# A fiber based frequency distribution system with enchanced output phase stability

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***Abstract*—Experimental results on the stability of the output phase of a frequency distribution system from several days of measurement is presented, in addition to a discussion regarding the influence of control loop parameters. The setup handles the issue that the output phase stability of a system depends on perturbations along the transmission length. This is especially critical if the signal is transmitted through optical fiber, at lengths of a few 100 m. An experimental evaluation using a laser based transmitter at a wavelength of 850 nm, and 625 m of multimode fiber where 575 m where placed outdoor, a temperature dependence of 100 ps/°C was detected. To compensate for these slow variations in real time, a setup using two-way transmission, in conjunction with an adjustable optical delay, was constructed. This device is adjusted to induce a delay variation of equal magnitude but opposite direction, in comparison to the delay change of the fiber. Calculating the modified Allan deviation of the transmitted signal, it is apparent that without active compensation, the deviation at τ below 1000 s is comparable to the values from the measurement system without transmission. At longer integration times, however, the slow variations in the fiber transmission will deteriorate the modified ADEV substantially. When activating the dynamic adjustment of pre-delay in the system, the deviation at shorter times will increase with a few dB, however, the modified ADEV decreases continuously with τ, eventually below the values for the uncompensated system. In conclusion, activating a dynamically controlled pre-delay in a fiber based frequency transmission system will induce a small penalty on fast variations of the output phase, however giving a remarkable improvement on slower variations. The usefulness of this added functionality must therefore be determined by the application of the signal.***

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## I. Introduction

Within the campus of SP there are six multimode fiber links distributing a frequency of 10 MHz from time and frequency laboratory to other laboratories, e.g. the Josephson lab who are using it to realize the Swedish voltage reference. These links differ in distance where the longest one is a few hundred meters and connects labs in two separate buildings. This link is buried 50 – 100cm below the ground, and is therefore affected by the variations in outside temperature as well as heated by the radiation from the sun. All other links are located inside buildings and should not suffer from any large temperature variations. Occasional temperature drops in the stairwells does however occur during winter, why instability may be an issue also for these links.

A fiber based frequency distribution system, based on actively controlling the transmitter delay to compensate for undesirable delays in the fiber, is demonstrated and evaluated [1]. The result is a slightly deteriorated performance at short timescales and a noticeable improvement at longer timescales. With further improvement of the control algorithm, the performance at short timescales is expected to be enhanced.

## II. Background

In the experimental setup, a 10 MHz signal is transmitted over 625 m of multimode fiber (GI 62,5/125), of which 575 m is located outdoors. The test fibers are of commercial grade purchased from an electronics distributor, and are assumed to have typical and relevant temperature dependence. In order to evaluate the transmission quality, measurements of the phase stability are made between the output signal at the user end compared with the transmitted signal from the H-maser. These measurements revealed temperature dependences of 17 ps/°C

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per 100 m in fibers manufactured 2008 and up to 50 ps /°C per 100 m in fibers manufactured 2000.

## III. EXPERIMENTAL AND REFERENCE SETUP

The important parts of the frequency distribution system, commercially available and previously installed at the institute, is schematically shown in figure 1. A master oscillator is connected to an electronic distibution amplifier, of which one output is connected to the input of the fiber optic transmitter. This system distributes optical signals over multimode fibers, to receivers which converts the optical signal to an electrical and distributes this on a few outputs. The recievers are equipped with internal oscillators that phase-lock to the input, which relaxes the requirement on optical signal quality. Nevertheless, the timing of the optical signal is crucial.

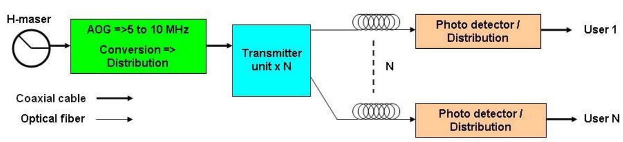


Figure 1. Fiber based reference system for distribution of 10 MHz to N users

The proposed improvement includes the addition of a transmitter at the user end, for returning the signal in a 2-way setup, and a bidirectional electronically controlled optical delay for active compensation. The delay is assembled from optomechanic components, with an operation as sketched in figure 2. The thin lines corresponds to optical fibers, dashed lines are the light beams, and the thick lines are electrical connections.

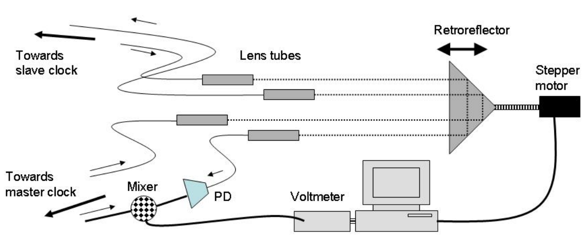


Figure 2. Tuneable delay including retroreflector and measurement equipment

The proposed, actively stabilized, frequency transfer system is schematically shown in figure 3. Each link is expanded with a return-fiber, and the variations in phase of the returned signal is detected. Based on this detection, the optical delay is adjusted to minimze these variations. This system requires a fiber pair to each user, and a variable optical delay in each link.

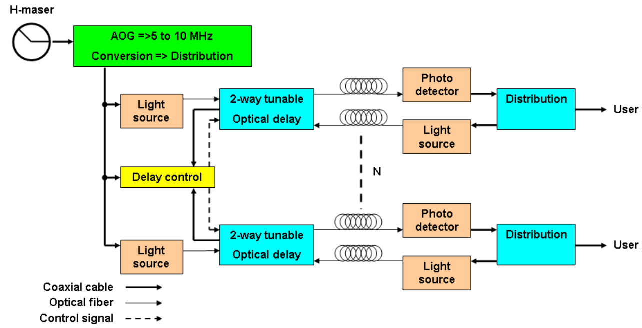


Figure 3. Proposed 10 MHz fiber distribution system with compensation for N users

The experimental setup is a single-user system based on the proposed technique, as shown in figure 4. Due to the additional loss in the optical delay, the LED based transmitters in the commercial devices are replaced with lasers, still emitting at 850 nm. Furthermore, the analysis requires that both ends of the transmission, denoted 1 and 2 in figure 4, is located at the same location.

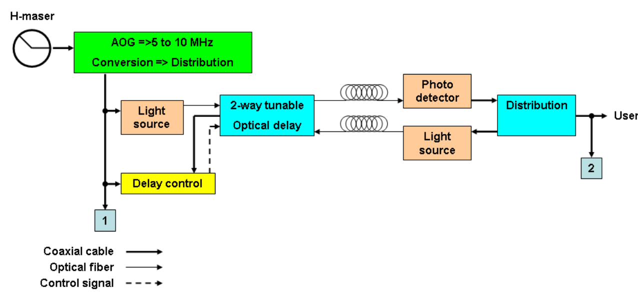


Figure 4. Experimental 2-way setup with bidirectional electronically controlled optical delay for active compensation

## IV. THEORY

The phase change of a frequency, transferred over a link, $\Delta_{\varphi transfer,}$ can be described by (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.

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

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

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

Where $t_{lag0}$ is the time lag at the time of calibration and $\Delta t_{lag}$ is the lag difference due to variations in transmission delay. In the proposed system, the main contribution to $\Delta t_{lag}$ is presumed to be delay variations in the fiber transmission (including variations in the repeater at distant site). To compensate for this, a tuneable delay is inserted at the master site, which will induce a delay equally influencing both the uplink and the downlink.

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

This tuneable delay adds both a constant, and a variable parameter to the equation, and the time transfer can now be described as (3) where $t_{tun}$ and $t_{link}$ are the delay of the tuneable delay and the transmission link, respectively. The objective is to continuously adjust the delay, such that

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

Thereby enabling increased real time phase stability in a frequency transfer. The solution is based on two way transfer in the fiber link, requiring a second fiber parallel to the first (duplex). This fiber must be as identical as possible, since any discrepancies will reduce the quality of the phase stability. The signal transmitted from the master site, to the distant site and back is described by (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 $\Delta t_{tun}$ such that this difference is constant. This will only occur when $\Delta t_{tun} = -\Delta t_{link}$ which is the desired relation.

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

### A. *Influence of asymmetry*

If there is an asymmetry in the duplex fiber length, i.e. if 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 full effect. If an asymmetry of $\Delta t_{asymm}$ is taken into account, equation (3) becomes

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

and after active compensation, the residual temperature dependence is

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

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 is assumed, which would correspond to residual temperature dependence below 4 ps for outdoor temperature between -20 and +40 °C. The influence of asymmetry will therefore be neglected in further analysis.

## V. RESULTS

The phase of the output signal is measured over a few days, both with and without active compensation, and the values are compared with the outdoor temperature. A Time Interval Counter (TIC) [2] was used to measure the transmitted and received signal in order to evaluate the phase stability. Without compensation, a strong correlation is found, as shown in figure 5, while when the compensation is inserted in figure 6, a repetitive variation is noticed, uncorrelated with temperature.

In figure 7, the modified Allan deviation is calculated for the fiber transmission, without (blue circles) and with (red squares) active compensation. For comparison, the typical data for the H-maser used in the experiment (gray diamonds) and for the TIC with 50 ps resolution and 60 sample averaging (green triangles) is included. It is apparent that without active compensation, the deviation at Tau below 1000s is comparable to the values from from the TIC. At longer integration times, however, the slow variations in the fiber transmission will deteriorate the modified ADEV substantially. When activating the dynamic adjustment of pre-delay in the system, the deviation at shorter times will increase with a few dB, however, the modified ADEV decreases continuously with Tau, eventually below the values for the uncompensated system.

Some of the oscillations that can be seen after compensation in the fiberlink are related to the steering algortihm of the tunable delay. The movement of the delay is performed by a steppermotor with an algorithm that does not activate if the required step is smaller than in the region of 1cm. These oscillatons are of the magnitude of ±0.1ns and should bee able to be decreased to ±0.05ns with a better steering.

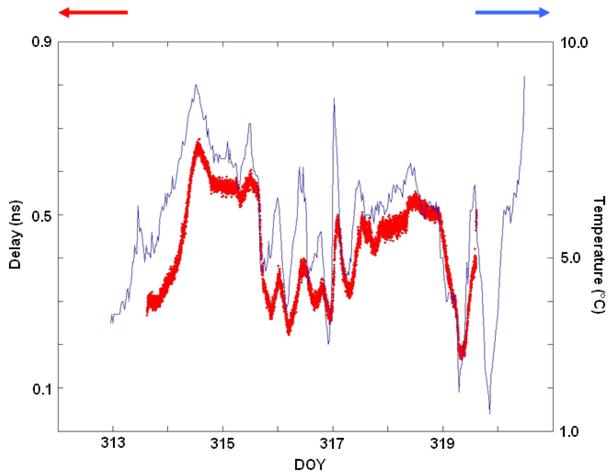


Figure 5. Results with measurement without delay compensation from DOY 313 to DOY 318. Red curve shows the time delay while blue curve is the outdoor temperature

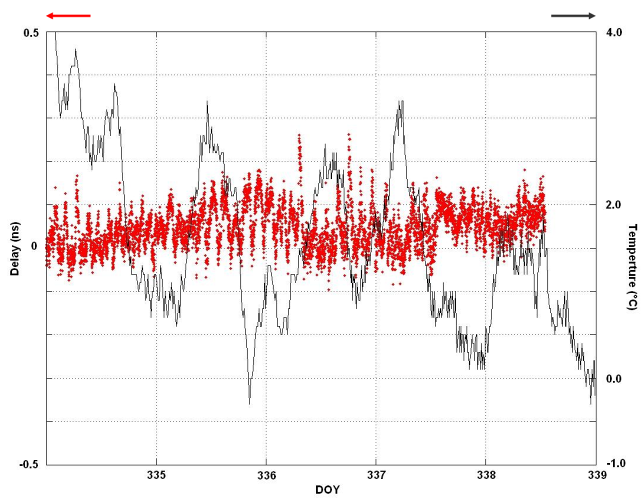


Figure 6. Results with measurement with delay compensation from DOY 334 to DOY 339. Red curve shows the time delay while blue curve is the outdoor temperature

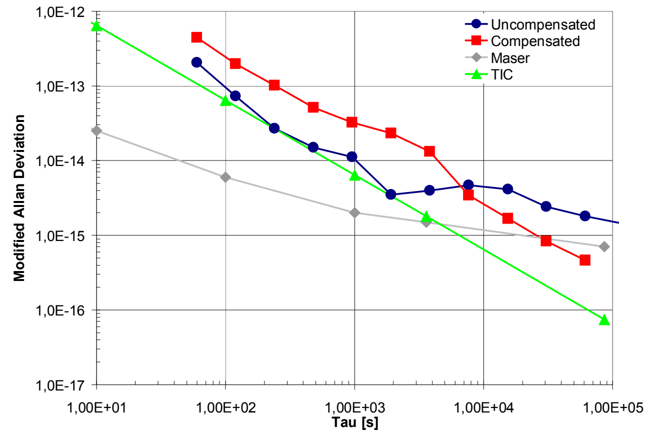


Figure 7. Frequency stability for the uncompensated and compensated fiber link. Typical ADEV for the TIC and the H-maser is included for comparison

## VI. Conclusion

The evaluation has shown that in frequency distribution where hundreds of meters of fiber run outdoors, the delay time varies with to 10 - 50 ps/°C. Old fiber shows worse temperature dependence. If such precision is within requirements, commercial equipment will be cost efficient and the frequency performance may be satisfactory. For better long term precision, a 2-way active compensating setup is recommended. Demonstration of the possibility to remove temperature dependency in real time is made with rather cheap equipment. Reduction of the short term stability will need work on steering algorithm and update frequency of the system. A better tuneable delay, without free space path will enhance the stability in short term. For that purpose should a fiber stretcher be suitable. Laser based solution for transmitting the signal is necessary due to lack of intensity for commercial frequency transfer equipment, based on LED at 850 nm in multimode fibers.

## Reference


[1] S-C. Ebenhag, P.O. Hedekvist, C. Rieck, H. Skoogh, P.Jarlemark, and K. Jaldehag, "Evaluation of Output Phase Stability in a Fiber Optic Two-Way Frequency Distribution System", Proceedings of the Precise Time and Time Interval Meeting 2008. Paper 11 (2008).

[2] Pendulum Instruments, "Start-up Measurements on Oscillators: Using the CNT-90/CNT-91 to measure oscillator start-up*", White paper from Pendulum Instruments*, November 2007