Implementation of a Super-resolution Algorithm to Improve Spatial Resolution of Optical Signals

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***Abstract*—An Optical Time Domain Reflectometer (OTDR) is the most widely used instrument to monitor problems in currently installed optical fiber. It evaluates the physical characteristics of optical fiber, such as transmission loss and connection loss. It is important to increase the spatial resolution to accurately detect optical path problems using an OTDR. When the pulse width is greater than twice the distance between the two reflectors, the two reflected pulses overlap, and it is not possible to distinguish the reflected signal. To overcome these limitations, this paper proposes a spatial resolution–enhancement method by applying a super-resolution algorithm. As a result of digital signal processing implementation in TMS320C6455T DSP board, it is possible to analyze the event interval more precisely by improving the resolution when applying the super-resolution algorithm.**

Keywords—optical time domain reflectometer; spatial resolution; cross-correlation; super-resolution algorithm.

I. INTRODUCTION

The wired communications market is switching to fiber to the home (FTTH). With downsizing of base stations due to the competition of fourth-generation (4G) LTE services and the spread of optical repeaters, the mobile communications market has widely spread to antenna towers within a 25 km radius. With the advent of 5G and revitalization of the Internet of Things market, the use of optical fiber will increase sharply in the future. The OTDR is the most widely used instrument for monitoring problems in currently installed optical fiber. The OTDR is designed to test FTTx networks and evaluate the physical properties of the fiber, such as transmission loss and connection loss. The OTDR is widely used in the manufacture, construction, and maintenance of fiber optic communications systems. It is important to increase the spatial resolution to accurately detect optical path problems using an OTDR. Spatial resolution is the most representative parameter for OTDR performance, along with dynamic range. When the pulse width is less than twice the distance between two reflectors, the signals from them are reflected without overlap, and the reflected signal can be distinguished. However, when the pulse width is greater than twice the distance between the two reflectors, the reflected pulses overlap, and it is not possible to distinguish the reflected signal. Spatial resolution must be increased to distinguish the signal. To increase the spatial resolution, a narrow pulse width of 10 ns or less should be used. However, as the width of the pulse narrows, the distance of measurable optical fiber is shortened, and a receiver having a large reception bandwidth is required. As the receiving bandwidth increases, the amount of noise in the receiver increases proportionally, so the dynamic range of the OTDR decreases. That is, a conventional OTDR based on a single pulse has a tradeoff relationship between spatial resolution and dynamic range. To overcome this problem, a cross-correlation–based OTDR method was proposed [1]. Although this method has several advantages, such as increasing the dynamic range without sacrificing spatial resolution, it is still limited by the electron modulation bandwidth [2]. Therefore, a new super-resolution algorithm is needed to overcome these limitations and improve resolution.

In this paper, we propose a method of improving the spatial resolution of an OTDR based on cross-correlation by applying a super-resolution algorithm. We evaluate the spatial resolution performance of the OTDR by comparing the proposed method with a cross-correlation–based OTDR via Digital Signal Processing (DSP) implementation.

This paper is organized into five sections. Section 2 describes the cross-correlation–based OTDR system, and Section 3 analyzes the super-resolution algorithm for resolution enhancement. Section 4 describes the algorithm's implementation and offers an analysis of the results. The main conclusions are in Section 5.

II. CROSS-CORRELATION BASED OTDR SYSTEM

A cross-correlation–based OTDR can be divided into three major parts, as shown in Figure 1: the transmitter, which mixes the downstream data signal with a pseudo noise signal, the part of the optical fiber that experiences various losses and reflections, and the receiver, which receives and analyzes the signal. The data signal is separated into a reference signal for correlation using a tap, a signal back-reflected from the optical fiber and received through a photodetector, and an OTDR trace that can be drawn by cross-correlation with the reference signal. A cross-correlation–based OTDR using a Golay signal can obtain the OTDR trace through cross correlation of $v(\mathrm{t})$ and Golay signals received through a Photo Diode (PD). The

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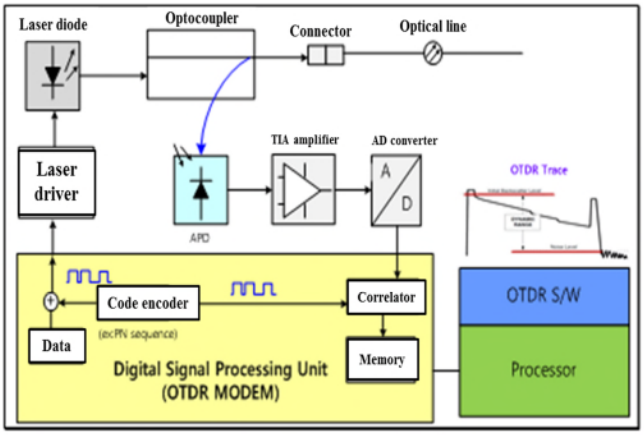

Figure 1. Cross-correlation-based OTDR system model

cross-correlation result of the two signals, $C(\gamma)$, can be expressed as:

$$\begin{aligned} C(\gamma) &= \int_0^{m\Delta t} v(t)s(t-\gamma)dt \\ &= \int_0^{m\Delta t} v_0(t)s(t-\gamma)dt + \\ &\quad \int_0^{m\Delta t} n_{thm}(t)s(t-\gamma)dt + \int_0^{m\Delta t} n_q(t)s(t-\gamma)dt \\ &= C_0(\gamma) + C_{thm}(\gamma) + C_q(\gamma) \end{aligned} \quad (1)$$

Cross correlation between the signal returned from the OTDR and the Golay signal has a range of *0* to $m\Delta t$, where *m* is the length of the Golay signal, given as $m = 2^{\text{golay}} - 1$, and Δt is the interval between one bit in the Golay signal. That is, $m\Delta t$ is the time corresponding to one period of the Golay signal. $C_0(\gamma)$ denotes the measured reflectivity, $C_{thm}(\gamma)$ denotes the thermal noise generated from the TIA(Transimpedance Amplifier), and $C_q(\gamma)$ denotes the ADC(Analog to Digital Converter) quantization term. $C_{thm}(\gamma)$ and $C_q(\gamma)$ are terms related to the noise level when there is no backscattering signal on the OTDR trace, and $C_0(\gamma)$ determines the shape of the OTDR trace.

III. Analysis of the Super-Resolution Algorithm to Improve Resolution

When the pulse width is more than twice the distance between the two reflections, the signal in which the two reflected pulses overlap and are reflected is not distinguishable. Therefore, a super-resolution algorithm to distinguish it is necessary. Among the signal processing methods available, the Multiple Signal Classification (MUSIC) algorithm is the most widely used. Although computational complexity is high, it is known as a technology that can provide highly accurate estimations [3]. The MUSIC algorithm is used to estimate the spatial spectrum of an incoherent signal. When the signal is coherent, the coherent signal will be combined into one signal, and the received independent signal is reduced in size due to the interference signal. This leads to less covariance matrix rank reduction and a larger number of eigenvalues than the incoming signal. To solve this problem, a method for reconstructing a conjugate matrix of a data matrix was proposed [4]. The proposed technique is based on the eigenvalue decomposition of the autocorrelation matrix of received signal $C(\gamma)$. The procedure for implementing the proposed OTDR-based super-resolution algorithm is as follows. The energy value of signal $C(\gamma)$, cross-correlated to find the reflection point of the raw data signal, is calculated, and the peak value extracted. This is a result of not applying the algorithm. Second, $C(\gamma)$ is applied to the resolution algorithm to derive reflection point results. We compare the performance of the second resolution algorithm by outputting the first and second results together. First, covariance matrix R of the received signal is expressed with Equation (2):

$$R_x = \mathrm{E}\{C(\gamma)C^H(\gamma)\} = \mathrm{APA}^H + \sigma_n^2 I = R_s + R_w \quad (2)$$

where *H* denotes the Hermitian transpose, and A is the signal gain value (A = 1). From Equation (1), covariance matrix *R* can be represented by the combination of signal covariance matrix R_s and noise covariance matrix R_w. $P = \mathrm{E}\{C(\gamma)C^H(\gamma)\}$ is the $k \times k$ covariance matrix of the signal. Assuming that additive noise is not correlated. The mean of noise is 0, and variance is equal to σ_n^2, and the covariance matrix can be expressed as $R_w = \sigma_n^2 I$. R_s is an *m*-by-*m* matrix with explicit matrix coefficients (Rank), where *m* is the number of signals reflected in the event interval. Therefore, each *(m-k)* eigenvector corresponds to a noise vector *m* by a *k* that has eigenvalue 0. As a result, the signal vector is orthogonal to the (*m-k*) noise vector. If there is no correlation between *k* signals, rank(APA^H) = *k*. Using this, covariance matrix R of the received signal is divided into a signal subspace and a noise subspace, and can be expressed by Equation (3):

$$R_x = \mathrm{APA}^H + \sigma_n^2 I = U_S \Lambda_S U_S + U_N \Lambda_N U_N \quad (3)$$

where $U_S = [u_1, u_2, \cdots, u_k]$ is the signal eigenvector matrix, and $U_N = [u_{k+1}, u_{k+2}, \cdots, u_m]$ is the noise eigenvector matrix, which then make transformation matrix *T*, where *T* is an m-order inverse unit matrix referred to as a transition matrix:

$$T = \begin{bmatrix} 0 & 0 & \cdots & 1 \\ 0 & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & 0 \\ 1 & 0 & \cdots & 0 \end{bmatrix} \quad (4)$$

when $\mathrm{Y} = TC_0^*(\gamma)$, $C_0^*(\gamma)$ is a complex conjugate of $C_0(\gamma)$. The covariance matrix Y is as follows:

$$R_y = \mathrm{E}\{YY^H\} = TRY^*(r)T \quad (5)$$

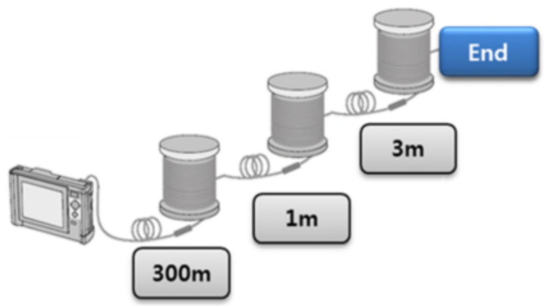

Figure 2. OTDR measurement environment

Figure 3. TMS320C6455T DSP board

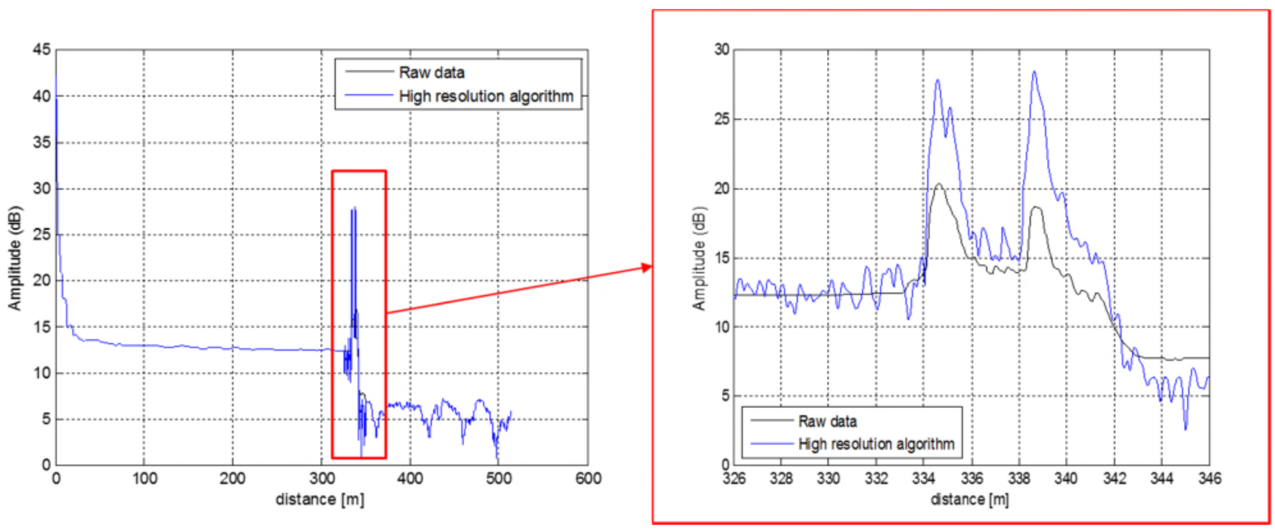

Figure 4. High resolution algorithm DSP implementation result

Here, R is the sum of R_x and R_y, and the reconstructed conjugate matrix can be obtained using the above equation:

$$R = R_x + R_y = \mathrm{APA}^H + T[\mathrm{APA}^H]^* T + 2\sigma_n^2 I \quad (6)$$

According to matrix theory [5], if **u** is an eigenvector corresponding to the zero eigenvalue of matrix APA^H, **u** must be an eigenvector corresponding to the eigenvalue of matrix $T[\mathrm{APA}^H]^* T$. Thus, the matrices R_x, R_y, and R has same noise subspaces. When eigenvalue decomposition is performed on R, eigenvalues and eigenvectors are obtained.

The noise subspace between the eigenvectors can be distinguished according to the number of signals to be estimated, as follows:

$$R = \widehat{U}_S \widehat{\Lambda}_S \widehat{U}_S + \widehat{U}_N \widehat{\Lambda}_N \widehat{U}_N \quad (7)$$

The MUSIC spatial spectrum is composed of the new noise subspaces, as follows:

$$F_{improved} = \frac{1}{A^H \widehat{U}_N \widehat{U}_N^H A} \quad (8)$$

IV. Algorithm Implementation and Results Analysis

In this section, we analyze performance by implementing the super-resolution algorithm in TMS320C6455T DSP board. First, the measurement environment is shown in Figure 2. Three events were created, 334 m and 335 m, and 338 m from the starting point, followed by the endpoint. The measurement parameters were set to a wavelength of SM1310 nm at a distance of 500 m. The pulse width was 3 ns, with the average amount of data at 2^{14}. The refractive index was 1.46, the total size of the data was 10,000 samples, and the data sampling interval, 5 cm. Figure 3 shows the TMS320C6455T DSP board that was used. The DSP chip used in the emulator implementation is a Texas Instruments TMS320C6455; the CPU operates at 1.2 GHz, flash

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memory was 2 MB, and Dynamic Random Access Memory (DRAM), 512 MB. However, with flash memory at 2 MB, if the program becomes complicated and the amount of computation increases, operation of the program becomes possible through DRAM. In this case, although the amount of DRAM is large, it is possible to expand the program, but the operating speed is slower than operation through flash memory. To configure the real-time system, consideration of memory management is also required [6].

The results of the DSP implementation in the above measurement environment are shown in Figure 4. Results from the DSP were stored and represented in Matlab. The black graph represents the raw data, and the graph outlined in red is from the super-resolution algorithm. It can be confirmed that an event occurs near 330 m in the total length of 500 m. If you look at the enlargement, you can see that the first event occurred at 334 m, and there is an event after another 1 m, and you can see that an event occurs after another 3 m. With raw data, you cannot decompose 1 m of 334 m and 335 m. From applying the resolution algorithm, the resolution improves, and the 1 m event interval that the raw data cannot decompose is correctly decomposed. The size of the signal level is also improved by about 8 dB, so the event interval can be more accurately distinguished.

V. CONCLUSION

In general, the performance of an OTDR is determined by its dynamic range and spatial resolution. In this paper, we analyzed the MUSIC algorithm to improve the resolution performance of the OTDR, and we implemented an improved MUSIC algorithm to compensate for the incoherent characteristics of the MUSIC algorithm. As a result of analyzing the performance of the algorithm through DSP implementation, we correctly decomposed events of 1 m intervals that could not have been resolved before, and the variation of the signals was also reduced. Compared with the raw data, the signal level improved by about 8 dB.

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