Advanced International Journal for Research (AIJFR)
E-ISSN: 3048-7641 ● Website: www.aijfr.com ● Email: editor@aijfr.com

WDM-Assisted Simplex Coded OTDR for Enhanced Fiber Sensing

Tiasha Maji [1], E.S. Shivaleela [2]

[1] Department of Electronics and Telecommunication Engineering, Kalinga Institute of Industrial Technology, Bhubaneswar, Odisha, India.
[2] Department of Electrical Communication Engineering, Indian Institute of Science, Bengaluru, Karnataka, India.

Abstract
Optical time-domain reflectometry (OTDR) is widely used for fiber characterization and fault detection. However, its performance is often limited by weak Rayleigh backscatter and receiver noise, which reduce the achievable signal-to-noise ratio (SNR). Simplex-coded OTDR addresses this limitation by transmitting Hadamard-matrix-derived pulse sequences that improve the SNR compared with conventional single-pulse approaches. However, existing implementations rely on sequential single-wavelength measurements, which limit acquisition efficiency and reduce overall measurement speed. This paper proposes a wavelength-division multiplexing (WDM)-assisted simplex-coded OTDR architecture that introduces wavelength-domain parallelism into the conventional simplex coding framework. Independent simplex-coded pulse sequences are encoded onto distinct optical wavelengths, simultaneously launched into the fiber under test, and individually decoded after wavelength demultiplexing. Theoretical analysis confirms that the proposed architecture fully preserves the simplex coding gain of each wavelength channel while achieving an **effective system-level gain** that scales with both the number of parallel WDM channels and simplex code length.

Keywords: Optical Time-Domain Reflectometer, Simplex Codes, Wavelength-Division Multiplexing, Signal-to-Noise Ratio, Hadamard Matrix.

1. Introduction
Although OTDR is widely used for optical fiber characterization and fault localization, improving its measurement sensitivity and sensing capabilities remains an active area of research. In particular, overcoming the effects of receiver noise while preserving spatial resolution remains a key challenge in conventional OTDR systems.

To address these limitations, researchers have developed coded OTDR techniques to improve the SNR without compromising spatial resolution [1,2]. Among them, simplex-coded OTDR has demonstrated significant SNR enhancement by employing hadamard-matrix-based pulse coding and inverse decoding [3]. Nevertheless, conventional simplex-coded OTDR systems operate sequentially over a single wavelength channel, limiting the acquisition efficiency and preventing the effective utilization of wavelength-domain resources.

WDM provides a natural solution by enabling simultaneous transmission of multiple independently encoded optical channels [4]. Motivated by this capability, this paper proposes a WDM-assisted simplex-coded OTDR architecture that combines simplex coding with wavelength-domain parallelism to enable concurrent multi-wavelength interrogation while preserving the conventional encoding and decoding processes.

The proposed framework develops a mathematical model for multiplexed transmission and decoding and presents an analytical evaluation of the resulting system-level performance. The analysis demonstrates that parallel wavelength acquisition enhances the effective system-level performance while maintaining the probe pulse width and spatial resolution, providing a scalable approach for improved optical fiber monitoring and characterization in the future.

2. System Overview

Figure 1: Architecture of the proposed WDM-assisted simplex-coded OTDR system

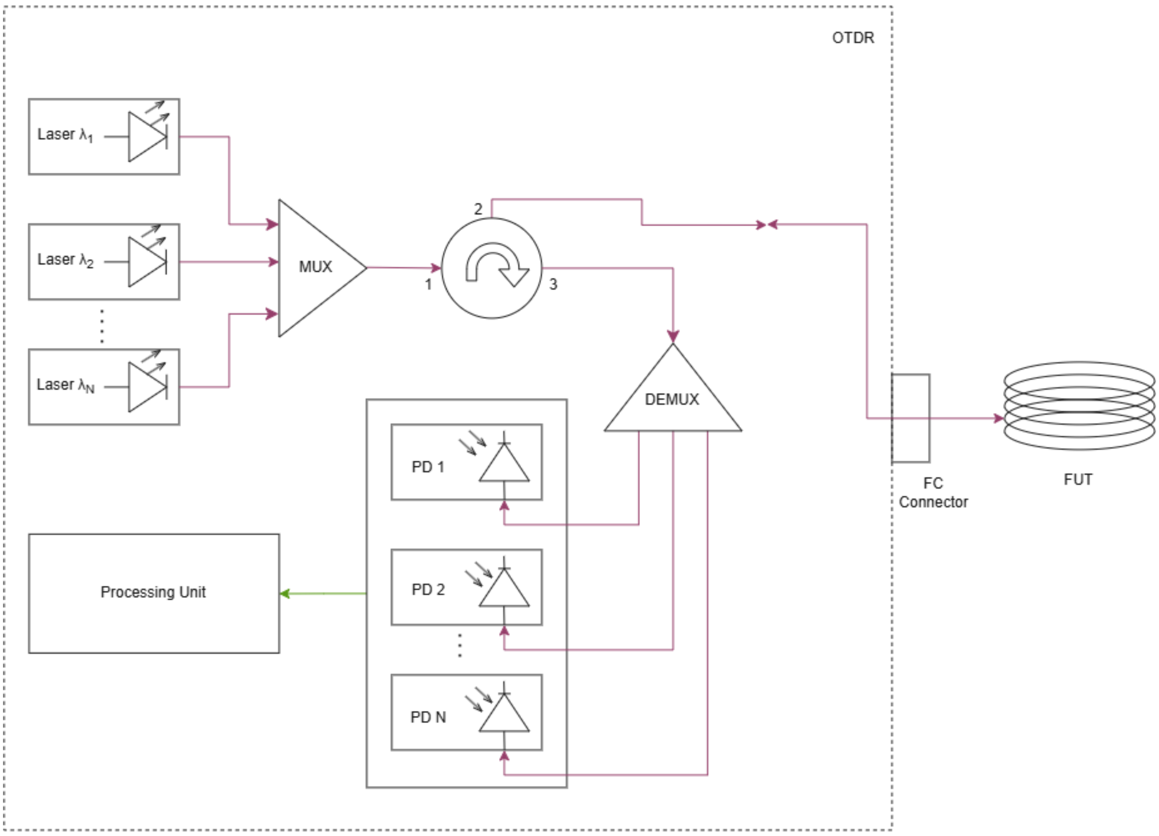

Figure 1 illustrates the proposed WDM-assisted simplex-coded OTDR architecture showing multiple laser sources operating at distinct wavelengths ($\lambda_1,\lambda_2,\ldots,\lambda_n$), a wavelength multiplexer, an optical circulator, a wavelength demultiplexer, an array of photodetectors, and a processing unit.

Each laser source generates a simplex-coded optical pulse sequence assigned to its corresponding wavelength channel. The WDM multiplexer combines the encoded signals and launches them simultaneously into the fiber under test (FUT) through port 2 of the optical circulator. As the optical pulses propagate along the fiber, the Rayleigh backscattered signals return through the same fiber and the circulator redirects them to the demux via port 3.

The demultiplexer separates the received backscattered signals into individual wavelength channels, and an independent photodetector detects each channel. The processing unit processes the resulting electrical signals and performs inverse simplex decoding to reconstruct the fiber impulse response for each wavelength channel.

By combining simplex coding with WDM, the proposed architecture enables simultaneous multi-wavelength interrogation while preserving the conventional simplex encoding and decoding process. This parallel acquisition strategy improves measurement efficiency and provides the foundation for the system-level gain analysis discussed in the next section.

3. Simplex Code

The previously proposed OTDR employs simplex coding for optical pulse encoding and decoding. Following the method proposed by De Lee et al. (2006) [1], the coding process uses a unipolar simplex matrix S consisting of binary values 1 and 0, where 1 indicates the presence of an optical pulse and 0 indicates its absence. The simplex matrix can be derived from a normalized Hadamard matrix and is used to generate coded pulse sequences for OTDR measurements.
The following example demonstrates the time-domain application of the Hadamard transform using a simplex matrix of order 3:

$$S = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

Each row of the simplex matrix corresponds to a unique coded pulse sequence. In a conventional simplex-coded OTDR, the system transmits these sequences sequentially and the resulting coded traces are processed using the inverse simplex matrix to recover the original OTDR response with improved SNR [1].

4. Proposed method: WDM-Assisted OTDR Signal Model and Gain Analysis

This work adopts the same simplex coding principle as the basis of the proposed architecture. Unlike the conventional approach, the coded sequences are assigned to different wavelength channels and transmitted simultaneously through WDM. Specifically, each wavelength channel λ_n is assigned the n-th row of S_L as its coded pulse sequence, thereby preserving the invertibility condition $S_L^{-1}S_L=I$ across all active channels. The proposed channel assignment enables parallel interrogation of the fiber while preserving the simplex encoding and decoding methodology [1].

The n-th wavelength channel λ_n transmits the n-th row of S_L as its simplex-coded optical pulse sequence. The composite WDM signal simultaneously launched into the FUT is the superposition of all N encoded channels:

$$S_{TX}(t) = S_{L,\lambda_1}(t) + S_{L,\lambda_2}(t) + \cdots + S_{L,\lambda_N}(t) \quad (1)$$

$$\eta(t) = S_L \Psi(t) + e(t) \quad (2)$$

$$S_L^{-1}\eta(t) = \Psi(t) + S_L^{-1}e(t) \quad (3)$$

$$\widehat{\Psi}(t) = S_L^{-1}\eta(t) \quad (4)$$

The processing unit decodes the received signal to recover the fiber impulse response. Assuming ideal WDM isolation, each channel is processed independently, with receiver noise transformed through the decoding operation.

Inverse simplex decoding transforms the noise term and, as reported by Lee et al., provides a net SNR improvement over conventional single-pulse OTDR. For an ideal receiver, the restored trace exhibits a mean square error of $\frac{4\sigma^2}{(L+1)^2}$, whereas conventional averaging OTDR yields $\frac{\sigma^2}{L}$ under the same measurement time. The resulting simplex coding gain is :

$$G_{SC} = \frac{L+1}{2\sqrt{L}} \quad (5)$$

This gain increases monotonically with code length L and is the direct consequence of the SNR improvement achieved through simplex encoding and inverse decoding.

The proposed architecture interrogates N wavelength channels simultaneously, each carrying one row of S_L and each independently receiving the full coding gain G_{SC}. Since the system acquires N coded measurements within a single acquisition cycle rather than sequentially, the effective system-level gain is:

$$G_\lambda = N(G_{SC}) = N\left(\frac{L+1}{2L}\right) \quad (6)$$

The increase in coding gain corresponds to an improvement in the achievable dynamic range. Assuming a fiber attenuation coefficient α (dB/km), the following expression estimates the additional one-way sensing distance:

$$\Delta R \approx \frac{\Delta DR}{2\alpha}, \qquad \Delta DR = 20\log_{10}(G)$$

where ΔR is the estimated additional sensing distance, ΔDR is the dynamic range improvement in decibels, G denotes the corresponding gain (G_{SC} or G_λ), and α is the fiber attenuation coefficient. These expressions analytically estimate the potential sensing range enhancement achievable through coding gain and WDM-assisted parallel acquisition.

Thus, the estimated sensing range enhancement scales with the corresponding gain and provides an analytical indication of the potential performance improvement achievable through simplex coding and WDM-assisted parallel acquisition under comparable operating conditions.

Since WDM parallelism does not alter the probe pulse width or per-channel launch conditions, the spatial resolution remains unchanged:

$$\Delta z_{WDM} = \Delta z_{Simplex}$$

5. Results and Analysis

Table 1 summarizes the combined effect of increasing the simplex code length L and the number of wavelength channels λ_N on the effective system-level gain and the corresponding analytical sensing range improvement.

Table 1: Simplex Coding Gain Vs Effective System-Level Gain with Estimated Sensing Range

Code length, L	Gain/Range, G_{SC} /ΔR km	Wavelengths, λ_N	Gain/Range, G_λ /ΔR km
3	1.155/3.042	$\lambda_{1,2,3}$	3.464/26.975
7	1.512/8.985	$\lambda_{1,2,..7}$	10.584/51.232

The sensing range values are analytical estimates computed from the corresponding gain values assuming a fiber attenuation coefficient of 0.2 dB/km under ideal operating conditions [5, 6]. The analytical sensing range estimates are calculated from the corresponding coding gains under ideal operating conditions. As the simplex code length increases from L=3 to L=7, the simplex coding gain increases from 1.15 to 1.51, resulting in an estimated sensing range improvement from 3.04 km to 8.96 km. Similarly, the effective system-level gain increases from 3.46 to 10.58, corresponding to an estimated sensing range enhancement from 26.95 km to 51.23 km.

These results show that combining simplex coding with WDM-based parallel acquisition improves the effective system-level performance while preserving the probe pulse width and, consequently, the spatial resolution of the OTDR system.

6. Conclusions

We have proposed a WDM-assisted simplex-coded OTDR architecture that integrates wavelength-division multiplexing with simplex coding to enable parallel fiber interrogation. By assigning independent simplex-coded pulse sequences to multiple wavelength channels, the proposed framework exploits wavelength-domain parallelism while preserving the conventional simplex encoding and decoding process.

We have developed a mathematical model for multiplexed transmission, backscatter reception, and inverse simplex decoding and presents the corresponding gain analysis. The theoretical results demonstrate that each wavelength channel retains the simplex coding gain, while WDM-based parallel acquisition enhances the effective system-level performance. The performance evaluation further indicates that increasing both the simplex code length and the number of wavelength channels enhances the effective system-level gain and extends the analytical sensing range under ideal operating conditions. Overall, the proposed architecture offers a scalable approach for improving measurement efficiency and signal acquisition capability without altering the probe pulse width or compromising spatial resolution. Future work will focus on simulation and experimental validation of the proposed framework, including the investigation of wavelength crosstalk, insertion losses, and receiver noise under practical operating conditions.

References

1. De Lee H., Yoon P., Kim T., Park I., Park N., “Optimization of SNR Improvement in the Noncoherent OTDR Based on Simplex Codes”, Journal of Lightwave Technology, 2006, 24 (1), 322–328.
2. Lee D., Yoon H., Kim N.Y., Lee H., Park N., “Analysis and Experimental Demonstration of Simplex Coding Technique for SNR Enhancement of OTDR”, 2004 1st IEEE Lightwave Technologies in Instrumentation and Measurement Conference, 2004, 118–122.
3. Park J., Bolognini G., Lee D., Kim P., Cho P., Di Pasquale F., Park N., “Raman-Based Distributed Temperature Sensor With Simplex Coding and Link Optimization”, IEEE Photonics Technology Letters, September 2006, 18 (17), 1879–1881.
4. Baudzus L., Krummrich P.M., “CDM-Based λ-OTDR for Rapid TDM- and WDM-PON Monitoring”, IEEE Photonics Technology Letters, June 2014, 26 (12), 1203–1206.
5. G.P. Agrawal, Fiber-Optic Communication Systems, 5th ed., Hoboken, NJ, USA, Wiley, 2021.
6. A.H. Hartog, An Introduction to Distributed Optical Fibre Sensors, Boca Raton, FL, USA, CRC Press, 2017.