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Range-Angle Dependent Beampattern Synthesis Method for OFDM-Based Passive Radar

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Abstract: Frequency diverse array (FDA) radar applies a tiny frequency offset across its adjacent transmitting array elements to generate a range-angle-dependent beampattern. The increased degrees-of-freedom (DOFs) in range domain can help improve the performance of radar in target detection, localization, and clutter suppression. Passive radar utilizes uncontrollable external signal as illuminator, which makes it difficult to apply traditional frequency diverse process method. However, the third-party illuminator such as Orthogonal Frequency Division Multiplexing (OFDM) signal usually consists of several closely spaced modulated carriers, and it has been widely selected as the illuminator for passive radar in recent years. Considering the orthogonality between even separated subcarriers, we propose a new frequency diverse process method by extracting and processing each subcarrier of received data independently and attempt to provide a range-angle dependent beampattern for OFDM passive radar. Numerical results and real data analyses verify the superiority of frequency diversity process on the received data of OFDM passive radar.

Key words: passive radar; frequency diverse; Orthogonal Frequency Division Multiplexing (OFDM) signal; range-angle dependent beampattern

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0 Introduction

Passive radar is a bistatic radar that exploits third-party non-cooperative illuminators for target detection. The target echoes are received with an antenna array, which can adopt an adaptive digital beamforming technique to suppress signals from interference directions and maximize signals from desired angles[1]. However, when the interferences and targets are distributed at different range bins but in the same directions, they cannot be distinguished effectively by this method. Therefore, it is quite necessary to explore a new adaptive digital beam focusing method with a higher degree of freedom.

Frequency diverse array (FDA) introduces a tiny frequency offset across its array elements to obtain a range-dependent transmitting beam pattern[2-4], which has attracted wide interest in recent years. The range-dependent beampattern can be utilized for range-dependent interference suppression[5], moving target indication[6, 7], and range ambiguity resolution[8]. The researches on FDA recently focus on theoretical analysis[9,10], beampattern optimization[11, 12], and range-angle decoupled methods[13].

However, all the researches above depend on a complex frequency diverse signal transmitting system, but passive radar exploits an uncontrollable third-party emitter as the illuminator. With the development of digital television and communication, more and more Orthogonal Frequency Division Multiplexing (OFDM) signals are adopted as the external illuminator for passive radar due to its higher transmission efficiency and spectrum utilization. An OFDM signal is synthesized with multiple subcarriers, which makes it possible for the received signals to be processed in FDA manner.

To generate a range-dependent beam pattern for OFDM-based passive radar, this paper proposes a novel frequency diverse process method for passive radar received data. This process only deals with the received OFDM baseband signal without any changes of hardware for the existing passive radar system, which makes it simpler and more flexible. The theoretical analysis of this range-angle dependent beamforming method is discussed in this paper. Numerical and real data results show that better beampattern and detection performance can be achieved for OFDM passive radar with two-dimensional beamforming method for OFDM passive radar.

1 Signal Processing Model

The passive radar system shown in Fig. 1 is consisted of a third-party illuminator transmitter and a radar receiver. The surveillance channel with a Uniform Linear Array (ULA) having N array elements and the reference channel with an antenna directly pointed to the third-party transmitter compose the passive radar receiver. The carrier frequency of third-party illuminator is f_c, and the spacing distance d between two adjacent array elements of the surveillance channel is the half-wavelength $\lambda/2$.

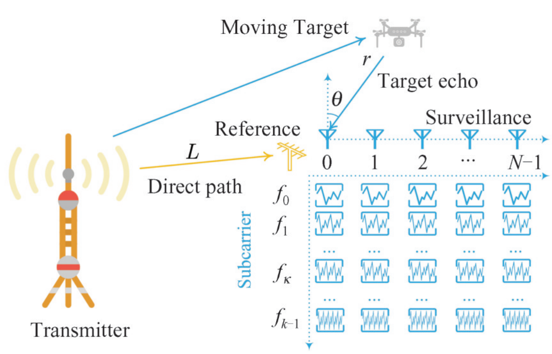


Fig. 1 Passive radar system

The third-party illuminator of opportunity in this paper is an OFDM signal with K orthogonal frequency subcarriers, and the m-th OFDM symbol can be formulated as

$$u_m(t)=\sum_{k=0}^{K-1} C_{m,k}\exp\left(\mathrm{j}2\pi\frac{k}{T_u}(t-T_g-mT_s)\right) \quad (1)$$

where $mT_s+T_g\leqslant t\leqslant(m+1)T_s$. m and k denote the sequence number of OFDM symbols and subcarrier frequencies, respectively, $C_{m,k}$ denotes the digital information modulated on the k-th subcarrier for the m-th OFDM symbol. T_g and T_u represent the time length of the guard interval and the effective transmitting signal. Thus, the total time length of a complete OFDM symbol is $T_s=T_g+T_u$. Assuming a target locates at (r,θ) in bistatic coordinates and moves with doppler shift f_d, the m-th OFDM signal received by the n-th surveillance channel and reference channel can be expressed as

$$\mathrm{surv}_{m,n}(t)=\exp(-\mathrm{j}2\pi f_c\tau_n)u_m(t-\tau_n)\exp(\mathrm{j}2\pi f_d t) \quad (2)$$

$$\mathrm{ref}_m(t)=\exp(-\mathrm{j}2\pi f_c\tau_{\mathrm{direct}})u_m(t-\tau_{\mathrm{direct}}) \quad (3)$$

where $\tau_n=r-nd\sin\theta/c$ represents the time delay from transimitter to the n-th survelliance array element (c denotes the speed of light), and $\tau_{\mathrm{direct}}=L/c$ denotes the propogation delay of direct path.

The pure direct path waves received with reference channel can be utilized to reconstruct transmitting baseband signals, which can be designed as the Matched Filter (MF) for survelliance channel to extract moving parameters after clutter suppression. A range-doppler two dimensions (2D) matched filter is adopted to extract bistatic distances and doppler simultaneously. However, the doppler shift caused by target movement can be approximated as a fixed value for each OFDM symbol. Therefore, the 2D matched filter can be simplified into two independent matched filters (i.e., a range MF and a doppler MF). Range MF, doppler MF and Digital Beam Forming (DBF) can be handled independently. The signal processing flow starts with range MF, which is followed by digital beamforming and doppler MF. The m-th output signal after range MF for the n-th array element can be derived as (4).

$$\begin{aligned}\mathrm{Rs}_{m,n}(t)&=\mathcal{F}^{-1}\{\mathcal{F}[\mathrm{surv}_{m,n}(t)]\odot\mathcal{F}[\mathrm{ref}_m(t)]^*\}\\&=\sum_{k=0}^{K-1}\|C_{m,k}\|\exp(-\mathrm{j}2\pi f_c\frac{r-L}{c})\exp(\mathrm{j}2\pi f_c\frac{nd\sin\theta}{c})\\&\quad\cdot\exp(\mathrm{j}2\pi\frac{k}{T_u}t')\exp(\mathrm{j}2\pi f_d mT_s)\end{aligned} \quad (4)$$

where $t'=t-(r-L)/c-T_g-mT_s$, and $mT_s+T_g\leqslant t\leqslant(m+1)T_s$. $\mathcal{F}[\cdot]$ represents the Fourier Transform and $\mathcal{F}^{-1}[\cdot]$ represents the Inverse Fourier Transform. $\odot$ denotes the Hadamard product. It can be seen from (4) that $\mathrm{Rs}_{m,n}(t)$ is synthesized by K orthogonal frequency signals and each signal contained can be processed independently. And further derivation shown in (5) contains a coupling term of subcarrier frequency and bistatic distance, and it indicates that a range-dependent beampattern can be obtained with passive radar received signal.

$$\mathrm{Rs}_{m,n}(t) \approx \sum_{k=0}^{K-1} \|C_{m,k}\| \exp(-\mathrm{j}2\pi f_{\mathrm{c}} \frac{r-L}{c}) \exp(\mathrm{j}2\pi f_{\mathrm{d}} m T_{\mathrm{s}}) \times \exp(\mathrm{j}2\pi [f_{\mathrm{c}} \frac{nd\sin\theta}{c} - \frac{k}{T_{\mathrm{u}}} \frac{r-L}{c}]) \exp(\mathrm{j}2\pi \frac{k}{T_{\mathrm{u}}} (t-T_{\mathrm{g}}-mT_{\mathrm{s}})) \tag{5}$$

since the beamforming weights can be applied to each dependent subcarrier, a well designed weight vectors can be formulated as (6) to obtain a beampattern steered to (r_t, θ_t) in space.

$$\boldsymbol{a}(r_t, \theta_t) = \boldsymbol{a}(r_t) \otimes \boldsymbol{a}(\theta_t) \tag{6}$$

where $\otimes$ indicates the Kronecker product, and $\boldsymbol{a}(r_t)$ and $\boldsymbol{a}(\theta_t)$ are shown as following.

$$\begin{aligned} \boldsymbol{a}(r_t) &= \left[1 \quad \dots \quad \exp(-\mathrm{j}2\pi \frac{k}{T_{\mathrm{u}}} \frac{r_t - L}{c}) \quad \dots \quad \exp(-\mathrm{j}2\pi \frac{K-1}{T_{\mathrm{u}}} \frac{r_t - L}{c}) \right] \\ \boldsymbol{a}(\theta_t) &= \left[1 \quad \dots \quad \exp(\mathrm{j}2\pi f_{\mathrm{c}} \frac{nd\sin\theta_t}{c}) \quad \dots \quad \exp(\mathrm{j}2\pi f_{\mathrm{c}} \frac{(N-1)d\sin\theta_t}{c}) \right]^{\mathrm{T}} \end{aligned} \tag{7}$$

The normalized beam pattern after range-angle 2D beamforming method can be represented as (8).

$$B_m(r,\theta) = \sum_{n=0}^{N-1}\sum_{k=0}^{K-1} \|C_{m,k}\| \exp(-\mathrm{j}2\pi f_{\mathrm{c}} \frac{r-L}{c}) \cdot \exp(\mathrm{j}2\pi f_{\mathrm{d}} m T_{\mathrm{s}}) \exp(\mathrm{j}2\pi [f_{\mathrm{c}} \frac{nd(\sin\theta - \sin\theta_t)}{c} - \frac{k}{T_{\mathrm{u}}} \frac{r-r_t}{c}]) \exp(\mathrm{j}2\pi \frac{k}{T_{\mathrm{u}}} (t-T_{\mathrm{g}}-mT_{\mathrm{s}})) \tag{8}$$

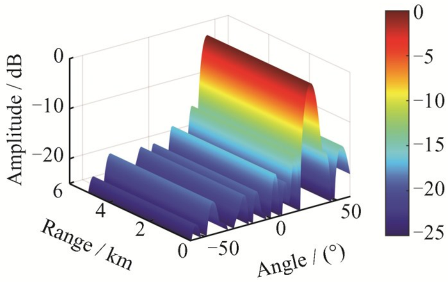
It can be seen from (8) that local maxima can only be obtained at (r_t, θ_t). The beampattern of current beamforming method can be steered to a distinct angle only. When targets and interferences are located at different distances but a same angle, the traditional beamforming method can not effectively suppress the inteference signals. However, the range-angle two-dimensional beamforming method possesses a higher degree of freedom and can accumulate the beam energy on a point. Thus the signals of inteferences and targets can be handled separately and better performance can be obtained.

2 Experiment Results

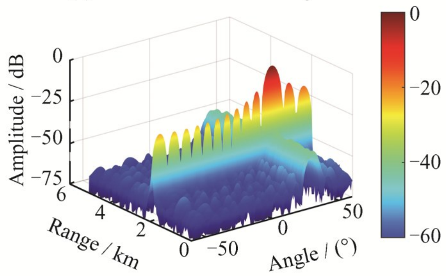
To verify the range-angle dependent beamforming model proposed in this paper, several numerical and outdoor experiments were carried out. The simulation parameters of numerical experiments are listed as follows. The illuminator of opportunity is an OFDM signal which is consisted of 3 780 subcarriers and modulated with 4QAM. The carrier frequency of the transmitting signal is 756 MHz. An omnidirectional antenna located at L = 1 km away is utilized for signal transmitting. A ULA containing N = 16 array elements and an antenna directly pointed to transmitter work as the surveillance channel and the reference channel, respectively. The target locates at (3 km, 30°) and moves with bistatic velocity v = 10 m/s. It should be noted that the parameters will be the same unless stated otherwise.

The beampattern performance is analyzed for traditional beamforming and range-angle two-dimensional beamforming method in Fig. 2. The beampattern formed with the traditional beamforming method is shown in Fig. 2(a). It can be seen that traditional beampattern can only be steered to a certain angle and spread across all range bins. The final Signal to Noise Ratio (SNR) will inevitably suffer from the beam gain provided to interferences distributed at the same angle. However, a range-dependent beampattern can be synthesized with two-dimensional beamforming method as shown in Fig. 2(b). It can be seen that the energy is focused on a single point to provide beam gain for targets only. When the SNR of the target echo is −65 dB, the results of echo signals before and after applying the range-angle two-dimensions beamforming method are shown in Fig. 3. With traditional beamforming method, the received signals that come from different range bins but at a same angle will also benefit from the beampattern as shown in Fig. 2(a), and the target echo will be neglected by noise base before two-dimensional beamforming method as shown in Fig. 3(a). However, the beamforming method proposed in this paper can realize two-dimensional scanning and focus the beam energy on a single point, so that only the target echo can obtain the maximum beam gain. It can be shown from Fig. 3(b) that the target peak after two-dimensional beamforming method is highlighted.

The SNR is a vital parameter that indicates the performance of radar in target detection and localization. In order to evaluate the performance improvement brought by range-angle dependent beamforming method for passive radar, the next simulation will mainly focus on the output SNR of traditional beamforming method and two-dimensional beamforming method proposed in this paper. With input SNR = −65 dB, the final range-doppler maps after applying traditional beamforming method and two-dimensional beamforming method are respec-

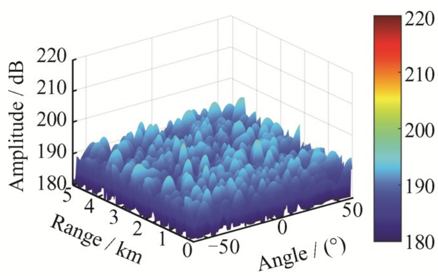


(a) Traditional beamforming method

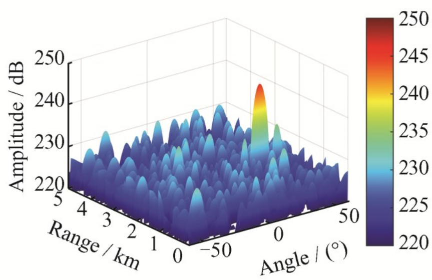


(b) Range-angle dependent beamforming method

Fig. 2 Beampattern performance analysis



(a) Traditional beamforming method

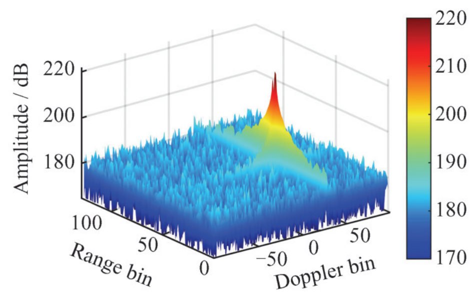


(b) Two-dimensional beamforming method

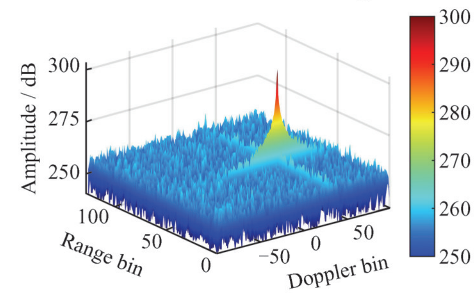
Fig. 3 Signals before and after two-dimensional beamforming method

tively shown in Fig. 4(a) and (b). And the statistical results of output SNR of different beamforming method are also listed in Fig. 4 to analyze the performance improvement for passive radar. The average statistical output SNR with traditional beamforming method is 45 dB while it is 50 dB with two dimensional bemforming method. It proves that the range-angle dependent beamforming method can help obtain a better SNR and radar performance by focusing energy on a single point. Furthermore, the ouput SNR simulation results varying with different input SNR (−60 to −10 dB) for passive radar RD map is analyzed in Fig. 4(c).

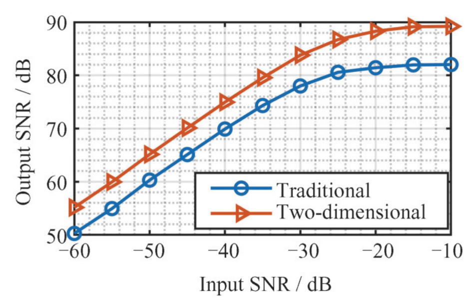
It can be shown from the numerical results that the range-angle dependent beamforming method can achieve about 5-8 dB output SNR improvement compared with traditional beamforming method. And the improvement brought by the range-angle dependent beamforming method also seems insensitive to input SNR. To verify the effectiveness of the proposed method, an outdoor experiment is conducted in Alsahan League, China in July 2021, where a Digital Television Terrestrial Multimedia Broadcasting (DTMB) signal transmitted by Alashan League Radio and Television Transmission Tower is used as the illuminator, which is synthesised by 3 780 sbucarriers. The carrier frequency f_0 is 714 MHz. One antenna is pointed towards the transmission station to receive the reference signal and a 7 element ULA with inner-element spacing d = 0.25 m is pointed to-



(a) Traditional beamforming method SNR_{out}=45 dB



(b) Range-angle dependent beamforming method SNR_{out}=50 dB

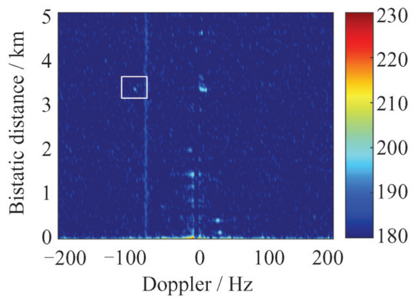


(c) Output SNR varying with input SNR

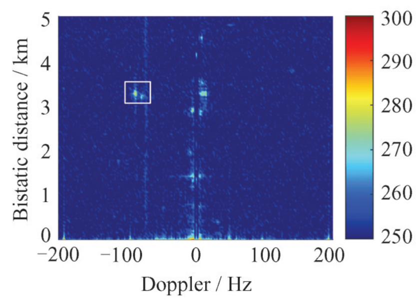
Fig. 4 Digital beamforming results analysis

wards the detection area to receive the echos reflected by targets. The signals analyzed in this section are collected after the clutter suppression steps. The signals analyzed in this paper is consisted of 1024 OFDM symbols. Two drones are working as cooperative targets. One was located at about 3.3 km away while the other was 1.7 km. The results are shown in Fig. 5.

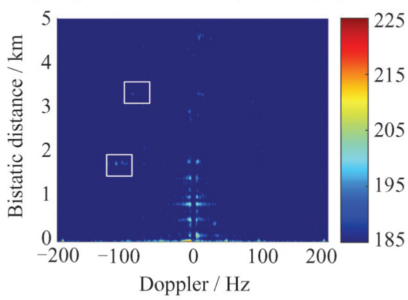
The beampattern steered to 40° with traditional beamforming and range-angle dependent beamforming method is shown in Fig. 5(a) and (b). Although the moving target located at about 3.3 km can be detected with both two methods, the target peak with range-angle dependent beamforming method can benefit from more focused energy and obtain a better SNR. Another beampattern experiment also shows the superiority of range-angle dependent beamforming method. Figure 5(c) and (d) is the beampattern steered to 30° with the traditional and novel proposed beamforming method. It can be seen that the target peak located at 1.7 km can be highlighted and obtain better detection probability with range-angle dependent beamforming method. Moreover, the target located at about 3.3 km is almost neglected with the traditional method, but it is easily detected with the method proposed in this paper as shown in Fig. 5(d).



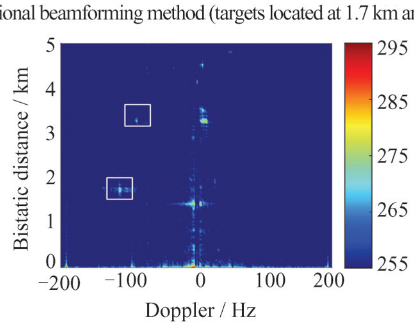
(a) Traditional beamforming method (target located at 3.3 km)



(b) Range-angle dependent beamforming method (target located at 3.3 km)



(c) Traditional beamforming method (targets located at 1.7 km and 3.3 km)



(d) Range-angle dependent beamforming method (targets located at 1.7 km and 3.3 km)

Fig. 5 Digital beamforming results analysis

3 Conclusion

A novel frequency diverse process method is proposed for OFDM-based passive radar in this paper. A range-angle dependent beampattern can be generated with range-angle two-dimensional beamforming method without any hardware changes for current passive radar. It is also the first time for frequency diverse processes to be analyzed with outdoor field experiments. Simulation results indicate that range-angle dependent beamforming method for OFDM passive radar can focus energy on a single point to obtain a better performance compared with current methods, and outdoor field experiments verify the effectiveness and superiority of the method proposed in this paper.

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