Wavelength-Division Multiplexed Fiber-Connected Sensor Network for Source Localization

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***Abstract*— A fiber-connected source localization sensor network based on optical wavelength-division multiplexing technology is proposed and demonstrated. Thanks to the wavelength-division multiplexed architecture, the signals from the emitter received by different sensors can be identified by different optical carriers, and no clock synchronization or parameter estimation is required at the sensor nodes, which greatly simplifies the entire system. Also, since the received signals are separated in the wavelength domain, the proposed system is suitable for both pulsed and nonpulsed signal source localization, independent of the format of the emitted signal. A proof-of-concept experiment for two-dimensional localization of a wireless fidelity signal is demonstrated. Spatial resolution of less than 17 cm is achieved.**

***Index Terms*— Source localization, time difference of arrival, wavelength-division multiplexing, sensor network.**

I. INTRODUCTION

SOURCE localization has drawn great attention during the past few decades due to its wide applications in many areas such as radars, sonars, electronic warfare, wireless communications and so on [1], [2]. One common technique is to measure the time difference of arrivals (TDOAs) of the signal from the emitter to spatially separated sensor nodes in a sensor network [3], [4]. These sensors are conventionally connected to a central station by electrical cables or wireless, so the signal transmission is lossy, sensitive to the electromagnetic interference (EMI) and has limited working bandwidth [5], [6]. For broadband frequency spectra surveillance applications, the transmission loss, bandwidth and sensitivity to EMI are critical parameters. In addition, the sensor nodes in many traditional sensor networks have to pre-process the received signals, which requires precise clock synchronization, making the system complicated. Recently, several photonic approaches to realize position location have been reported [7], [8]. Thanks to the low loss, immunity to EMI and broad bandwidth brought by the photonic techniques, the schemes in [7] and [8] can realize high-resolution localization based on optical time-division multiplexing (OTDM). However, the OTDM structure requires ultrashort pulses to avoid signal overlap between different sensor nodes, which cannot be applied for the localization of arbitrary source. In addition, the length of the single mode fiber (SMF) between the adjacent sensors must be strictly selected according to the pulse repetition, pulse duration, sensor nodes separation and detection zone, making the system only applicable for some specific applications.

In this Letter, a fiber-connected sensor network for both pulsed and non-pulsed signal source localization based on optical wavelength-division multiplexing (WDM) technology is proposed and demonstrated. Thanks to the low loss and large bandwidth of the optical fiber, the signals received by different sensor nodes, which are identified by different optical carriers, are directly sent to the central station for processing. The sensor nodes only perform RF amplification and electrical-to-optical conversion, making the sensor nodes very simple. The centralized signal processing also allows for much complex algorithm to realize accurate time difference estimation. Since the received signals are separated in the wavelength domain, the proposed system is suitable for both pulsed and non-pulsed signal source localization, which is quite important for passive source localization system. The proposed system can also be used for passive localization of a target, in which condition the received signals are reflected from the target instead of from the source directly [8]. By using signal processing methods, such as using adaptive filters [9], the time differences between the reflected signals can be obtained to realize the target localization. A proof-of-concept experiment of signal source localization is carried out. Two-dimensional localization of a wireless fidelity (WIFI) signal source with a spatial resolution of less than 17 cm is realized.

II. PRINCIPLE

The schematic diagram of the proposed fiber-connected sensor network for source localization is shown in Fig. 1, which comprises a central station and several sensor nodes connected by optical fiber. The central station generates a number of CW lightwaves with different wavelengths,

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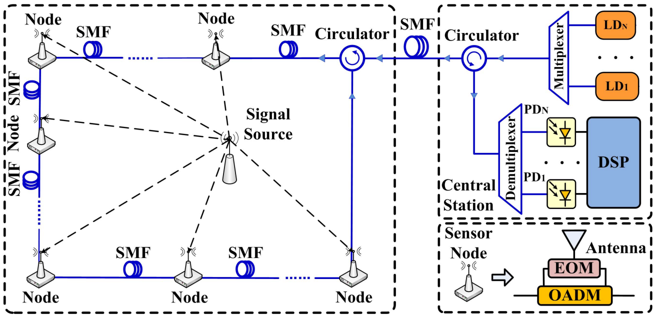

Fig. 1. Schematic diagram of the proposed wavelength-division multiplexed fiber-connected sensor network for source localization. LD: laser diode; EOM: electrical-to-optical modulator; OADM: optical add-drop multiplexer; PD: photodetector; SMF: single-mode fiber.

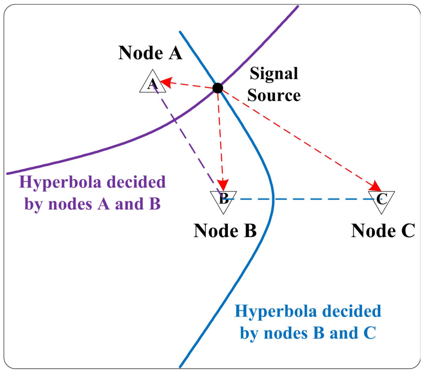

Fig. 2. Geometric model of two-dimensional source localization with three nodes.

which are sent to the sensor nodes. Each sensor node contains an antenna, an electrical-to-optical modulator (EOM) and an optical add-drop multiplexer (OADM). The OADM is used to drop the wavelength allocated to the sensor node, and the signal collected from the free space by the antenna is modulated on this wavelength at the EOM. The modulated optical signal is then added back to the WDM signal through the OADM and propagates to the next sensor node. After transmission in the ring sensor network, all the wavelengths are modulated and sent back to the central station. Since each node is assigned a particular wavelength, the signals received from different sensor nodes which are used to calculate the TDOAs for position information extraction can be easily identified at the central station.

In the proposed system, clock synchronization is not required, because all the received signals are sent to the central station via known lengths of SMF. For a stationary signal source, each TDOA defines a hyperbola in which the emitter must lie. Thus the source location is determined from the intersection of a set of TDOAs defined hyperbolic curves for two-dimensional position location or hyperboloids for three-dimensional position location. A two-dimensional localization scenario using three sensor nodes is shown in Fig. 2. The intersection point of the two hyperbolas decided by the TDOA between nodes A and B and that between nodes B and C gives the position of the signal source. From the above analysis, we can obtain the following relations,

$$\begin{cases} L_{\mathrm{SA}} - L_{\mathrm{SB}} = c(t_{\mathrm{SA}} - t_{\mathrm{SB}}) \\ L_{\mathrm{SC}} - L_{\mathrm{SB}} = c(t_{\mathrm{SC}} - t_{\mathrm{SB}}), \end{cases} \tag{1}$$

where c is the velocity of electromagnetic wave in vacuum, L_{SA}, L_{SB} and L_{SC} are the distances between the signal source and the nodes A, B and C, t_{SA}, t_{SB} and t_{SC} are the time of arrivals for the direct radiation from the signal source to the sensor nodes A, B and C, respectively. For a signal source with unknown position (x,y), and denoting the coordinates of the sensor nodes A, B, C as $(x_{\mathrm{A}}, y_{\mathrm{A}})$, $(x_{\mathrm{B}}, y_{\mathrm{B}})$ and $(x_{\mathrm{C}}, y_{\mathrm{C}})$, respectively, a set of equations for hyperbolas can be achieved,

$$\begin{cases} \sqrt{(x - x_{\mathrm{A}})^2 + (y - y_{\mathrm{A}})^2} - \sqrt{(x - x_{\mathrm{B}})^2 + (y - y_{\mathrm{B}})^2} \\ = c(t_{\mathrm{SA}} - t_{\mathrm{SB}}) \\ \sqrt{(x - x_{\mathrm{C}})^2 + (y - y_{\mathrm{C}})^2} - \sqrt{(x - x_{\mathrm{B}})^2 + (y - y_{\mathrm{B}})^2} \\ = c(t_{\mathrm{SC}} - t_{\mathrm{SB}}). \end{cases} \tag{2}$$

Since the positions of the three sensor nodes are fixed, $(x_{\mathrm{A}}, y_{\mathrm{A}})$, $(x_{\mathrm{B}}, y_{\mathrm{B}})$ and $(x_{\mathrm{C}}, y_{\mathrm{C}})$ are the known parameters. The parameters $(t_{\mathrm{SA}} - t_{\mathrm{SB}})$ and $(t_{\mathrm{SC}} - t_{\mathrm{SB}})$ are the TDOAs which can be obtained in the central station using TDOA estimation algorithm (e.g. generalized cross-correlation method [10]). It should be noted that the TDOAs obtained from the algorithm always include the transmission delays, which can be eliminated by delay calibration.

By solving (2), the location of the signal source, i.e. (x,y), can be obtained. Since the equations are nonlinear, the solution is not easy to get. Thus many methods have been developed to obtain precise position estimation at reasonable noise levels, such as Taylor-series method [11] and Chan's algorithm [12]. In our work, Chan's algorithm is applied as it is noniterative and needs less computational intensity. It should be noted that localization ambiguity might occur when the source is placed between or near the extended line of the two baselines. Thus the sensor nodes should be arranged carefully according to the detection zone, to avoid the localization ambiguity. In addition, four or more sensor nodes can be used to realize three-dimensional localization by placing the sensors at different planes [13].

The proposed system based on optical WDM technology can also be applied to locate multiple signal sources. The TDOA of each signal source can be obtained by using more complex TDOA estimation algorithms [1] and blind source separation methods [14]. Compared with the system based on OTDM [8], the proposed system based on WDM is suitable for both pulsed and non-pulsed signal source localization since the received signals are separated in the wavelength domain.

III. EXPERIMENT RESULTS AND DISCUSSION

A proof-of-concept experiment is carried out for two-dimensional localization of a WIFI signal source using three sensor nodes. A multi-channel laser source (Agilent N7714A) is used to generate three optical lightwaves at 1551.72, 1550.12 and 1548.51 nm, which are assigned to node A, B and C, respectively. Two dense wavelength division multiplexers (DWDMs) with 200-GHz channel spacing are used to multiplex /demultiplex the three channels. At each

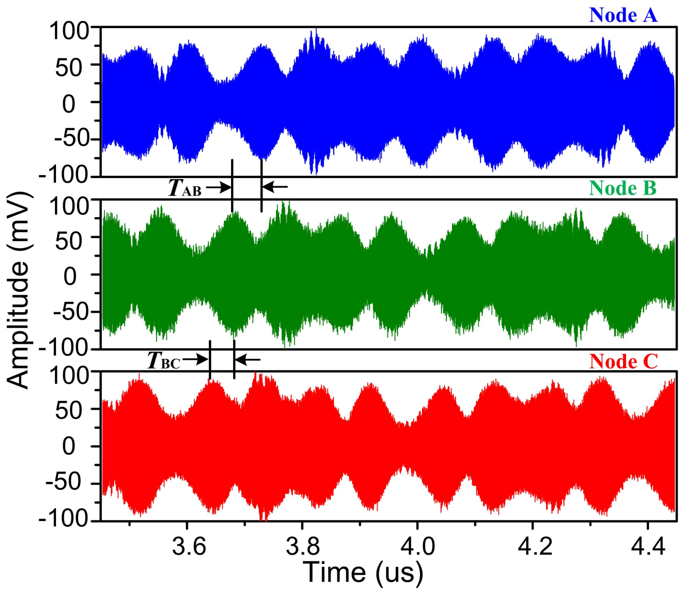

Fig. 3. The waveforms recorded at the output of the PDs for nodes A, B and C, respectively.

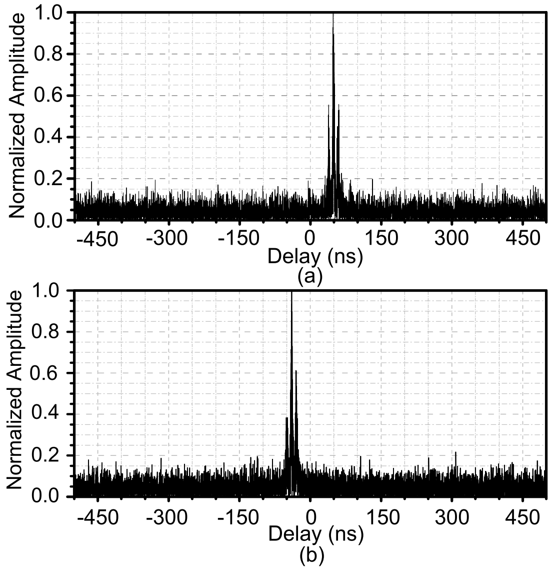

Fig. 4. Generalized cross-correlation results for achieving TDOAs between (a) nodes A and B and (b) nodes B and C.

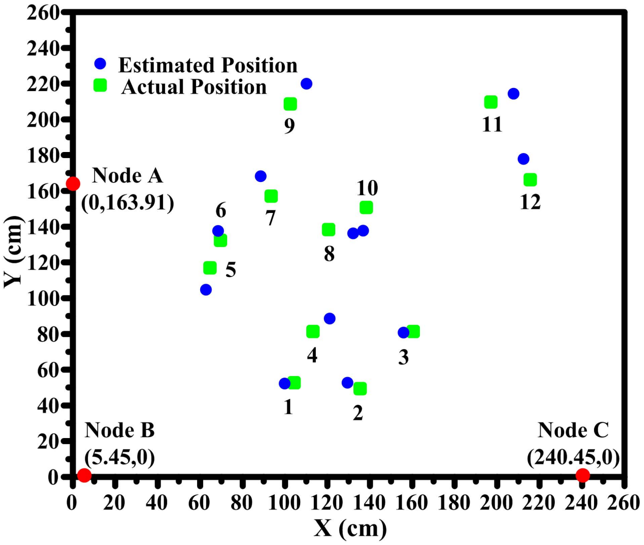

Fig. 5. The geometric locations of twelve samples of the estimated positions and their corresponding actual positions.

sensor node, a 200-GHz OADM is applied to separate the allocated wavelength from the WDM signal. Nodes A, B and C are located at (0 cm, 163.91 cm), (5.45 cm, 0 cm), (240.45 cm, 0 cm), respectively. An antenna and a Mach-Zehnder modulator (MZM) are used in each node to collect the emitted signal from the source and modulate it onto the corresponding optical carrier. The source signal is generated by a WIFI wireless router with working frequency between 2.4 and 2.48 GHz and a bandwidth of 20 MHz. A four-channel 4-GHz real-time oscilloscope (Agilent DSO9404A) with a sampling rate of 10 GSa/s is used to record the waveforms at the output of the PDs in the central station. The recorded data are processed and analyzed off-line.

Fig. 3 shows the recorded waveforms at the output of the three PDs in the central station corresponding to nodes A, B and C, respectively. The time difference between the waveforms can be observed clearly. By analyzing the power spectrum of the sampled time sequences, the signal-to-noise ratio (SNR) of the received signals is about 17 dB. The generalized cross correlation method using maximum likelihood estimator [10] is applied to get the accurate time difference, with the results shown in Fig. 4. By searching the peak of the correlation result, we can easily get that the time difference between nodes A and B is 48.5 ns (from Fig.4 (a)) and that between nodes C and B is −39.3 ns (from Fig.4 (b)). The system delay between nodes A and B or nodes B and C is obtained by subtracting the true delay from the estimated one. With the TDOAs and the given positions of the nodes A, B and C, the location of the signal source is estimated by Chan's algorithm to be (88.60 cm, 168.21 cm). As compared with the actual position of (93.53 cm, 156.97 cm), the localization error is 12.27 cm. The multipath effect will spread the correlation peak when the delays of different paths are close to each other; and multiple peaks will appear when the delays of different paths are far separated and the indirect-path signals are large enough. Thus the multipath effect will influence the TDOA estimation. Signal processing algorithms to restrain the multipath effect should be used [15]. In the experiment, the influence of multipath effect can be ignored since there are not obvious obstacles in the localization area.

To further investigate the accuracy of the proposed localization system, measurements are performed with twelve different source locations. The twelve estimated positions and the corresponding actual positions are shown in Fig. 5, with the position values and the location errors shown in Table I. The source locations for all these positions are successfully realized. Since the locations of the three nodes are carefully arranged, no localization ambiguity is observed. For more sensor nodes, the distribution of the sensor nodes can be evaluated by geometric dilution of precision [16]. From the data of Table I, we can find the maximum localization error of the system is less than 17 cm. The position precision is mainly depended on the accuracy of the estimated TDOA

TABLE I
TWELVE SAMPLES OF THE ACTUAL POSITION AND THE ESTIMATED POSITION OF THE TARGET

Sample	Actual Position	Estimated Position	Error (cm)
1	(104.28, 52.68)	(99.93, 52.18)	4.38
2	(135.43, 49.26)	(129.52, 52.64)	6.81
3	(160.46, 81.22)	(155.97, 80.69)	4.52
4	(113.21, 81.31)	(121.07, 88.53)	10.67
5	(64.73, 116.82)	(62.74, 104.63)	12.35
6	(69.66, 132.24)	(68.44, 137.55)	5.45
7	(93.53, 156.97)	(88.60, 168.21)	12.27
8	(120.63, 138.32)	(136.83, 137.66)	16.21
9	(102.52, 208.51)	(110.22, 219.81)	13.67
10	(138.43, 150.72)	(132.13, 136.16)	15.86
11	(197.12, 209.57)	(207.80, 214.36)	11.70
12	(215.71, 166.17)	(212.50, 177.80)	12.06

which is affected by the type of the received signal and the TDOA estimation algorithm applied.

Additionally, the localization area in the experiment is only a few square meters, which is limited by the experimental condition. The fibers used in the experiment have lengths of just around ten meters, thus the dispersion influence can be ignored. For the localization in a large area when long fibers are used, the dispersion of the fiber should be considered, and dispersion compensation methods should be used to eliminate the influence [17].

IV. CONCLUSION

A fiber-connected sensor network for both pulsed and non-pulsed signal source localization based on optical WDM technology was proposed and demonstrated. Thanks to the nature of low loss, wide bandwidth and immunity to electromagnetic interference of the optical schemes, the received signals at the sensor nodes were transmitted with negligible distortion to the central station via known lengths of SMF. As a result, no clock synchronization or parameter estimation was required in the sensor nodes. The complex signal processing was removed from each sensor node to the central station, making the sensors very simple, and more complex algorithm can be adopted in the central station for precise time difference estimation. The experiment for two-dimensional localization of a WIFI signal source shows that the system has a spatial resolution of less than 17 cm.

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