active delay compensation is shown in Figure 5, displaying two and a half days of measurement between measurement points 1 and 2 in Figure 2. It is apparent that there is a noticeable noise; however, there is no visible correlation to the outdoor temperature. Thus, it is shown that the compensation is functional for slow variations; however, it increases the fast variations in phase.

The frequency stability of the signals transmitted over an uncompensated and a compensated link are compared in Figure 6. After uncompensated transmission, the frequency shows a decreasing MDEV for Tau below 2000 s, but then there is a bump at a longer integration time. This is identified as the time scales on which the slow delay variations in the fiber will manifest themselves. Using active compensation, with a basic proportional regulation of the tuneable delay at an approx. 1 Hz update frequency, the noise increases with 3-4 dB; however, the bump disappears and the stability at integration times above 6000 s is improved compared with the uncompensated transmission.

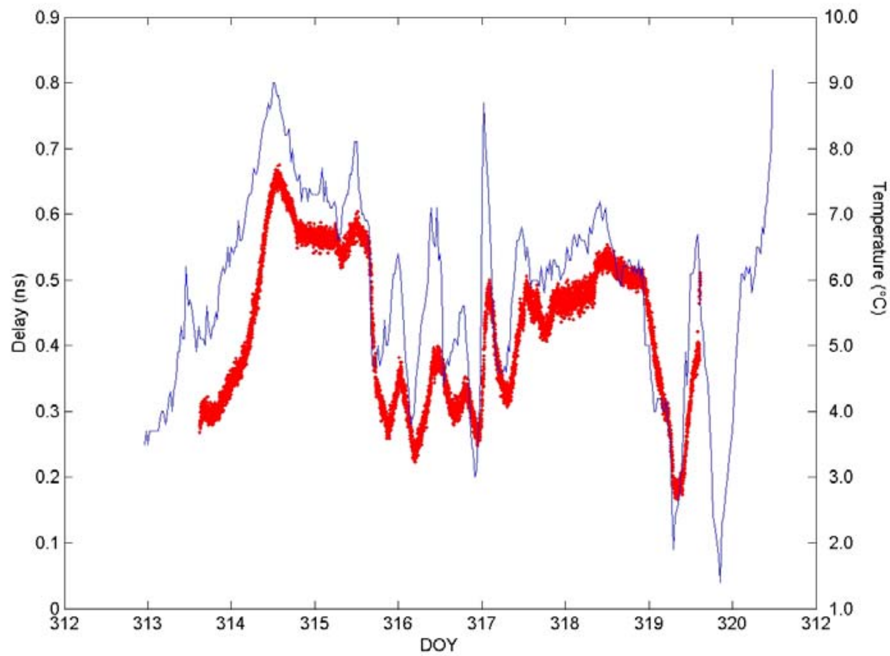

Figure 4. Results with measurement without delay compensation from DOY 313 to DOY 318. The red dots shows the delay (left scale, arb. ref.), while the blue line shows the outdoor temperature (right scale).

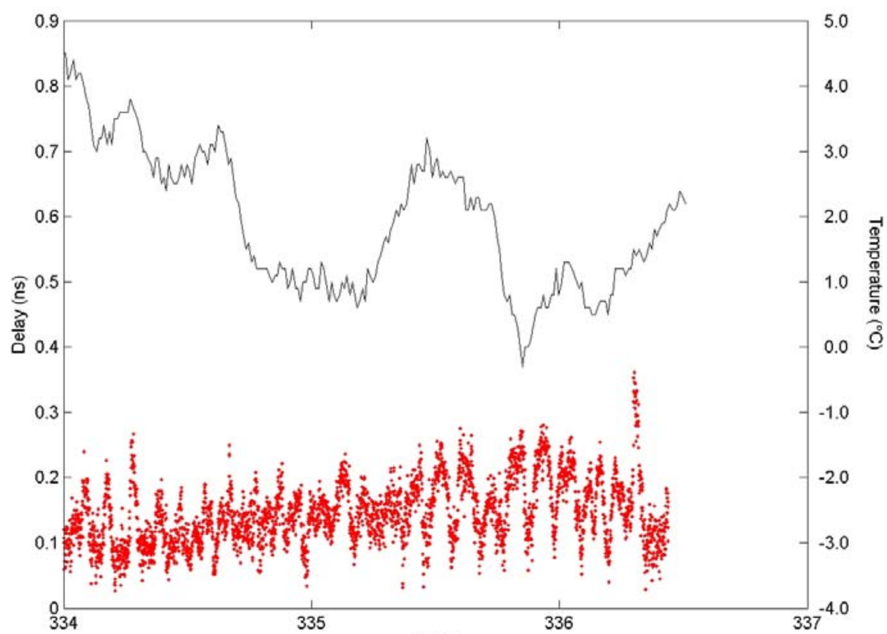

Figure 5. Results with measurement with active delay compensation, from DOY 334 to DOY 336. Dots show the measured delay (left scale, arb. ref.); the line shows outdoor temperature (right scale).

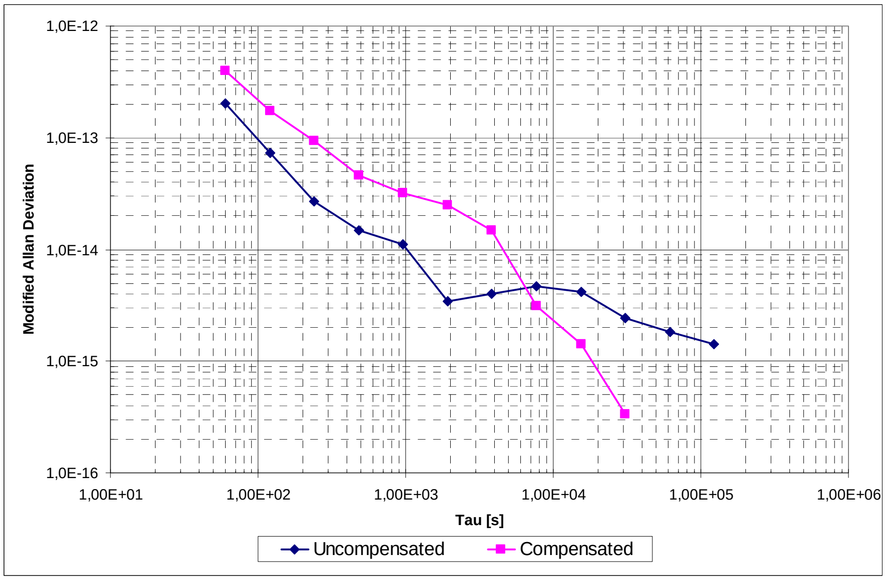

Figure 6. Frequency stability for the uncompensated and compensated fiber link.

CONCLUSION

A proof-of-concept has been shown, verifying the possibility of removing the temperature dependence, in real time, of a frequency transfer link with a transmission delay that inherently varies with 100 ps/°C. The remaining inaccuracy is dependent on other parameters, such as the control algorithm and update frequency of the adjustable delay. For further investigation, the commercial frequency equipment, operating at 850 nm in multimode fibers, has proven insufficient, and future development includes optical components with improved performance, such as a change to single-mode fibers, and lasers with a longer wavelength. Furthermore, other types of delays will be evaluated in conjunction with improvement of the algorithm controlling the delay-compensation unit. A large setback of changing from commercial equipment is that the build in distribution amplifiers has to be replaced by an external one at every slave site. The evaluation has shown that, for frequency distribution with less precision, commercial equipment will be the most cost-effective and the frequency performance may be satisfactory. However, for high-precision frequency transfer between the same campus labs, off-the-shelf fiber-optic frequency transfer equipment leaves little or no room for additions to improve performance. To achieve this, a completely new solution is recommended.

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