Dot-shaped beamforming analysis based on OSB log-FDA

WANG Bo1,*, XIE Junwei1, ZHANG Jing2, and ZHANG Haowei1
1. Air and Missile Defense College, Air Force Engineering University, Xi’an 710051, China;
2. Highway Railway College, Shaanxi Vocational and Technical College of Transport, Xi’an 710018, China

Abstract: The range and angle information of the frequency diverse array (FDA) cannot be exclusively determined at the output of the array because of the range-angle coupled transmit beampattern. The best decoupling approach is to form a dot-shaped beampattern rather than the S-shaped beampattern of the basic FDA. Considering the degradation of the output signal-to-interference-plus-noise ratio (SINR) caused by the coupled beampattern, we propose a dot-shaped beamforming method based on the analyzed overlapping subarray-based using a logarithmic offset and a subarray-based planar FDA using a logarithmically increasing frequency offset, with elements transmitting at multiple frequencies. Several simulation results demonstrate the effectiveness of the proposed method in transmit energy focusing, sidelobe suppression and array resolution.

Keywords: subarray-based frequency diverse array (SB FDA), planar frequency diverse array (PFDA), decoupling, dot-shaped beamforming.

DOI: 10.23919/JSEE.2020.000009

1. Introduction

Phased array (PA) radar has been widely used for several decades in civil and military applications to improve signal processing performance. It is one of the most popular types of radar [1 – 3]. However, the range-related interference cannot be directly suppressed by beamforming without multiple antennas or a multibeam antenna based on a PA. In contrast to PA, frequency diverse array (FDA) was initially designed by Antonik to form a time-range-angle dependent transmit beampattern [4 – 6]. It can achieve a time-range-angle dependent beampattern by adding a relatively small fixed frequency offset between the elements. It has sparked many interesting investigations due to the additional controllable degrees of freedom of the array [7 – 13]. However, the range and angle information of the basic FDA cannot be exclusively determined at the output of the array because of the range-angle coupled transmit beampattern [14 – 16]. The best decoupling approach is to form a dot-shaped beampattern rather than an S-shaped beampattern, which generates maxima at multiple ranges and angle values [17 – 20]. This paper mainly works on the analysis of the dot-shaped beamforming method.

At present, fruitful achievements have been obtained on the dot-shaped beamforming technology. Khan et al. proposed a logarithmic frequency offsets based FDA (log-FDA) to achieve a beampattern with a single maximum at the target location [21]. Then some improvements in transmit beampatterns have been shown for multiple input multiple output FDA (MIMO-FDA) by using a variable logarithmic offset, followed by a detailed signal model for better estimation of targets at the receiving side [22 – 24]. However, the FDA using logarithmic frequency offsets achieves a poor resolution in both range and angle dimensions. The pattern synthesis for the FDA radar transmitter is also optimized by jointly considering flexible magnitude response and sidelobe suppression in [25]. Based on the design of the array configuration, Wang proposed a subarray-based FDA radar, which can be used to localize the target in the range-angle domain [26]. The contributions of this paper are as follows. (i) A dot-shaped beamforming method based on the overlapping subarray-based FDA using logarithmically increasing frequency offset (OSB log-FDA) is analyzed. (ii) The mainlobe of the OSB log-FDA is further optimized by considering the array elements transmitting at multiple frequencies. The analyzed dot-shaped beamforming technology is able to offer directional gain to detect weak targets in the target direction and suppress range-dependent interferences from other directions. It can also be widely used in communication, radar, and navigation systems.

2. Data model

2.1 Basic FDA

Fig. 1 shows the configuration of the basic FDA [27]. Under the narrowband assumption, FDA can be realized by
employing a tiny frequency offset relative to the carrier frequency across the array elements. The signal transmitted by the nth element can be written as

$$s_n(t) = \exp(j2\pi f_n t), \quad n = 0, 1, \ldots, N - 1$$  \hspace{1cm} (1)

where \( f_n = f_0 + n\Delta f \) \((n = 0, 1, \ldots, N - 1)\), \( f_0, \Delta f \) and \( N \) represent the carrier frequency, fixed frequency offset and the number of array elements, respectively.

The signal received by a specific far-field target with the angle \( \theta \) and slant range \( R \) for the first element is a superposition of the delayed and attenuated version of the transmitted signal:

$$s_n(t - \frac{r_n}{c}) = \exp\left[j2\pi f_n \left(t - \frac{r_n}{c}\right)\right]$$  \hspace{1cm} (2)

where \( r_n = R - nd\sin\theta \) is the range of the target from the \( n \)th antenna element, \( d \) denotes the element spacing, and \( c \) is the speed of light.

The array factor generated by the FDA at the far-field target \((R, \theta)\) can be given as

$$AF(t; R, \theta) = \sum_{n=0}^{N-1} \frac{1}{r_n} \exp\left[j2\pi f_n \left(t - \frac{R}{c} + \frac{nd\sin\theta}{c}\right)\right] \approx \frac{\sin \left[N\pi \left(\Delta ft - \frac{\Delta f R}{c} + \frac{df_0\sin\theta}{c}\right)\right]}{\sin \left[\pi \left(\Delta ft - \frac{\Delta f R}{c} + \frac{df_0\sin\theta}{c}\right)\right]}.$$  \hspace{1cm} (3)

### 2.2 Log-FDA

There is a range-angle coupling inherent in the transmit beampattern of the basic FDA because of the linear incremental synchronization between the element spacing and the fixed linear frequency offset. In order to eliminate the synchronization, it is suggested to adopt a nonlinear frequency offset, such as the logarithmical frequency offset, to decouple the beampattern in range and angle domains \([21–24]\).

The frequency fed to the \( n \)th element of log-FDA can be rewritten as

$$f_n = f_0 + \log(n + 1)\delta, \quad n = 0, 1, \ldots, N - 1$$  \hspace{1cm} (4)

where \( \log(\cdot) \) represents the natural logarithm of a number. \( \delta \) is a small configurable parameter, measured in hertz, to control the frequency offset.

The array factor generated by the log-FDA will be

$$AF(t; R, \theta) = \sum_{n=0}^{N-1} a_m e^{j2\pi \log(n+1)\delta(t-R/c)} e^{j2\pi f_0 nd\sin\theta}$$  \hspace{1cm} (5)

where \( a_m = e^{j2\pi \log(n+1)\delta R_0/c - f_0 nd\sin\theta} \) represents the complex weights, which are used to steer the maximum at the expected far-field target location \((R_0, \theta_0)\).

### 2.3 Planar FDA (PFDA)

In this paper, we also extend the dot-shaped beamforming method for the basic FDA to planar array geometries proposed in \([28]\), with array elements equidistant distribution in the \(X\) axis and \(Y\) axis shown in Fig. 2.

![Configuration of PFDA](image)

The signal transmitted by the element \((n, m)\) in the PFDA can be expressed as

$$s_{nm}(t) = \exp(j2\pi f_{nm} t)$$  \hspace{1cm} (6)

where \( f_{nm} = f_0 + n\Delta f_x + m\Delta f_y \) \((n = 0, 1, \ldots, N - 1, m = 0, 1, \ldots, M - 1)\). Considering a far-field target \((x_0, y_0, z_0), R_0, \varphi_0, \theta_0\) of the target can be reached. Taking the element \((0, 0, 0)\) as the reference of the array, the range between the reference element and the observed point is \( R_0 = \sqrt{x_0^2 + y_0^2 + z_0^2} \). Then the range between the element \((n, m)\) and the observed far-field target can be expressed as \( R_{nm} = \sqrt{(x_0 - x_n) + (y_0 - y_m) + z_0^2} \). The signal arriving at the far field target can be written as

$$s_{nm} \left(t - \frac{R_{nm}}{c}\right) = \exp \left[j2\pi f_{nm} \left(t - \frac{R_{nm}}{c}\right)\right].$$  \hspace{1cm} (7)

The overall signal observed at \((\hat{R}_0, \hat{\theta}_0, \hat{\varphi}_0)\) in the far field can be written as
The signal radiated by the subarray design of the array configuration is given by
\[ s(t; \hat{R}_0, \hat{\theta}_0, \varphi_0) = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} \alpha(\hat{R}_0, \hat{\theta}_0, \varphi_0) s_{nm}(t - \frac{R_{nm}}{c}) = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} \exp \left\{ j2\pi f_{nm} \left( t - \frac{R_0 - \hat{R}_0}{c} \right) + \frac{nd_x (\sin \theta_0 \cos \varphi_0 - \sin \hat{\theta}_0 \cos \hat{\varphi}_0)}{c} + \frac{nd_y (\sin \theta_0 \sin \varphi_0 - \sin \hat{\theta}_0 \sin \hat{\varphi}_0)}{c} \right\} \]  

(8)

where \( \alpha(\hat{R}_0, \hat{\theta}_0, \varphi_0) \) denotes the complex weights, which are used to steer the maximum at the expected far-field target location \((\hat{R}_0, \hat{\theta}_0, \varphi_0)\).

3. Subarray-based dot-shaped beamforming

In order to decouple the FDA range-angle dependent beampattern, the best way is to form a dot-shaped beampattern without periodicity in the maximum rather than the trailing beampattern of log-FDA. It can be achieved by the design of the array configuration [29–33] as well as the design of the frequency offset [34–36]. In this section, we analyze the dot-shaped beamforming method based on the OSB log-FDA.

3.1 OSB FDA

The essence of subarray-based FDA (SB FDA) is to divide the basic FDA into multiple subarrays, which employ the same or distinct frequency offset. Taking the leftmost element as the reference, the configuration of the overlapping subarray-based FDA (OSB FDA) is shown in Fig. 3.

![Fig. 3 Configuration of OSB FDA](image)

The total element number of this array is \( N \). It is observed that the basic FDA is divided into \( N - M + 1 \) overlapping subarrays, respectively, denoted as \( \{S_1\}, \{S_2\}, \ldots, \{S_{N-M+1}\} \), each of which consists of \( M \) elements. The signal radiated by the subarray \( l \) toward the specific far-field target \((R, \theta)\) can be expressed as
\[ x_{nl}(t, R, \theta) = w_{nl}^H u_l(t, R) s_l(t) \]  

(9)

where \( s_l(t) \) denotes the transmit signal of the \( l \)th subarray, \( w_{nl} \) is the weight vector, and \( u_l \) denotes the steering vector.

3.2 Elements transmitting at multiple frequencies

The basic FDA transmits an identical baseband waveform at each element with a coherent single frequency. In this section, we use multi-carrier frequencies on each element of the OSB FDA to decouple the transmit beampattern.

The signal of the \( n \)th element simultaneously transmitting the \( l \)th frequency component can be written as
\[ x_{nl}(t) = w_{nl} \exp \left\{ j2\pi f_{nl} \left( t - \frac{R}{c} \right) \right\} \]  

(12)

where \( f_{nl} = f_0 + \Delta f_n + \Delta f_l \) denotes the radiation frequency of the \( n \)th element transmitting the \( l \)th frequency component, \( \Delta f_n = \lg(n+1) \Delta f \) \((n = 0, 1, \ldots, N-1)\) is the frequency offset between the \( n \)th element and the reference element, and \( N \) is the array number for the given array aperture. \( \Delta f_l = \lg(l+1) \Delta f \) \((l = 0, 1, \ldots, L-1)\) denotes the frequency offset of each array element transmitting the \( l \)th frequency component, and \( L \) is the total number of frequency components transmitted by each array element.

The total signal received by the far-field observation target can be expressed as
\[ x_n(t, R, \theta) = \sum_{n=0}^{N-1} \sum_{l=0}^{L} x_{nl}(t) = \sum_{n=0}^{N-1} \sum_{l=0}^{L} w_{nl} \exp \left\{ j2\pi f_{nl} \left( t - \frac{R}{c} \right) \right\} \]  

(13)

where \( w_{nl} \) denotes the transmit weight for each array element, and \((R, \theta)\) is an arbitrary far field observation point. The transmit beampattern of the log-FDA transmitting at multiple frequencies can be given as
\[ B(t, R, \theta) = \left| \sum_{n=0}^{N-1} \sum_{l=0}^{L} w_{nl} e^{j2\pi f_{nl} \left[ \lg(l+1) \right] (t - \frac{R}{c})} \right|^2 \]  

(14)

4. OSB PFDA

Most existing reports in the literature of the dot-shaped beamforming only focus on the basic FDA. In practice,
the radar application requires the ability to beam steer in higher dimensionalities, which will exceed the capability of the one-dimensional uniform linear array. In this section, we divide the basic PFDA proposed in [28] into the overlapping subarray-based PFDA (OSB PFDA) as shown in Fig. 4.

Fig. 4 shows a 6 × 6 PFDA, which can be divided into four subarray-based FDAs each with 3 × 3 array elements. The array elements in the green wireframe constitute the subarray 1. The array elements in the orange wireframe constitute the subarray 2. The array elements in the blue wireframe constitute the subarray 3. The array elements in the purple wireframe constitute the subarray 4. The dot-shaped beam can be achieved by employing a nonlinear frequency offset across each subarray elements. The transmit beampatterns of the three OSB-PFDAs and the basic PFDA are presented in Figs. 11 – 14 for 10 dB off the peak value.

5. Simulation results

In this section, simulations are performed to verify the effectiveness of the proposed approach. We assume a basic FDA of 20 sensors spaced a half-wavelength apart. The rest of the parameters are listed in Table 1.

| Table 1 Simulation parameters | Numerical value |
|-------------------------------|-----------------|
| FDA element number            | 20              |
| Subarray element number       | 10              |
| Carrier frequency/GHz         | 10              |
| Frequency offset/kHz          | 2               |
| Array element space c/2f₀     |                 |
| Target location (R, θ)/(km, °)| (200, 30)       |

Example 1 Transmit beampattern of the four FDAs.

Fig. 5 shows the transmit beampattern of the log-FDA. Fig. 6 shows the transmit beampattern of the OSB-FDA with a fixed frequency offset. Fig. 7 shows the transmit beampattern of the OSB log-FDA. Fig. 8 shows the transmit beampattern of the OSB log-FDA transmitting at multiple frequencies.
The decoupling method with a logarithmically increasing frequency offset, which is shown in Fig. 5, achieves a poor resolution in both range and angle dimensions. It can be seen from Fig. 6 that the OSB-FDA with a fixed frequency offset forms a trailing beam in the scanning position. The OSB-FDA with a fixed frequency offset has a certain effect on eliminating the inherent range-angle coupling. However, the multiple maxima at different ranges in Fig. 6 are easy to be disturbed. The decoupling method can be optimized by the introduction of the logarithmical frequency offset to remove the periodicity in the maximum as shown in Fig. 7. Considering the sidelobe’s magnitude, the performance of the OSB log-FDA is further optimized in Fig. 8.

**Example 2  Comparison of angle and range dimensional beampattern.**

We also examine the resolution in the range and angle dimension of the four analyzed FDAs. Fig. 9 shows the comparison in angle dimensional beampattern. Fig. 10 shows the comparison in range dimensional beampattern.

The beampattern of the log-FDA has a wide spread in the maxima, which may result in an ambiguous tracking performance. It is shown in Fig. 9 (b) – Fig. 9(d) that the beamwidth in the angle of these three OSB log-FDAs is between 10° and 20°, while the log-FDA is several times of it.

![Log-FDA in angle dimensional beampattern](image)

![OSB-FDA in angle dimensional beampattern](image)

![Log-FDA in range dimensional beampattern](image)

![OSB-FDA in range dimensional beampattern](image)
WANG Bo et al.: Dot-shaped beamforming analysis based on OSB log-FDA

Fig. 10 Comparison in range dimensional beampattern

It is shown in Fig. 10(b) – Fig. 10(d) that the beamwidth in the range of the three SB FDAs is also much smaller than that of the log-FDA. We can conclude that the three analyzed OSB-FDA schemes can produce narrow beam steering to the target. With the same total frequency offset, the OSB log-FDA transmitting at multiple frequencies has the best decoupling performance in both angle and range domains. It can also be seen in Fig. 11 that the SINR of the proposed SB FDA is better than that of the log-FDA.

Thus, the proposed system has a better robustness against interference. Fig. 12 shows the detection probability versus the SNR for the proposed subarray-based FDA and log-FDA. The proposed FDA exhibits better detection performance compared to the log-FDA.

Fig. 11 Performance comparison of SINR of different FDA radars

Example 3 Dot-shaped beamforming for the OSB PFDA.

Based on Section 4, we analyze the dot-shaped beamforming for the OSB PFDA in this example. Consider a basic $8 \times 8$ PFDA spaced a half-wavelength apart. The target locates at $(50 \text{ km}, 50 \text{ km}, 150 \text{ km})$, $\Delta f_x = 2 \text{ kHz}$, $\Delta f_y = 2 \text{ kHz}$, the carrier frequency is $10 \text{ GHz}$. Fig. 13 shows the $10 \text{ dB}$ beamwidth of the mainbeam of the basic PFDA with a carrier frequency $f_{nm} = f_0 + \log(n + 1)\Delta f_x + \log(m + 1)\Delta f_y$. Then we divide the basic $8 \times 8$ PFDA into four $5 \times 5$ OSB PFDAs. Fig. 14 shows the $10 \text{ dB}$ beamwidth of the mainbeam of the OSB PFDA with a fixed linear frequency offset. Fig. 15 shows the $10 \text{ dB}$ beamwidth of the mainbeam of the OSB PFDA with a logarithmic frequency offset. Fig. 16 shows the $10 \text{ dB}$ beamwidth of the mainbeam of the OSB PFDA with a logarithmic frequency offset transmitting at multiple frequencies.
Fig. 13 Transmit beampattern of basic PFDA with carrier frequency $f_{nm}$

Fig. 14 Transmit beampattern OSB PFDA with fixed frequency offset

Fig. 15 Transmit beampattern of OSB PFDA with logarithmical frequency offset

Fig. 16 Transmit beampattern of OSB PFDA with logarithmical frequency offset transmitting at multiple frequencies

It can be seen from Fig. 13 and Fig. 14 that the beampatterns both have a wide spread of the maxima, which may result in an ambiguous tracking performance. Fig. 15 and Fig. 16 show that the transmit beampatterns of the two OSB PFDA's can both form a dot-shaped beam in the target position. (i) Considering the overlay airspace of the main-lobe, Fig. 13 > Fig. 14 > Fig. 15 > Fig. 16. (ii) Considering the sidelobe’s magnitude, Fig. 16 is the most ideal.

6. Conclusions

FDA radar has received increasing attention in recent years because of the controllable degrees of freedom of the array. In this paper, the dot-shaped beam based on the OSB
FDA is realized. Comparisons of the proposed OSB log-FDA transmitting at multiple frequencies with log-FDA in simulations show the improvement in transmit beam-patterns. The subarray-based structure simplifies the processing and assembly of the array, providing a wide signal bandwidth. It also has a wide application prospect in the fields of range-angle joint estimation, front-view detection and imaging of radar targets. Further research will be carried out on the basis of the time-invariant SB FDA.

References

[1] HANSEN R C. Phased array antennas. Hoboken: John Wiley & Sons, 2009.
[2] KEIZER W P M N. Low sidelobe phased array pattern synthesis with compensation for errors due to quantized tapering. IEEE Trans. on Antennas Propagation, 2011, 59(12): 4520 – 4524.
[3] FENN A J. Adaptive antenna and phased arrays for radar and communications. Norwood: Artech House, 2008.
[4] ANTONIK P, WICKS M C, GRIFFITHS H D, et al. Frequency diverse array radars. Proc. of the IEEE Conference on Radar, 2006: 215 – 217.
[5] WICKS M C, ANTONIK P. Frequency diverse array with independent modulation of frequency, amplitude, and phase. U.S. Patent 7319427B2, 2008: 01 – 15.
[6] WICKS M C, ANTONIK P. Method and apparatus for a frequency diverse array. U.S.Patent 7511665B2, 2009: 03 – 31.
[7] LIU Y, RUAN H, WANG L, et al. The random frequency diverse array: a new antenna structure for uncoupled direction-range indication in active sensing. IEEE Journal of Selected Topics in Signal Processing, 2017, 11(2): 295 – 308.
[8] LI S, ZHANG L, LIU N, et al. Adaptive detection with conic rejection to suppress deceptive jamming for frequency diverse MIMO radar. Digital Signal Processing, 2017, 69: 32 – 40.
[9] LI Z, ZHANG Y, GE Q, et al. A robust deceptive jamming suppression method based on covariance matrix reconstruction with frequency diverse array MIMO radar. Proc. of the IEEE International Conference on Signal Processing, 2018: 1 – 5.
[10] HU J S, YAN S H, SHU F, et al. Artificial-noise-aided secure transmission with directional modulation based on random frequency diverse arrays. IEEE Access, 2017, 5: 1658 – 1667.
[11] XIONG J, WANG W Q, GAO K D. FDA-MIMO radar: TDOA estimation: CRLB, MSE, and resolution analysis. IEEE Trans. on Aerospace and Electronic Systems, 2018, 54(1): 284 – 294.
[12] CHEN B X, CHEN X L, HUANG Y, et al. Transmit beampattern synthesis for the FDA radar. IEEE Antennas and Wireless Propagation Letters, 2018, 17(1): 98 – 101.
[13] WANG W Q. Retrodirective frequency diverse array focusing for wireless information and power transfer. IEEE Journal on Selected Areas in Communications, 2019, 37(1): 61 – 73.
[14] HIGGINS T, BLUNT S D. Analysis of range-angle coupled beamforming with frequency-diverse chirps. Proc. of the International Waveform Diversity and Design Conference, 2009: 1 – 4.
[15] SHAO H Z, DAI J, XIONG J, et al. Dot-shaped range-angle beampattern synthesis for frequency diverse array. IEEE Antennas and Wireless Propagation Letters, 2016, 15: 1703 – 1706.
[16] LIU Y M. Range azimuth indication using a random frequency diverse array. Proc. of IEEE International Conference on Acoustics, Speech, and Signal Processing, 2016: 3111 – 3115.
[17] SHIN J, CHOI J H, KIM J, et al. Full-wave simulation of frequency diverse array antenna using the FDTD method. Proc. of the Asia-Pacific Microwave Conference, 2013: 1070 – 1072.
[18] CETINEPE C, DEMIR S. Multipath characteristics of frequency diverse arrays over a ground plane. IEEE Trans. on Antennas Propagation, 2014, 62(7): 3567 – 3574.
[19] BAIZERT P, HALE T B, TEMPLE M A, et al. Forward looking radar GMTI benefits using a linear frequency diverse array. Electronic Letters, 2006, 42(22): 1311 – 1312.
[20] LAN L, LAIO G S, XU J W, et al. Range-angle pencil-beamforming for non-uniformly distributed array radar. Multidimensional Systems and Signal Processing, 2018, 29: 867 – 886.
[21] KHAN W, QUreshi I M, SAEED S. Frequency diverse array radar with logarithmically increasing frequency offset. IEEE Antennas and Wireless Propagation Letters, 2015, 14: 499 – 502.
[22] KHAN W, QUreshi I M, BASIT A, et al. Performance analysis of MIMO-frequency diverse array radar with variable logarithmic offsets. Progress in Electromagnetics Research, 2016, 62: 23 – 34.
[23] KHAN W, QUreshi I M, BASIT A, et al. Transmit/received beamforming for MIMO log-frequency diverse array radar. Proc. of the International Bharhan Conference on Applied Science & Technology, 2016: 689 – 693.
[24] KHAN W, QUreshi I M, BASIT A, et al. Range-bins-based MIMO frequency diverse array radar with logarithmic frequency offset. IEEE Antennas and Wireless Propagation Letters, 2016, 15: 885 – 888.
[25] LI Q, HUANG L, SO H C, et al. Beampattern synthesis for frequency diverse array via reweighted $l_1$ iterative phase compensation. IEEE Trans. on Aerospace Electronic Systems, 2018, 54: 467 – 475.
[26] WANG W Q. Subarray-based frequency diverse array radar for target range-angle estimation. IEEE Trans. on Aerospace and Electronic Systems, 2014, 50(4): 3057 – 1076.
[27] WANG Y X, HUANG G, LI W. Transmit frequency diverse array radar. IEEE Antennas and Wireless Propagation Letters, 2017, 16: 1003 – 1006.
[28] JONES A M, RIGLING B D. Planar frequency diverse array receiver architecture. Proc. of the Radar Conference, 2012: 145 – 150.
[29] SAMMARTINO P F, BAKER C J, GRIFFITH H D. Frequency diverse MIMO techniques for radar. IEEE Trans. on Aerospace Electronic Systems, 2013, 49(1): 201 – 222.
[30] WANG W Q, SO H C, SHAO H Z. Nonuniform frequency diverse array for range-angle imaging of targets. IEEE Sensors Journal, 2014, 14(8): 2469 – 2476.
[31] XU Y, SHI X, XU J, et al. Range-angle-decoupled beampattern synthesis with subarray-based frequency diverse array. Digital Signal Processing, 2017, 64: 49 – 59.
[32] WANG S L, XU Z H, LIU X H, et al. A novel transmit-receive system of frequency diverse array radar for multitarget localization. Electronics, 2018, 7: 408.
[33] ZHANG H W, XIE J W, SHI J P, et al. Sensor scheduling and resource allocation in distributed MIMO radar for joint target tracking and detection. IEEE Access, 2019, 7(1): 62387 – 62400.
[34] WANG W Q, SO H C. Transmit subapertureing for range and angle estimation in frequency diverse array radar. IEEE Trans. on Signal Processing, 2014, 62(8): 2000 – 2011.
[35] BASIT A, QUreshi I, KHAN W, et al. Beam pattern synthesis for an FDA radar with hammering window based non-uniform frequency offset. IEEE Antennas and Wireless Propagation Letters, 2017, 16: 2283 – 2286.
ZHANG H W, LIU W J, XIE J W, et al. Space-time allocation for transmit beams in collocated MIMO radar. Signal Processing, 2019, 164: 151 – 162.

Biographies

**WANG Bo** was born in 1991. He received his bachelor and master degrees from the Air and Missile Defense College, Air Force Engineering University, in 2013 and 2015, respectively. He is currently pursuing his Ph.D. degree in the Air and Missile Defense College. His research interests include signal processing and interference suppression technology based on FDA array radar.

E-mail: wbwangbo1991@163.com

**XIE Junwei** was born in 1970. He received his bachelor, master, and doctor degrees from the Air and Missile Defense College, Air Force Engineering University, in 1993, 1996 and 2009, respectively. He is currently a professor in the Air and Missile Defense College. His research interests include novel radar systems as well as jamming and anti-jamming. He has published more than 100 refereed journal articles, book chapters, and conference papers.

E-mail: xjw_xjw123@163.com

**ZHANG Jing** was born in 1991. She received her bachelor degree from Xi’an University of Architecture and Technology, in 2013. She received her master degree from the College of Science, Air Force Engineering University, in 2015. She is currently a lecturer in Shaanxi Vocational and Technical College of Transport. Her research interests include signal processing and interference suppression technology based on FDA array radar.

E-mail: zj_zhangjing1991@163.com

**ZHANG Haowei** was born in 1992. He received his bachelor and master degrees from the Air and Missile Defense College, Air Force Engineering University, in 2014 and 2016, respectively. He is currently pursuing his Ph.D. degree in the Air and Missile Defense College. His research interests include multifunction radar resource management and intelligent scheduling.

E-mail: zhw_xhzf@163.com