New Methods for Non-Destructive Underground Fiber Localization using Distributed Fiber Optic Sensing Technology

Hansi Liu
NEC Laboratories America, Inc
Priceton, NJ, U.S
haliu@nec-labs.com

Ming-Fang Huang
NEC Laboratories America, Inc
Priceton, NJ, U.S.
mhuang@nec-labs.com

Yuheng Chen
NEC Laboratories America, Inc
Priceton, NJ, U.S.
yuhengchen@nec-labs.com

Xiaoran Fan
Rutgers University
North Brunswick, NJ, U.S.
ox5bc@winlab.rutgers.edu

Ting Wang
NEC Laboratories America, Inc
Priceton, NJ, U.S.
Ting@nec-labs.com

Marco Gruteser
Rutgers University
North Brunswick, NJ, U.S.
gruteser@winlab.rutgers.edu

***Abstract*— To the best of our knowledge, we present the first underground fiber cable position detection methods using distributed fiber optic sensing (DFOS) technology. Meter level localization accuracy is achieved in the results.**

***Keywords*— Fiber optics sensor, underground cable poisoning**

I. Introduction

Society's unyielding and exponentially increasing data demands (e.g. imminent 5G) have spurred Global telecom carriers to build large scale optical fiber infrastructures [1]. Localizing and visualizing the underground fiber cables is of great significance for telecom carriers and network providers to maintain the facilities efficiently. Recently, there is a growing demand for high-precision underground cable localization using non-destructive methods, especially for old deployed cable which was lack of GPS location and up-to-date cable route information. Underground object localization can be performed using vibration sensors such as geophones and accelerometers [2]. However, they are limited to detecting large/bulky objects which have very different properties than the surrounding soil and are buried deep under the ground. Other methods utilizing Electromagnetic (EM) wave and ground penetrating radar (GPR) [3], which requires comprehensive planning of the scan pattern and carefully inspection of the data to find out the potential locations of the objects in interest. Optical fiber, in fact, is a material which can be used as a sensor as well. By adding sensing functions on fiber infrastructure, new feature has sparked a lot of interests in many fields with a broad scope of potential applications such as road traffic monitoring [4], seismic profiling [5], near-surface soil property estimation [6] and earthquake seismology [7].

In this paper, a new non-destructive method to locate underground cables by distributed fiber optic sensing (DFOS) technology is proposed and experimentally demonstrated. With the help of point vibration excitations and time difference of arrivals (TDOA) estimation, meter-level localization accuracy has been achieved in an in-homogeneous buried environment.

II. Proposed Method and System Setup

Fig. 1 shows the diagram of proposed scheme to locate underground cable position. The scheme consists of three steps as impulse-like vibration excitation, TDOA estimation of the received signals from DFOS and a new algorithm for non-linear least square optimization and fiber segment localization.

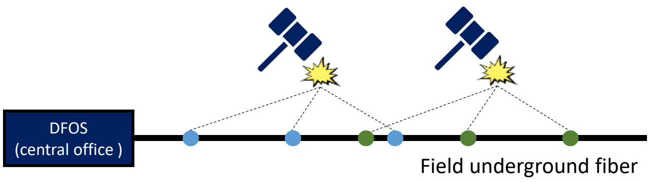

Fig.1: Diagram of proposed architecture

The DFOS system is sitting in the central office and connected to the field underground fiber whose position is unknown. By detecting relative phase shift of the reflectance of coherent Rayleigh scattering light wave, the environmental vibration information can be captured by DFOS systems. It employs short optical pulses along with on-chip fast processing to enable an equivalent sensor resolution as small as 1 meter. The details of DFOS systems can be found in [4]. Inspired by seismic survey, the hammer-plate method is adopted as the excitation source to produce impulsive isotropic point vibration. Fig. 2(a) illustrates the top down view of the experimental configuration for data collection. For every test, a sequence of impulsive vibration are excited at different source locations (X_{s_i}) and received signal at 3 locations of fiber segments (X_{r_1}, X_{r_2}, and X_{r_3}) with L meters of consecutive spacing were recorded under synchronization of DFOS. Considering that the seismic vibration propagated underground is dominated by low frequencies, a band-pass filter was applied to the analyzer as pre-processing for TDOA estimations. Considering dispersion of different frequency components of vibration, as well as non-linear and in-homogeneous property of the soil medium, first arrival detection was chosen over cross correlation to compute time difference of arrival of signal, as first arrival detection methods are more robust to dispersion than cross correlation. In practice, the CuSum algorithm [8] was adopted to detect anomaly or sudden increments of the signal and determine the timestamps for each signal's first arrival moment. Eventually, time differences of arrival with respect to a specific received point are computed as TDOA.

To better understand how TDOA information is fully utilized to estimate the position of fiber segment, the geometry in Fig. 2(a) is studied in this subsection. The coordinates of each vibration source is denoted as X_{s_i}, and the coordinates of the 3 consecutive received points are denoted as X_{r_1}, X_{r_2}, X_{r_3} respectively, where X_{s_i} is known and X_{r_1}, X_{r_2}, X_{r_3} are unknowns that determine a 2D location of the fiber segment. Fig. 2(b) describes the received signal at 3 DFOS received points. The red dots represent the anomaly or sudden

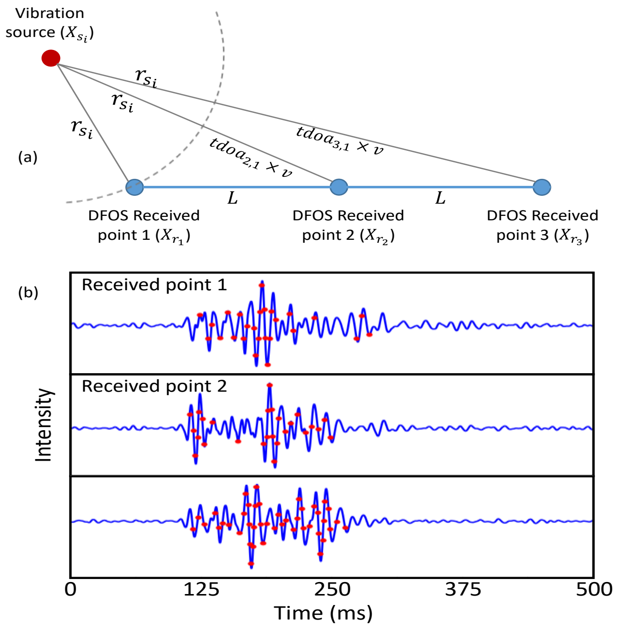

Fig. 2: (a) Top down view of the experimental configuration. (b) Waveform captured from received signals

changes detected by the CuSum algorithm. The first red dot is used to indicate the first arrival timestamp of the vibration. Assuming that most of the vibration energy arrives at received points through direct path, the following systems of equations can be obtained:

$$\begin{cases} r_{s_i} - \left\|X_{s_1} - X_{r_1}\right\|_2 = 0 \\ r_{s_i} + tdoa_{i_{2,1}} \times v - \left\|X_{s_1} - X_{r_2}\right\|_2 = 0 \\ r_{s_i} + tdoa_{i_{3,1}} \times v - \left\|X_{s_1} - X_{r_3}\right\|_2 = 0 \end{cases} \quad (1)$$

where s_i is the vibration source index and r_{s_i} denotes the vibration's transmission path from source s_i to received point 1. $tdoa_{i_{k,1}}$ denotes the TDOA between received signals at receiver point k and 1. v represents the vibration propagation speed in the vicinity of the fiber segment. Notice that the underground signal propagation speed is an unknown variable. One assumption has been made as it is constant in the vicinity of the fiber segment. Considering that most of the time the structure of the underground fiber is a line segment and the received points are co-linear, the following system of equations is obtained:

$$\begin{cases} \left\|X_{r_1} - X_{r_2}\right\|_2 = L \\ \left\|X_{r_2} - X_{r_3}\right\|_2 = L \\ \left\|X_{r_1} - X_{r_3}\right\|_2 = 2L \end{cases} \quad (2)$$

Working out the equations in (1) and (2) analytically is cumbersome and complicated due to the second order non-linearity. Instead, a system of residuals is defined by replacing the zeros in (1) with error terms as following:

$$\begin{cases} r_{s_i} - \left\|X_{s_1} - X_{r_1}\right\|_2 = e_{i,1} \\ r_{s_i} + tdoa_{i_{2,1}} \times v - \left\|X_{s_1} - X_{r_2}\right\|_2 = e_{i,2} \\ r_{s_i} + tdoa_{i_{3,1}} \times v - \left\|X_{s_1} - X_{r_3}\right\|_2 = e_{i,3} \end{cases} \quad (3)$$

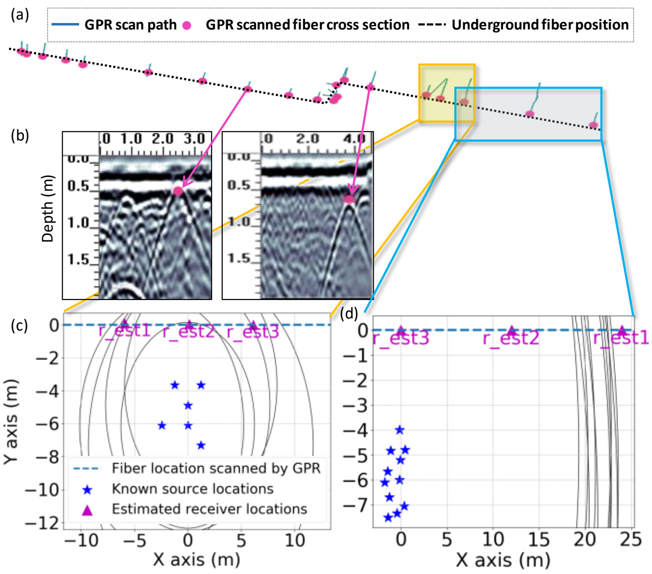

Fig. 3: (a) Underground fiber segment cross sections and topology determined by GPR scans. (b) GPR scanned data for selected sections. (c) and (d) Estimated fiber received points and fiber section structure in 2D.

where $e_{i,j}$ denotes the error between the source-receiver distance and actual signal transmission range. To make (3) identical as (1), all of the error terms should be as close to zero as possible. In this manner, a non-linear least square optimization with non-linear constraint is formulated as following:

$$\min_{X_{r_1}, X_{r_2}, X_{r_3}} \sum_{i}^{M} \sum_{j}^{N} e_{i,j}^2$$

$$s.t. \begin{cases} \left\|X_{r_1} - X_{r_2}\right\|_2 = L \\ \left\|X_{r_2} - X_{r_3}\right\|_2 = L \\ \left\|X_{r_1} - X_{r_3}\right\|_2 = 2L \end{cases} \quad (4)$$

where M is the number of vibration sources and N = 3 is the number of received points on the fiber segment. Based on the above optimization, the locations of the received points can be estimated, thus determine the location of the underground fiber segment. In order to evaluate the optimization result, the localization error is defined as the average Euclidian distances between ground truth fiber receiver points and the estimated ones.

III. PERIMENTAL RESULTS AND DISCUSSIONS

Fig. 3 shows the experimental results with signal responses of one hammer-plate strike captured by 3 consecutive received points on buried fiber segments. In order to have a ground truth cable location, one GPR (Sensors & Software Noggin 250 SmartCart) has been used for site scanning as shown in Fig. 3(a). Twenty line-scans were made in the field to determine the topology of the underground fiber with length of 120 m. When the GPR was scanning across a fiber cable, the intensity pattern of reflected electromagnetic wave forms a hyperbola. Fig. 3(b) presents two examples of underground signatures monitored by GPR, the pink dots at the tops of the hyperboles indicate the position and depth of cross sections of the underground fiber. It can be seen that the cable buried for tests are at the depth of 0.5 – 0.7 m.

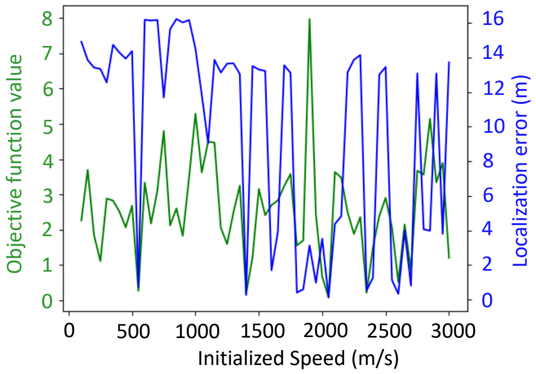

Fig. 4: Value of objective function and localization error under different speed initializations

Hence, the layout of the underground cable can be determined by connecting cross sections (pink dots in Fig. 3(a)) from multiple scans. Fig. 3(c) and 3(d) presents the localization results for two zoomed-in area of a 12 m and a 24 m fiber segment shown in Fig. 3(a), respectively. The result shows that the estimated fiber received points form straight line that is close to the ground truth structure determined by GPR. It is worth mentioning that the objective function in the proposed optimization method is non-convex. In order to achieve global minimum that corresponds to the smallest localization error, in practice, a brute-force search was conducted within a reasonable range of initialized speed and the optimization in (4) was considered multiple times. As Fig. 4 shows, each speed initialization leads to a local minimum. For the results shown in Fig. 3(c), at the initialization of v = 2050 m/s, the global minimum was reached where the averaged localization error is minimized to 0.13 meters for each fiber receiver point. Moreover, the value of v converged to 322.51 m/s. Notice that this value may not be the exact vibration speed in the soil since the outdoor environment is in-homogeneous. However, due to the assumption that the vibration is constant, this value can be regarded as the average transmission speed of the vibration, which is in consistent with the literatures in which vibration propagation speed in near-surface soil is reported around 100-500 m/s [1][10].

The localization result shown in Fig. 3(c) only provides the situation in which all 6 vibration sources are used. The relationship between the number of vibration sources and localization error is discussed. Here, subsets of the 6 vibrations sources in Fig. 5 were utilized to compute localization errors under different number of vibration sources and vary of received spacing. As shown in Fig. 5(a), when the number of vibration sources increases in the optimization algorithms, less localization error is achieved with lower median and standard deviation. The trade-off between the receiver point spacing and localization error is also explored in Fig. 5(b). When the spacing between two receiver points is 6 m, minimum localization error with smallest deviation is achieved.

IV. Conclusion

In this paper, a method for localizing underground fiber using distributed fiber optic sensing is proposed and experimentally demonstrated. By leveraging impulsive vibrations and TDOA information of received signals from multiple receiver points along a fiber segment, it is possible

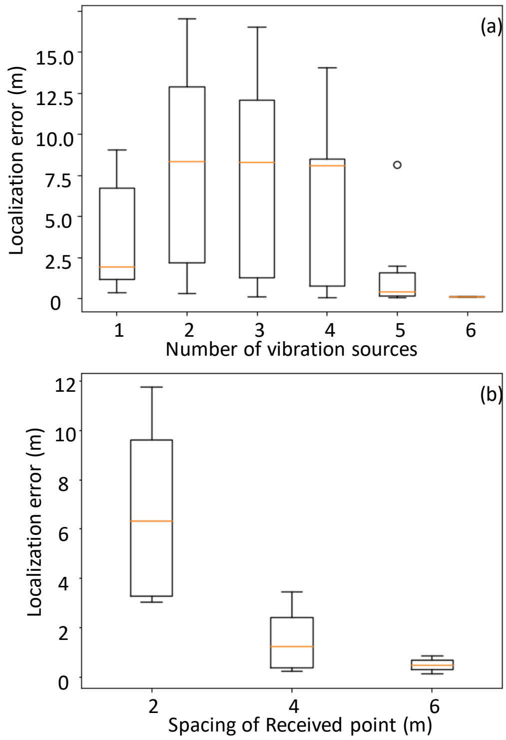

Fig. 5. Localization error as a function of (a) different number of vibration sources, (b) received spacing

to estimate the 2D location of a straight fiber segment by solving a non-linear optimization problem even when the vibration speed is unknown. Experiments show that meter-level accuracy for a 24 m fiber cable segment is achieved. Future works include conducting the experiment in more complex environments and larger scales.

References

[1] Fierce Telecom, From AT&T to Fatbeam: The top 10 (and more) biggest providers of fiber in the U.S., 2015.

[2] J. Muggleton, M. Brennan, and C. Rogers. Point vibration measurements for the detection of shallow-buried objects. Tunnelling and Underground Space Technology, 39:27–33, 2014.

[3] D. J. Daniels. Ground penetrating radar. Encyclopedia of RF and microwave engineering, 2005.

[4] M.-F. Huang *et al.*, *JLT*, vol. 38, pp. 75 – 81, 2020.

[5] A. Mateeva, J. Lopez, H. Potters, J. Mestayer, B. Cox, D. Kiyashchenko, P. Wills, S. Grandi, K. Hornman, B. Kuvshinov, et al. Distributed acoustic sensing for reservoir monitoring with vertical seismic profiling. Geophysical Prospecting, 62(4):679–692, 2014.

[6] R. D. Costley, G. Galan-Comas, C. K. Kirkendall, J. E. Simms, K. K. Hathaway, M. W. Parker, S. A. Ketcham, E. W. Smith, W. R. Folks, T. W. Milburn, et al. Spectral analysis of surface waves with simultaneous fiber optic distributed acoustic sensing and vertical geophones. Journal of Environmental and Engineering Geophysics, 23(2):183–195, 2018.

[7] N. J. Lindsey T. C. Dawe, and J. B. Ajo-Franklin. Illuminating seafloor faults and ocean dynamics with dark fiber distributed acoustic sensing. Science, 366(6469):1103–1107, 2019.

[8] E. S. Page. Continuous inspection schemes. Biometrika, 41(1/2):100–115, 1954.

[9] S. Castellaro and F. Mulargia. Vs 30 estimates using constrained h/v measurements. Bulletin of the Seismological Society of America, 99(2A):761–773, 2009.

[10] M. L. Oelze, W. D. O'Brien, and R. G. Darmody. Measurement of attenuation and speed of sound in soils. Soil Science Society of America Journal, 66(3):788–796, 2002.