Photonics PNT Based on Multi-Tone Continuous Wave Ranging

Mustafa Mert Bayer, Ataberk Atalar, Xun Li and Ozdal Boyraz
Department of Electrical Engineering and Computer Science, University of California, Irvine, California, USA
Author e-mail address: bayerm@uci.edu, aatalar@uci.edu, xunl12@uci.edu, and oboyraz@uci.edu

Abstract: When GPS signals are not available alternative positioning, navigation, and timing (PNT) systems become indispensable. We propose and experimentally demonstrate a photonic PNT system that localizes targets with ~10cm separation and <5cm resolution at a 1km distance.

1. Introduction

The importance of accurate location and velocity tracking has been an important subject since World War II for militaries due to the usefulness it provides for targeting, navigation, and planning [1]. Over the years, the advancements in GPS technology have created a wide range of civilian applications in addition to the military such as transportation [2], geophysical exploration, agriculture, and even structural health monitoring. Recently there is a growing interest in chip-scale photonics positioning, navigation, and timing (PNT) [3]. Up to date, different methods have been utilized such as using visible light for indoor navigation [4] or photonics-based multiple-input-multiple-output radar for navigation [5]. In this work, an alternative high precision approach for PNT is presented for target localization. The main approach is similar to the methods proposed previously for the phase-based multi-tone continuous wave (PB-MTCW) lidar applications [6–9], which is based on observing the phase shifts generated by the convolution of the phase-locked RF sidebands encoded on a CW optical carrier through an electro-optic modulator (EOM). Experimentally we demonstrate that a target can measure its position with respect to a remote transmitter with <1cm accuracy. Measurements are performed after ~1km fiber spool, which corresponds to ~1.5km optical path length in free space, and show clear identification of 10cm increments in the target position.

2. Working Principle

The proposed architecture for photonics PNT via the PB-MTCW approach is presented in Fig. 1. The CW laser operating at a frequency of ω_t in the transmitter side is modulated by a Mach-Zehnder modulator (MZM) that operates at the quadrature point under push-pull configuration. A total of *N* number of synthesized phase-locked RF frequencies (f_i) are fed to the RF input port of the MZM. The modulation generates sidebands in the optical spectrum as $\omega_t \pm \omega_i$, where $\omega_i = 2\pi f_i$. The modulated signal is pulsated via an EOM for higher peak powers, then amplified and transferred to the free space via a collimator (CL). Each ω_i accumulates a different phase with respect to its frequency and total propagation distance. The transmitted light is collected by the CL of the receiver side after propagating a distance *L* with the speed of light *c/n* and combined with a local laser source that has a frequency of ω_r to strengthen the collected modulation tones through a heterodyne detection system. The electric field of the laser in the receiver can be formalized as $E_r = A_r \exp(j\omega_r t + j\phi_0^r + j\phi_n^r(t))$, where A_r, ϕ_0^r and $\phi_n^r(t)$ are the amplitude, initial phase, and the laser phase noise, respectively. The local oscillator is a free-running laser without any frequency and phase locking to the remote transmitter, but the frequency difference between the two lasers is less than the detector bandwidth. The resultant beam is sent to the photodetector (PD) to generate the photocurrent (I_{pd}) as shown in Eq.(1). I_{DC} is the DC portion of the photocurrent and the self-beating terms are neglected for simplicity.

$$I_{pd} = I_{DC} + 2\alpha_m A_t A_r \cos\left((\omega_t - \omega_r)t + \omega_t \frac{L}{c} + \Phi + \phi_n^t(t) - \phi_n^r(t) \right) - \frac{m}{2}\alpha_m A_t A_r \left[\begin{array}{l} \sum_{i=1}^{N} \cos\left((\omega_t - \omega_r + \omega_i)t + (\omega_0 + \omega_i)\frac{L}{c} + \Phi + \phi_i^{RF} + \phi_n^t(t) - \phi_n^r(t) \right) \\ + \sum_{i=1}^{N} \cos\left((\omega_t - \omega_r - \omega_i)t - (\omega_0 - \omega_i)\frac{L}{c} + \Phi - \phi_i^{RF} - \phi_n^t(t) - \phi_n^r(t) \right) \end{array} \right] \quad (1)$$

Here, A_t is the amplitude of the transmitted light, *m* is the modulation index, α_t is the linear attenuation, $\Phi = \phi_0^t - \phi_0^r$ is the initial phase, ϕ_i^{RF} ϕ_0^t and $\phi_n^t(t)$ are the initial RF phase, initial carrier phase, and the laser phase noise, respectively. It is possible to locate the shifted tones with a priori-knowledge of the preselected tone frequencies. The highest peak power will be realized at ω_t-ω_r and it is possible to use this peak as a reference to locate the modulation tones. Then, digital bandpass filters near the RF tones can be used to get the waveforms of the individual tones. However, each resultant peak will have a contribution of phase noise from both lasers. To eliminate these, tones at $\omega_t - \omega_r + \omega_i$ or $\omega_t - \omega_r - \omega_i$ are RF mixed and the noise-free intermediate frequency (IF) components have the formalism of $A_i A_j \cos\left(\Delta\omega_{i,j} t \pm \Delta\phi_{i,j}\right)$, where $\Delta\phi_{i,j}$, and $\Delta\omega_{i,j}$ are the phase and frequency differences of i^{th} and j^{th} tones ($i \neq j$), respectively. Then, the target distance can be computed through $L = \left(2\pi n + \Delta\phi_{i,j}\right)c / \Delta\omega_{i,j}$, where *n* is an integer. By using the results generated by multiple tones, it is possible to triangulate the *L* as in [6,9].

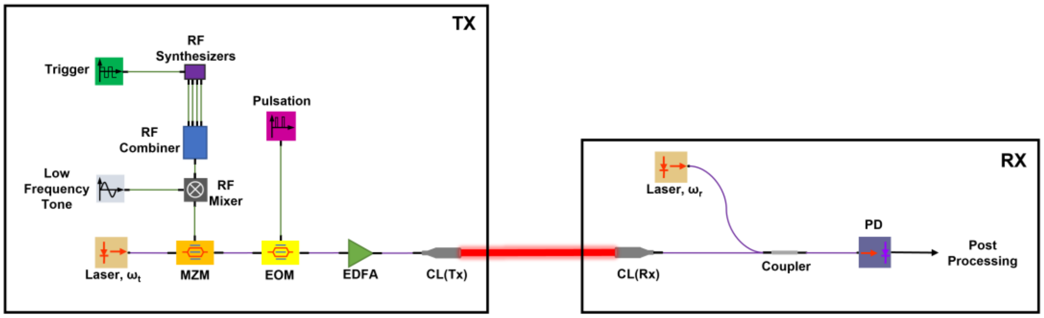

Fig. 1 Schematic of the proposed phase-based multi-tone continuous-wave PNT architecture with transmitter and receiver sides.

Results and Discussion

We developed a test bench to perform proof-of-concept experiments. Architecture similar to Fig. 1 is utilized. Three phase-locked RF tones are fed to the MZM. A tunable 1540.107nm CW laser source with <1MHz linewidth is employed at the transmitter side. After the MZM and EDFA, the light is brought to a 1km fiber spool (actual length is unknown) that is connected to a CL to get to free space. A beamsplitter (BS) is placed between a target reflector that is anchored on a linear translational stage. The stage is moved with ~10cm steps for each position. The backscattered beam is propagated back to the BS. The echo signal is coupled to a single-mode fiber and a 70/30 coupler is used to convolve the detected signal with the local CW laser source on the receiver side. The tunable laser is set to operate at 1540.070nm. Finally, the beam is transferred to a PIN InGaAs PD with 10GHz bandwidth. For data acquisition, we employed an 8GHz bandwidth oscilloscope with a 100µs time window, 10kHz frequency resolution, and ~24ps time resolution. The results are tabulated in Table 1. For coarse positioning, we utilized two tones at 100kHz and 200kHz, respectively, and compared the phase variations while the target was stationed at position 1. The coarse ranging yield 1314m and we set the actual distance of position 1 as 1314m. 10 measurements are performed at each position, and the standard deviation of each set of measurements is <5cm, which indicates the resolution of the PB-MTCW positioning system. It is possible to compare the average values to realize the 10cm stage motion in between each position as a total propagation distance of 20cm.

Table 1. Experimental Measurement Results

Target Positions	Position 1	Position 2	Position 3	Position 4
Measurements (m)	1.97	2.12568	2.39815	2.63212
	1.9736	2.20288	2.39833	2.63121
	1.9736	2.24139	2.47499	2.63103
	1.97	2.12604	2.35946	2.6294
	1.9736	2.24067	2.35892	2.63157
	2.0083	2.24103	2.39851	2.6385
	2.00779	2.24212	2.35928	2.59809
	2.00906	2.24103	2.39668	2.59234
	2.00779	2.2036	2.39888	2.5918
	2.00906	2.24103	2.3987	2.59161
Avg. (m)	1.99028	2.21055	2.39419	2.61677
Actual Distance (m)	1314	1314.2203	1314.4039	1314.6265
σ (m)	0.01915	0.047251	0.033826	0.020277

3. Conclusion

We demonstrate a new photonics PNT based on PB-MTCW ranging system and verify the theoretical background with a working example by localizing closely spaced stationary targets over a long distance.

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5. References

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