

# Fiber-distributed ultra-wideband radar network based on wavelength reusing transceivers

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**Abstract:** A fiber-distributed ultra-wideband (UWB) radar network based on wavelengthreusing transceivers is proposed and demonstrated. In the proposed system, wavelengthdivision multiplexing technology is applied to connect a central unit (CU) and several spatially separated transceivers. The optically generated UWB pulses in different transceivers are designed to have different polarities or shapes, so the CU can easily identify which transceiver the echo UWB pulse is emitted from. By applying the wavelength reusing, the wavelength of the uplink UWB pulse can also be used by the CU to identify which transceiver it is received by. Therefore, with very simple cooperative signal processing in the CU, the information of the target in the radar detection area can be extracted. In addition, because the fiber lengths in the network are known, clock synchronization in the transceivers is not required, which simplifies further the entire system. In an experiment, 2-D localization with localization accuracy of about one centimeter is achieved using the proposed radar network with two distributed transceivers.

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## 1. Introduction

Ultra-wideband (UWB) impulse radars have attracted considerable interests in the past decades because of the ground penetration, high range resolution, foliage penetration, low probability of intercept, high immunity to multipath effect, and frequency spectrum sharing provided by the impulse UWB pulses [1–6]. To increase the radar coverage, the capability of counter-stealth and multi-target detection, the angle resolution, and to obtain the information of the target from multiple perspectives, distributed UWB radar systems with spatially separated transceivers were proposed [4–11]. A typical distributed UWB radar contains a central unit (CU) and many transceivers, connected mainly by electrical cables [10] or wireless [5,11]. Due to the limited bandwidth (or multipath fading) and large transmission loss of these transmission media, one has to generate the UWB pulses and process the received UWB echoes in each transceiver. To make the cost and complexity of the transceiver acceptable, only very simple signal processing algorithms can be applied, inevitably reducing the performance of the radar network. In addition, the performance of the entire system would be further deteriorated by the complicated and inaccurate clock synchronization among the UWB transceivers [12,13].

On the other hand, with the rapid development of microwave photonics in the past three decades [14–16], the conventional implementation of radars can possibly be revolutionized by the photonic technologies, which provide advantages regarding broad bandwidth, low transmission loss and immunity to electromagnetic interference [17–21]. One attractive technology for the distributed UWB radar systems is called UWB over fiber [22-24], which generates the UWB signals using optical approaches, and transmits them to the remote antennas via optical fiber. By using this kind of technology, the signal processing can be moved from the transceivers to the CU which significantly simplifies the transceivers. Since more hardware resources can be integrated into the CU, algorithms that are more complex can be applied to improve the performance of the radar. Several UWB radars based on UWBover-fiber technology have been demonstrated [25–31]. In [25,26], photonic techniques are used to construct UWB noise radar systems, in which the optical UWB noise signal is produced in the CU and transmitted to a remote antenna through optical fiber. In the remote antenna unit, the received UWB echo signal is converted to be an optical signal and then sent back to the CU to calculate the range profile of the target. These two works demonstrated UWB noise radar systems with just one transceiver which can only achieve one-dimensional localization, i.e., can only measure the distance of the target. In [27], we demonstrated a distributed MIMO chaotic radar with two transmitters and two receivers, achieving twodimensional localization. However, in [25-27], two independent light sources, one for downlink and one for uplink, are used in each transceiver link, which makes the system complicated and bulky. If wavelength reuse can be applied [28-32], the cost and complexity of the transceiver can be significantly reduced, and the wavelength management requirement in the CU can be relieved. In [33,34], we also demonstrated fiber-distributed tristatic and bistatic UWB radar with wavelength reuse, respectively. However, their numbers of the transceivers are also limited to 2 or 3. In [35], we demonstrated a fiber-connected UWB sensor network for localization based on optical time-division multiplexing technology and

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centimeter-level accuracy was achieved. However, optical time-division multiplexing can only support a limited number of remote sensors, or the radar detection area should be shrunk if additional remote sensors are added. In addition, the network in [35] is passive, so extra UWB sources in the radar detection area are required, and their locations should be known.

In this paper, a fiber-distributed UWB radar network based on wavelength reusing transceivers is proposed and experimentally demonstrated. In the proposed system, an array of optical carriers are combined by a wavelength-division multiplexer and then phase modulated by a Gaussian pulse train in the CU. The phase modulated carriers are transmitted to the remote radar detection area through a length of single-mode fiber (SMF) and then split using a wavelength-division demultiplexer. The split carriers are respectively introduced to several spatially separated transceivers where each optical phase-modulated signal is powersplit into two branches. One branch is converted into an optical UWB pulse train via the phase-modulation-to-intensity-modulation conversion in an optical frequency discriminator [22]. By appropriately designing the optical frequency discriminator in the transceivers, the polarities and shapes of the UWB pulses generated in different transceivers can be different. The UWB pulse train is emitted to the free space after optical-to-electrical conversion. The other branch of the optical phase-modulated signal is remodulated by the received UWB echo signals at an intensity modulator, and then transmitted back to the CU. In the CU, directdetection is applied which removes the optical phase information, realizing the wavelength reuse. The transceivers which receive the UWB signals can be identified in the CU by the optical carrier wavelengths because of the wavelength-division multiplexing technology [36], [37]. The transceivers which emit the UWB signals can be identified by the polarities or shapes of the UWB pulses. Therefore, the information of the target in the radar detection area can be effectively extracted using very simple cooperative signal processing in the CU. In addition, clock synchronization in the transceivers is not required because the fiber lengths in the network are known. A 2-D localization experiment is performed. Using the proposed radar network with two distributed transceivers, localization accuracy of about one centimeter is achieved.

## 2. Principle

Figure 1 illustrates the schematic diagram of the fiber-distributed UWB radar network based on wavelength reusing transceivers, which consists of a CU and several transceivers in the radar detection area, connected by optical fibers.



Fig. 1. Schematic diagram of the proposed fiber-distributed UWB radar network based on wavelength reusing transceivers. PM: phase modulator; OC: optical circulator; WDM: wavelength-division multiplexer; PD: photodetector; SMF: single-mode fiber; OS: optical splitter; OFD: optical frequency discriminator; EA: electrical amplifier; EC: electrical circulator; MZM: Mach-Zehnder Modulator.

In the CU, N optical carriers generated by a laser array are multiplexed by a wavelengthdivision multiplexer (WDM<sub>1</sub>), phase modulated by Gaussian pulses, and then delivered through a length of SMF to the radar detection area. In the radar detection area, the N phasemodulated optical carriers are split by a wavelength-division demultiplexer (WDM<sub>2</sub>) to N

spatially separated transceivers. Each transceiver consists of an optical circulator, an optical power splitter, an optical frequency discriminator, a photodetector (PD), a Mach-Zehnder Modulator (MZM), two electrical amplifiers, a UWB antenna and a UWB electrical circulator [32]. The optical signal is split into two branches by the optical splitter. The optical frequency discriminator, which can be directly implemented by an optical filter, is inserted in one branch, performing the phase modulation to intensity modulation conversion, generating an optical UWB pulse train. After photodetection, the UWB pulses are radiated via the UWB antenna. It should be noted that the polarities or shapes of the generated UWB pulses in different transceivers are set to be different by locating the carrier wavelengths at different slopes of the optical frequency discriminators [22]. In the other branch, the optical signal from the optical power splitter is reused as the light source, which is introduced to the MZM, intensity-modulated by the received echo UWB pulses and then fed back to the CU via WDM<sub>2</sub>. Using a direct-detection device (i.e., the PD) in the CU, the downstream information carried by the phase of the optical signal is dropped, while the upstream information (i.e., the received echo UWB pulses) in the intensity of the received optical signal is detected. In this way, the transceiver is able to generate and receive UWB pulses without extra light source. To identify the signals received by different transceivers, the optical wavelength-division multiplexed downstream signals are demultiplexed by another wavelength-division demultiplexer (WDM<sub>3</sub>) in the CU, respectively photodetected and cooperatively processed to extract the information of the target. It should be noted that it is very easy for the CU to identify which transceiver the received UWB pulses are generated by, since the generated UWB pulses in different transceivers have different polarities or shapes. One feature of the approach is that the raw data of the echo received by the transceivers is directly sent to the CU for coherently processing. According to [7], the system sensitivity can be maximized, and the radar accuracy can be optimized. In addition, clock synchronization is not necessary in this system because all the pulses are sent to the CU via known lengths of SMF.



Fig. 2. Geometric method for localization using the proposed fiber-distributed ultra-wideband radar network: (a) geometric model; (b) the simulated UWB sequences received by Transceiver 1 and 2. T1: Transceiver 1; T2: Transceiver 2; Tar: Target;  $t_{11}$ ,  $t_{21}$ ,  $t_{12}$ , and  $t_{22}$ : the propagation times of the UWB pulses in the routes of T1-Tar-T1, T2-Tar-T1, T1-Tar-T2, and T2-Tar-T2, respectively;  $D_{11}$ ,  $D_{21}$ ,  $D_{12}$ , and  $D_{22}$ : the system delays for the routes of T1-CU-T1, T2-CU-T1, T1-CU-T2, and T2-CU-T2, respectively.

For simplicity, we consider a 2-D localization UWB radar network containing two transceivers for range measurement. Assume that the UWB antenna used in each transceiver is directional, we can estimate the 2-D position of the target with a traditional geometric method, as shown in Fig. 2(a). Typical UWB sequences received by Transceiver 1 (T1) and Transceiver 2 (T2) in the CU are simulated, which are shown in Fig. 2(b). In each period of the two sequences, we can observe two echo pulses, representing the pulses emitted from the transceiver itself and the other transceiver, respectively. They have different polarities

because the wavelengths of optical carriers in the two transceivers are respectively placed at the opposite slopes of the optical frequency discriminators. Therefore, it is easy to identify which transceiver the pulses are emitted by, as illustrated in Fig. 2(b). By using the clock reference provided by the Gaussian pulse generator, we can measure the time delays of  $t_{11} + D_{11}$ ,  $t_{21} + D_{21}$ ,  $t_{12} + D_{12}$  and  $t_{22} + D_{22}$ , where  $t_{11}$ ,  $t_{21}$ ,  $t_{12}$  and  $t_{22}$  are the propagation times of the UWB pulses in the routes of T1-Tar-T1, T2-Tar-T1, T1-Tar-T2, and T2-Tar-T2, and  $D_{11}$ ,  $D_{21}$ ,  $D_{12}$  and  $D_{22}$  are the system delays for the routes of T1-CU-T1, T2-CU-T1, T1-CU-T2, and T2-CU-T2, respectively. Since  $D_{11}$ ,  $D_{21}$ ,  $D_{12}$ , and  $D_{22}$  can be accurately obtained by a calibration operation,  $t_{11}$ ,  $t_{21}$ ,  $t_{12}$  and  $t_{22}$  can be calculated. Assume the 2-D positions of the target, T1 and T2 are (x, y),  $(x_1, y_1)$  and  $(x_2, y_2)$ , respectively, a set of equations for circles and ellipses can be obtained,

$$\sqrt{(x-x_1)^2 + (y-y_1)^2} = \frac{1}{2}ct_{11}$$
(1)

$$\left\{\sqrt{(x-x_2)^2 + (y-y_2)^2} = \frac{1}{2}ct_{22}\right\}$$
(2)

$$\sqrt{(x-x_1)^2 + (y-y_1)^2} + \sqrt{(x-x_2)^2 + (y-y_2)^2} = ct_{12}$$
(3)

$$\sqrt{(x-x_1)^2 + (y-y_1)^2} + \sqrt{(x-x_2)^2 + (y-y_2)^2} = ct_{21}$$
(4)

where c is the velocity of light in vacuum. It should be noted that (1) and (2) are enough to determine the location of the target, while (3) and (4) can be used to improve the position estimation accuracy. Theoretically,  $t_{21}$  and  $t_{12}$  should be equal, but it is not always true in reality since the target is not always an ideal point, so we use both of (3) and (4) to average the error. By implementing the algorithms such as Taylor-series method [38] and Chan's algorithm [39], we can solve the equation set (1)-(4) to obtain the coordinates of the target, i.e., (x, y).

The geometric analysis above is only applicable for the case of radar network with two transceivers. In practice, more transceivers can be applied in the radar network for localization with higher dimension and higher accuracy. We will discuss this case in Section 4.

## 3. Experiments

To demonstrate the feasibility of the proposed radar network, an experiment is carried out. First, we employ the proposed transceiver to measure the 1-D position, i.e., distance, of a target (a cylinder with a diameter of 12.7 cm and a height of 17.6 cm), investigating the main features of the transceiver. Then, two transceivers in a radar network are applied to measure the 2-D position of the same target.

#### 3.1 1-D localization with one transceiver



Fig. 3. Experimental setup of the proposed UWB transceiver for 1-D localization. TLS: tunable laser source, PC: polarization controller.

The experimental setup of the 1-D localization with a single transceiver is shown in Fig. 3. A laser source (Agilent 7714A) generates an optical carrier at 193.14 THz, which is modulated by a phase modulator with a bandwidth of 40 GHz (EOSPACE). A pulse pattern generator

(Anritsu MP1763C) generates a Gaussian pulse with a full width at half maximum (FWHM) of 80 ps, which is introduced to the RF port of the phase modulator. After transmission through a SMF with a length of 8 km, one part of the received signal is led to a programmable optical processor (Finisar Waveshaper 4000s) which serves as a tunable optical frequency discriminator and the other part is sent to an MZM with a bandwidth of 10 GHz and a halfwave voltage of 4.1 V (@ 1 GHz) which is baised at quadrature point. Due to the polarization sensitivity of the MZM, a polarization controller (PC) is inserted to optimize the polarization states of the lightwave. If a polarization-insensitive modulator (e.g. electro-absorption modulator) is applied to replace the MZM, the PC can be removed. By programming the optical processor to locate the wavelength of the carrier at different slopes of its transmission responses, UWB monocycles with opposite polarities can be generated at a PD (PD1). The PD has a 3-dB bandwidth of 30 GHz and a responsivity of 0.85 A/W @ 1550 nm. Figure 4 shows the optical spectrum of the optical carrier and the transmission responses of the tunable optical frequency discriminator, measured by an optical spectrum analyzer (YOKOGAWA AQ6370C) with a resolution of 20 pm. Figure 5(a) and 5(b) show the waveforms of the generated UWB monocycles with negative and positive polarities, respectively, measured by an 80-GHz sampling oscilloscope (Agilent 86100C). Their corresponding electrical spectra are shown in Fig. 5(c) and 5(d), respectively, measured by an electrical spectrum analyzer (Agilent N9030A) with a resolution bandwidth of 100 kHz and a bandwidth of 43 GHz. As can be seen in Fig. 5, the FWHMs of the generated UWB monocycles are about 60 ps, and the 10-dB bandwidths are about 7.5 GHz.



Fig. 4. The optical spectrum of the optical carrier and the transmission response of the tunable optical frequency discriminator with a negative or positive slope.



Fig. 5. The waveforms and electrical spectra of the generated UWB monocycles with (a)(c) negative and (b)(d) positive polarities.

To investigate the influence of the existence of the downstream information on the upstream signal, the downstream phase modulated optical signal is directly intensity modulated by an electrical UWB signal, transmitted back to the CU through the same 8-km SMF and then detected at a PD (PD2) with a 3-dB bandwidth of 10 GHz and a responsivity of 0.85 A/W @ 1550 nm. The eye diagrams at PD2 are shown in Fig. 6(a) and 6(b). In Fig. 6(a), the period of the upstream UWB pulses is set to be 1280 ps. As can be seen, a very small residual downstream pulse is present between every two upstream pulses which should be resulted from the phase-to-intensity conversion induced by fiber dispersion. In Fig. 6(b), the upstream UWB pulses and the residual downstream pulses are overlapped when the period of the UWB pulses is set to be 640 ps. As can be seen, the influence of the downstream information on the upstream signal can be neglected, demonstrating successful wavelength reuse. It should be noted that if the transmission fiber is much longer (>20km), this residual downstream pulse may not be neglected [40]. Nevertheless, in a settled system, this kind of residual downstream pulse is a prior information, we can easily suppress it using radar signal-processing algorithm such as the adaptive noise canceling algorithm [41].



Fig. 6. Eye diagrams of the upstream UWB pulses received at the CU with periods of (a) 1280 ps and (b) 640 ps.



Fig. 7. (a) The recorded waveforms when the target is 40 cm (upper) and 30 cm (middle) away, and the Gaussian pulse train (lower) served as the clock reference. (b) The corresponding waveforms after signal processing.

Then, a ranging experiment is carried out to measure the 1-D position of the target. In this case, the pulse pattern generator is set to produce a pulse train with a duty cycle of 1/400. A multi-port 32-GHz real-time oscilloscope (Agilent DSO-X 92504A) with a sampling rate of 40 GSa/s is used in the CU to record the waveforms at the outputs of PD2 and the Gaussian pulse train. The recorded waveforms are processed and analyzed off-line. Figure 7(a) shows the recorded waveforms of the received signal in one repetition period. The upper and middle curves are obtained when the target is placed at 40- and 30-cm away from the antenna, respectively, and the lower one is the input Gaussian pulse train served as clock reference. As can be seen, only the noises and the direct waves from the target are very weak. To reduce the random noise we accumulate the sequence with 64 periods, and to suppress the direct wave we adopt the adaptive noise canceling algorithm [41]. To further improve the localization

precision, the waveforms are interpolated eightfold using  $(\sin x)/x$  interpolation. After that, the waveforms are cross-correlated with a template pulse [42]. Figure 7(b) shows the waveforms after signal processing. As can be seen, the echo pulses are compressed.

To investigate the localization accuracy of the system, the point 30-cm away from the antenna is used as the reference position. Then with the parameters in Fig. 7(b), the estimated position of the point 40-cm away from the antenna can be calculated by (7.184-6.525) ns  $\times$  3  $\times$  10<sup>8</sup> m/s  $\div$  2 + 30 cm = 39.89 cm. The actual and estimated positions agree very well. Since the correlated pulse has a bandwidth of about 75 ps, the ranging resolution is about 1.125 cm. In our experiment, 20 samples of positions are tested, and the largest error is 0.5 cm. The ranging accuracy of the transceiver reaches sub-centimeter level.

## 3.2 2-D localization with two transceivers in the radar network

The experimental setup of the fiber-distributed UWB radar network with two transceivers for 2-D localization is shown in Fig. 8, and the photograph of the setup is shown in Fig. 9. The main parameters of the devices used in the experiment are as follows. The wavelengths of the two optical carriers are 1547.760 and 1553.300 nm (generated by Agilent N7714A), respectively. The optical frequency discriminator in Transceiver 1 is implemented by a tunable optical bandpass filter (Yenista XTM-50) and that in Transceiver 2 is realized by the programmable optical processor (Finisar Waveshaper 4000s). Other parameters are the same as those used in the 1-D localization experiment.



Fig. 8. Experimental setup of the fiber-distributed UWB radar network with two transceivers for 2-D localization.



Fig. 9. Photograph of the experimental setup of the fiber-distributed UWB radar network with two transceivers for 2-D localization. CU: central unit.

By adjusting the tunable optical bandpass filter and programming the optical processor, the two optical carriers are placed respectively at the opposite linear slopes of their transmission responses, as shown in Fig. 10. After detecting the output of the two optical frequency discriminators, UWB monocycles with opposite polarities are generated.



Fig. 10. The optical spectra of the two optical carriers and the transmission responses of the two optical frequency discriminators in Transceiver 1 and 2, respectively.



Fig. 11. The waveforms received by (a) Transceiver 1 and (b) Transceiver 2; (c),(d) the waveforms after signal processing; and (e) the Gaussian pulse train served as the clock reference.

Figure 11 shows the pulse sequences recorded at the multi-port real-time oscilloscope in the CU when the target is placed in the radar detection area. The waveforms received by Transceiver 1 and 2 are shown in Fig. 11(a) and 11(b), respectively. In Fig. 11(a) and 11(b), we can see that the desired signals are almost submerged by the noise. This noise is originated from the thermal noise of the system, shot noise of the active components (laser, amplifier, PD), Rayleigh scattering in the fiber, relative intensity noise (RIN) and phase noise of the laser, etc. By adopting the accumulation, the adaptive noise canceling algorithm and the cross-correlation algorithm, the desired signal can be finely extracted. The waveforms after processing are shown in Fig. 11(c) and 11(d), which are in the similar form to the simulated waveforms shown in Fig. 2(b). Using the Gaussian pulse train as the clock reference, the parameters  $t_{11} + D_{11}$ ,  $t_{21} + D_{21}$ ,  $t_{12} + D_{12}$  and  $t_{22} + D_{22}$  can be obtained by estimating the positive peak of the pulses with positive polarity and the negative peak of the pulses with negative polarity. After subtracting the system delay  $D_{11}$ ,  $D_{21}$ ,  $D_{12}$ , and  $D_{22}$  from  $t_{11} + D_{11}$ ,  $t_{21} + D_{22}$ , respectively, the parameters  $t_{11}$ ,  $t_{21}$  and  $t_{22}$  are achieved. Then, the target position can be calculated using (1) and (2).

Sample	Estimated Position (cm)	Actual Position (cm)	Error (cm)
1	(16.37, 20)	(16.70, 19.48)	0.62
2	(26.37, 10)	(26.74, 10.42)	0.57
3	(26.37, 30)	(26.66, 29.00)	1.04
4	(36.37, 10)	(36.63, 10.41)	0.49
5	(36.37, 20)	(36.55, 20.05)	0.19
6	(46.37, 0)	(46.69, 0.96)	1.01
7	(46.37, 30)	(46.36, 29.76)	0.24
8	(56.37, 10)	(56.80, 10.51)	0.67
9	(56.37, 20)	(56.46, 20.34)	0.35
10	(66.37, 0)	(66.42, 1.37)	1.37
11	(66.37, 30)	(66.33, 30.48)	0.48
12	(76.37, 10)	(76.72, 10.99)	1.05
13	(76.37, 20)	(76.24, 20.51)	0.52
14	(86.37, 0)	(86.40, 0.31)	0.31
15	(86.37.30)	(85.87, 31.23)	1.33

Table 1. Fifteen Samples of the Estimated and Actual Positions of the Target



Fig. 12. The geometric locations of fifteen samples of the estimated positions and the actual positions.

To demonstrate the 2-D localization accuracy of the system, fifteen measurements are taken when the target is respectively placed at fifteen different sample locations. By comparing the estimated positions with their actual positions, the errors of the measurements can be evaluated. Table 1 and Fig. 12 show the estimated and actual positions. As can be seen, the localization error is around 1 cm.

## 4. Discussion

#### 4.1 Multi-target localization

In the experiment, we only performed the localization of a single target. If two targets appear in the radar detection area, four equations for circles and four equations for ellipses can be obtained. The four equations for circles would result in four intersections, and only two of them represent the real positions of the targets. Then, with the four equations for ellipses, the other two false positions of the targets can be eliminated. Therefore, the proposed radar network with two transceivers can accurately identify the position of two targets. However, if more than two targets appear in the coverage area, the number of equations may not be sufficient to eliminate all the false positions of the targets, which may cause a false alarm.

Several methods can be adopted to achieve multi-target localization. By simply increasing the number of the transceivers in the radar network, which can increase the number of the equations for localization, the fake positions of the targets can be fully eliminated, and the positions of the real targets can be determined [43]. Multi-target localization can also be achieved based on the target characteristics [44]. Moreover [45], shows that for moving targets, the false positions of the targets can be easily eliminated because when a target is moving continuously, the coordinates of its corresponding false position change by a large amount within a very small time interval or even disappear.

## 4.2 Maximum number of transceivers

In the experiment, only two transceivers were constructed and tested due to the limited components, but for practical applications, more transceivers can be involved in the radar network to achieve localization with larger dimensions and higher accuracy. To identify the pulses emitted from different transceivers, different waveforms should be generated in different transceivers. According to [22], UWB monocycles and UWB doublets with different polarities can be generated based on a phase modulator and an optical frequency discriminator, simply by placing the carrier wavelength at different slopes of the transmission response of the optical frequency discriminator. Due to the significant waveform difference of the UWB monocycle and UWB doublet, they can be easily identified. Therefore, at least four transceivers can be incorporated in the radar network, which respectively generate the waveforms of a positive monocycle, a negative monocycle, a positive doublet and a negative doublet. In addition, if the optical filter is designed to achieve higher-order derivative of the Gaussian pulse, more transceivers might be applied.

## 4.3 Localization accuracy

The localization accuracy of the proposed radar network is mainly affected by three factors, i.e., 1) the ranging measurement accuracy, 2) the algorithm used to process the measurements, and 3) the geometry of the transceivers [46]. The ranging measurement accuracy is intrinsically determined by the property of the signal in terms of the bandwidth according to the well-known Cramér-Rao lower bound (CRLB) for a single-path additive white Gaussian noise (AWGN) channel [4],

$$\sqrt{\operatorname{Var}(d)} \ge \frac{c}{2\pi\sqrt{2S/N} \cdot B}.$$
 (5)

where Var(d) is the variance of the ranging measurement, *c* is the velocity of light in vacuum, *S/N* is the signal to noise ratio, and *B* is the bandwidth of the signal. Hence by increasing the bandwidth of the UWB signal, higher localization accuracy can be achieved. Moreover, adopting algorithms with higher accuracy such as interpolating method [47] can also improve the ranging measurement accuracy. Last but never the least, the localization error may also result from the geometric factors regarding the geometric dilution of precision, which is defined as the ratio of the accuracy of a position fix to the statistical accuracy of the ranging measurements [46]. If the location and number of the transceivers are not carefully selected, the geometric dilution of precision effect would become the dominant factor in limiting the localization accuracy [46].

The localization accuracy is also affected by all kinds of noise. The AWGN is the most common noise in radio systems. In our experiment, it is well suppressed by averaging and cross-correlation. Another kind of noise is the multipath noise induced by the multipath propagation. Due to multipath noise, multiple correlation peaks may be present after cross-correlation. This problem can be solved simply by detecting the first arriving signal path [42]. However, since our experiment was carried out in the laboratory environment which is a sparse multipath channel, multipath noise can be neglected.

## 5. Conclusion

A fiber-distributed UWB radar network was proposed and demonstrated based on wavelength reusing transceivers. The transceiver applies phase modulation to intensity modulation conversion to generate UWB pulses and performs wavelength reuse by intensity re-modulation. To identify the signals received by different transceivers, wavelength-division multiplexing technology is implemented, and to identify the pulses emitted from different transmitters, the carrier wavelengths of different transceivers are placed at different slopes of the optical frequency discriminators to generate UWB pulses with different polarities and shapes. An experiment was carried out to locate a target in the radar detection area, showing that the radar network has a localization accuracy of around 1 cm. The proposed radar network may find applications in distributed radar systems.

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