# Modeling of Phase-modulated Two-way Time Transfer Fiber-optic Links

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***Abstract*—We demonstrate a model of the signal-to-noise ratio based on a bidirectional time transfer link, where the signal is phase demodulated by a Michelson interferometer. The primary noise was the amplified spontaneous emission noise generated by amplifiers. The model was experimentally verified on 480 km fiber links.**

***Index Terms*—Phase modulation, time transfer, model, signal-to-noise ratio**

## I. Introduction

For long-distance fiber optic time transfer, bidirectional erbium-doped fiber amplifiers are required to compensate for link losses. However, amplifiers introduce amplified spontaneous emission (ASE) noise. The accumulated ASE noise can affect the performance of the time signal received at the remote end. When the signal-to-noise ratio (SNR) is too low, it can severely impact the performance of the compensation system, such as causing phase-locked loop (PLL) loss of lock. In 2013, the SNR modeling for intensity-modulated time transfer was studied. Subsequently, link parameters were optimized based on this model [1].

In recent years, time transfer based on the phase modulation have been investigated [2], [3]. However, most existing SNR analyses for time transfer systems are based on intensity-modulated systems and are not applicable to phase-modulated systems where signal is demodulated by delay interferometers.

In this paper, a modeling method based on phase modulation is proposed for analyzing the SNR at the threshold level of pulse rising edge. We investigate signal and noise propagation in a Michelson interferometer (MI). Rayleigh backscattering noise is suppressed by wavelength division multiplexer and isolator [4]. The proposed model mainly considered ASE noise and the laser phase noise into the intensity modulation conversion (PM-IM) noise.

## II. Principle

Fig. 1 is the diagram of the phase modulated time transfer over fiber link. The time signal is modulated onto an optical carrier by a phase modulator and then transmitted bidirectionally through an optical fiber link. At the demodulation end, the optical signal is first preamplified by a unidirectional optical amplifier. Subsequently, phase demodulation is carried out using a Michelson interferometer [3]. The bidirectional amplifiers in the link, while compensating for the link loss, generate ASE noise and amplify Rayleigh backscattering noise. Through wavelength division multiplexing and isolators, the Rayleigh backscattering noise can be suppressed. Narrow-band filtering is also applied to the ASE noise. However, the accumulated ASE noise can still degrade the SNR, affecting the performance of the link. Therefore, modeling and analyzing the link noise is extremely important.

The optical signal received at the remote end can be expressed as

$$\begin{aligned} E(t) &= E_0(t)\exp(j\theta(t)) + n(t), \\ E_0(t) &= \sqrt{P_{SL}}\exp(j(\omega t + \varphi_0)), \end{aligned} \tag{1}$$

where $P_{SL}$ is the the received signal optical power, $n(t)$ is the received ASE noise with power of $P_{ASE}$. $P_{SL}$ and $P_{ASE}$ can be estimated by the calculation in [1], [5]. $\omega$ is the frequency of the laser. $\varphi_0$ is the phase of the optical signal.

The received optical signal, after phase demodulation and single-port detection, can yield a photocurrent represented by $I_{RE}(t)$ [6], which can be expressed as:

$$\begin{aligned} I_{RE}(t) \propto\ & \frac{1}{2}|E_0(t)|^2 - \frac{1}{2}|E_0(t)|^2 cos(\omega\tau + \Delta\theta(t)) \\ & + n^{-*}(t)E_s^-(t) + n^-(t)E_s^{-*}(t) \\ & + |n^-(t)|^2, \end{aligned} \tag{2}$$

where $\tau$ is the delay difference of the MI, $E_s^-(t)$ and $n^-(t)$ is the output signal and ASE noise of the MI. The second line in (2) is the signal and ASE noise beating noise. The third line in (2) is the self-beating of ASE noise. Combining the analysis in [6], [7], the variances of the noise terms at the threshold in (2) are summarized in Table I with an optical bandwidth of $B_{opt}$ and electrical bandwidth of $B_{el}$ in the time transfer. The SNR can be estimated by

$$SNR^{cal} = \frac{\frac{1}{4}P_{SL}^2}{(\sigma_{s,sa}^2 + \sigma_{s,aa}^2 + \sigma_{NR}^2)}. \tag{3}$$

$\sigma_{NR}^2$ represents the other nosie, such as PM-IM noise [8] , the shot noise and the electrical amplifier noise [4].

## III. Experiment and results

Fig. (2) is the experiment setup to measure the SNR of the time transfer link. The SNR is measured by the high speed oscilloscope using the method in [4]. The oscilloscope is triggered by the pulse signal driving the laser. To mitigate the impact of link fluctuation, we set the pulse repetition frequency

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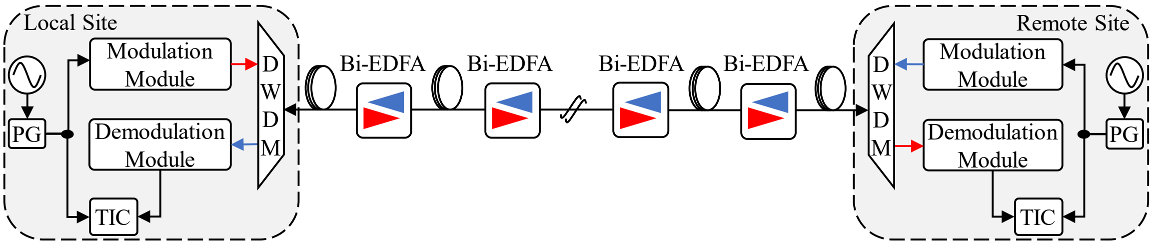


Fig. 1. Diagram of two-way time transfer link. PG, digital delay pulse generator; DWDM, dense wavelength division multiplexer. Bi-EDFA, bi-directional erbium-doped fiber amplifier; TIC, time interval counter.

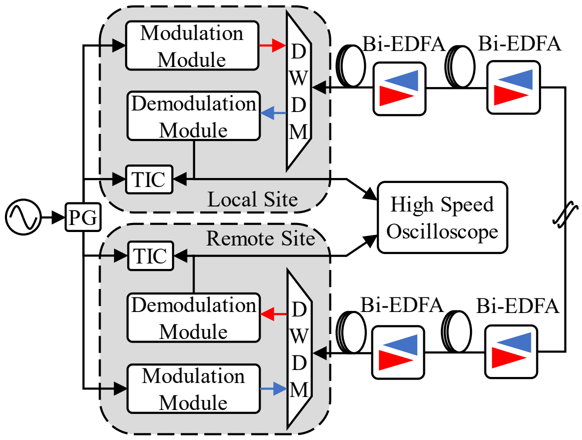


Fig. 2. Experiment setup used to verify the model of time transfer link.

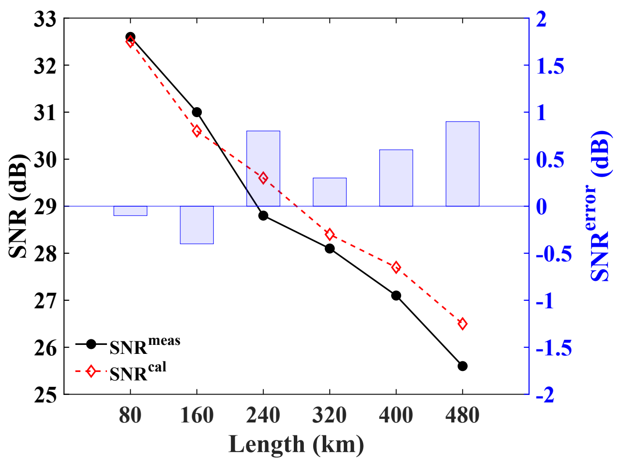


Fig. 3. Comparison of measured and calculated of the pulse signal at the remote site.

TABLE I
VARIANCES OF THE ELECTRICAL NOISES IN TIME TRANSFER.

| Term | Variances | Descriptions |
|---|---|---|
| $\sigma^2_{s,sa}$ | $P_{SL} P_{ASE} B_{el}/B_{opt}$ | signal-ASE beating |
| $\sigma^2_{s,aa}$ | $P^2_{ASE} \frac{(2B_{opt}-B_{el})B_{el}}{4B^2_{opt}}$ | ASE-ASE beating |

to 10,000. In the demodulation module, the MI is controlled at the bias point where the amplitude is minimal. Fig. (3) presents a comparison chart of the measured and estimated signal-to-noise ratios at various transmission distances. The right-hand axis provides the estimated error values. It can be observed that the estimated error is less than 1 dB.

## IV. CONCLUSION

In this study, we have established a SNR model for phase-modulated time transfer with bidirectional optical amplifiers. The Rayleigh backscattering noise is suppressed using wavelength division multiplexing and isolators. The ASE noise is primarily considered. We derived the photocurrent after the phase demodulation. Furthermore, we obtained the noise variances and the SNR at the threshold level. We compared the estimated values from this model with the experimental measurements on different transmission distances, and the error of SNR estimation is less than 1 dB.

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