Networked FDA-MIMO radar positioning to suppress dense false target jamming

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Abstract. Aiming at the dense false target jamming, the existing research does not consider the problems of true and false target identification and position estimation at the same time. A method of dense false target jamming suppression is proposed based on multiple-input multiple-output frequency diverse array (FDA-MIMO) radar network, which makes full use of the different characteristics of true and false targets in the space-time two-dimensional range distribution. It discriminates true and false targets and locates true targets and jamming sources in transmit-receive two-dimensional frequency domain. Then other radars in the information sharing network are instructed to silence sector at the location of the jamming source to reduce the jamming power into the radar. The netting radars capabilities of target detection and jamming suppression are improved by this method.

1. Introduction
A small frequency interval, compared with the carrier frequency, is applied across the adjacent elements of multiple-input multiple-output frequency diverse array (FDA-MIMO) radar. The signals transmitted by each element are orthogonal, making it have unique advantages in main lobe interference suppression, anti-interception performance, signal detection, parameter estimation, etc.[1-2]. It can identify deceptive false targets[3], estimate the real target position[4] and adaptively suppress the main lobe false target interference[5] by making full use of the range-angle coupling characteristics of the radar beam.

FDA-MIMO radar has three main ideas in the identification of true and false targets. One is to make use of the true and false targets difference of phase and spatial angular frequency between the elements[3], but the calculation is complicated and the error has a great influence. The second is to make use of the range-angle coupling characteristic of the transmission pattern to make the main lobe of the pattern pass through the target to be identified without passing through other targets. The target type is identified according to the difference of the received signal[6], but this method needs to know the location information of all targets accurately. When the number of false target jamming increases and the range from the target is close, the identification effect is poor. The third is to make use of the difference in range and polarization characteristics[7], but this method is complicated and amount of calculation is large. FDA-MIMO radar has two main methods for target positioning. One is to change the frequency interval to transmit and receive signals in turn, extract the range and angle from decoupled information and estimate the target position[8-9], but the calculation is more complicated. The second is to divide the array into multiple sub-arrays with different frequency intervals and uses multiple signal classification (MUSIC) algorithm to estimate the target position[10-12], but the range estimation error is large. Not only that, none of the appealed documents considers both the
identification of true and false targets and the estimation of target positions. There is almost no research on the influence of FDA-MIMO radar on other radars to suppress dense false targets after entering the network.

To solve the above problems, a method for FDA-MIMO radar into the network to suppress dense false target jamming is proposed in this paper by making full use of the difference in the space-time two-dimensional range dimension between false targets and true targets. Firstly, the true and false targets are identified in the transmit-receive two-dimensional frequency domain by transmitting signals in the form of linear frequency intervals. Secondly, the true targets and jamming source are located in the range-angle two-dimensional space by transmitting and receiving the signals with nonlinear frequency intervals. And FDA-MIMO radar adaptively suppress dense false target jamming in transmit-receive two-dimensional frequency domain. Finally other radars in the information sharing network are instructed to silence sector at the location of the jamming source to suppress the interference of dense false targets. The simulation verifies the effectiveness of the method.

2. FDA-MIMO signal model

Suppose the array composed of \(N\) elements with uniform spacing \(d\). The transmitted signal is a far-field narrow-band signal whose angle to the normal direction of the array is \(\theta\). The first element is selected as the reference array element and the range from the scattering point to the first element is \(r\).

The array model is shown in figure 1, where \(g_m(t)\) is the envelope of the signal emitted by the \(m\)th element.

![Figure 1. FDA-MIMO signal model](image)

The radiated frequency from the \(m\)th element is

\[
f_m = f_0 + (m-1)\Delta f, \quad m=1,2,\ldots,N
\]

(1)

Where, \(f_0\) is the carrier frequency of the first element and \(\Delta f\) is the frequency interval between the adjacent elements. Consider the transmitted signal as a far-field narrowband signal, the phase difference between the \(m\)th element and first element is given by

\[
\Delta \phi_m = \phi_m - \phi_0 = -2\pi(m-1) \left[ -\Delta f \frac{r}{c} + f_0 \frac{d \sin \theta}{c} + \Delta f \frac{d(m-1) \sin \theta}{c} \right]
\]

(2)

Where, \(c\) is the Speed of light. From (2), it is obvious that FDA-MIMO’s beam direction is related to the angle and range of the target and array, which is called range-angle coupling. Noticed that \(f_0 \gg N\Delta f\), the item 3 is negligible compared with the phase difference brought by the first two terms.

Ignoring various losses, Since the FDA-MIMO radar transmitting beam is omnidirectional, the transmitted signal of \(m\)th element can be expressed as

\[
s_m(t;\theta,r) = \frac{E}{\sqrt{N}} g_m(t) e^{-j2\pi f_0 t - j2\pi f_0 \frac{d \sin \theta}{c}} \quad 0 \leq t \leq T
\]

(3)
Where, \( E \) is the total energy for the transmitted signal, \( \mathcal{G}_m(t) \) is the unity-energy waveform of the signal transmitted by the \( m \)th element, \( T \) is the radar pulse duration and \( t \) is the time index within the radar pulse. Unlike the FDA radar, the FDA-MIMO radar combines the characteristics of the MIMO radar, so that the envelopes of the transmitted signals from different elements are orthogonal to each other. This can be expressed as

\[
\int_{\mathcal{R}} \mathcal{G}_m(t) \mathcal{G}_l^*(t-\tau)e^{j2\pi f(t-\tau)/c}dt = 0 \quad l \neq m, \forall \tau
\]  

(4)

Where, \((\cdot)^*\) denotes the conjugate operator, \(\tau\) is an arbitrary time delay.

Then the signal with \( f_n \) frequency received by the \( m \)th element can be expressed as

\[
y_{mn}(t;\theta,r) = e^{-j2\pi f_n(t-\tau)/c} \sum_{n=1}^{N} y_{mn}(t-\tau)e^{j2\pi f_n(t-\tau)/c}
\]

(5)

Therefore, the signal received by the entire array is expressed as

\[
Y(\theta,r) = \xi \sum_{n=1}^{N} y_{mn}(\theta,r) = \xi [y_{11}, y_{12}, \ldots, y_{1N}, y_{21}, \ldots, y_{NN}]^T = \xi b(\theta) \otimes a(\theta,r,\Delta f) = \xi v(\theta,r,\Delta f)
\]

(6)

Where, \(\xi\) is the target signal amplitude information, \(T\) means transpose, \(\otimes\) represent Kronecker product. \(v(\theta,r,\Delta f)\) is the array steering vector, \(a(\theta,r,\Delta f)\) is the transmit steering vector, \(b(\theta)\) is the receive steering vector. The specific expression is

\[
a(\theta,r,\Delta f) = a_\theta(\theta) \otimes a_r(r,\Delta f) = [1, e^{j2\pi f_0^\Delta}, \ldots, e^{j2\pi (N-1)f_0^\Delta}]^T \otimes [1, e^{-j2\pi f_0^\Delta}, \ldots, e^{-j2\pi (N-1)f_0^\Delta}]^T
\]

(7)

\[
b(\theta) = [1, e^{j2\pi f_0^e}, \ldots, e^{j2\pi (N-1)f_0^e}]^T
\]

(8)

Where, \(\otimes\) represents the Hadamard product, \(f_0\) is the working wavelength of the FDA-MIMO radar.

3. Identification and location of true and false targets for dense false targets jamming suppression

The received radar signals are mainly arbitrarily delayed to generate dense false target jamming by jammer using digital radio frequency memory (DRFM) technology. And the generated false targets can appear in any range, which can make the true target drown in the false targets. Especially when the angle of jamming is close or consistent with the target, the performance of the phased array that uses the angle-dimensional freedom to suppress jamming will deteriorate sharply, which will seriously affect the radar's ability to detect targets. The phase difference of the FDA-MIMO radar signal is related to the propagation range. The propagation range here refers to the range from the array to the jammer, which is reflected in transmit steering vector. The steering vector of the dense false target jamming released by the same jammer is the same\(^5\). The range arbitrarily delayed by jammer does not match the real range of jammer which can be used to identify true and false targets and locate jammer. Then other radars in the information sharing network are instructed to take corresponding anti-jamming measures such as sector silence to suppress dense false target jamming at the location of the jammer. The specific principle analysis is as follows.

Assuming that a real target is located at \((\theta_s^r, r_s^r)\), there are \(Q\) jammers releasing \(P\) false target jamming (\(Q \leq P\)). And the \(k\)th jammer is at \((\theta_{jk}^r, r_{jk}^r)\). The signal received by the entire array can be expressed as

\[
x = x_s + x_j + n = \xi_s v_s(\theta_s^r, r_s^r, \Delta f) + \sum_{k=1}^{P} \xi_{jk} v_{jk}(\theta_{jk}^r, r_{jk}^r, \Delta f) + n
\]

(9)

Where, \(x_s\) and \(x_j\) indicate the received target and jamming signal, respectively. \(n\) is Gaussian white noise with a mean value of 0 and variance of \(\Delta f^2\). \(\xi_s\) and \(\xi_{jk}\) respectively represent the received target amplitude information and the amplitude information of the \(k\)th jamming. \(v_s(\theta_s^r, r_s^r, \Delta f)\) and
\( v_s(\theta_r, r_s, \Delta f) \) respectively represent the target and the \( k \)th jamming signal. For the sake of simplicity, the following target and the \( k \)th interference are represented by \( v_s \) and \( v_{jk} \) respectively.

![Figure 2. Schematic diagram of space-time two-dimensional range distribution of true and false targets](image)

It may be assumed that the range corresponding to the true target echo in the time domain is \( r_{st} \). The position of the \( Q \) jammers is \( r_{s_i}(i=1, \cdots, Q) \). The position of the released false target jamming in the time domain can be expressed as \( r_{sk}(k=1, \cdots, P) \). Due to the jamming released by the jammer is randomly placed at different range gates which is generally different with jammer, that is \( r_{s_i} \neq r_{sk} \). As shown in figure 2.

With reference to equations (7) and (8), the transmit steering vector \( a(\theta_j, r_j, \Delta f) \) and receive steering vector \( b(\theta_j) \) of jamming can be obtained as follows:

\[
a(\theta_j, r_j, \Delta f) = \left[ 1, e^{j2\pi \frac{d}{\lambda_0} \sin \theta_j}, \cdots, e^{j2\pi \frac{d}{\lambda_0} (N-1) \sin \theta_j} \right]^T \otimes \left[ 1, e^{-j\frac{\Delta f}{c} r_j}, \cdots, e^{-j\frac{\Delta f}{c} (N-1) r_j} \right]^T
\]

\[
b(\theta_j) = \left[ 1, e^{j\frac{d}{\lambda_0} \sin \theta_j}, \cdots, e^{j\frac{d}{\lambda_0} (N-1) \sin \theta_j} \right]^T
\]

For the FDA-MIMO radar using linear frequency interval, the transmit spatial frequency \( f_{T,j} \) and receive spatial frequency \( f_{R,j} \) of jamming are defined as[13]:

\[
f_{T,j} = -2 \frac{\Delta f}{c} r_j + \frac{d}{\lambda_0} \sin \theta_j
\]

\[
f_{R,j} = \frac{d}{\lambda_0} \sin \theta_j
\]

Due to the difference in the space-time two-dimensional range domain between true targets and dense false targets, there will also be differences in transmit-receive two-dimensional frequency domain. The time range and airspace range of the true target’s echo are equal, so the position calculated according to the angle and time range of the true target is the same as the position obtained directly by spectrum estimation in the transmit-receive two-dimensional spatial frequency domain. The time range and airspace range of the false target’s echo are not equal, so the position calculated according to the angle and time range of the false target is the same as the position obtained directly
by spectrum estimation in the transmit-receive two-dimensional spatial frequency domain. The false target jamming and the true target can be distinguished by using this difference. When locating the true target and the jammer by FDA-MIMO radar using linear frequency interval, it will appear fuzzy [14]. Therefore, FDA-MIMO radar can use a non-linear frequency interval (such as exponential form: \( \Delta f_n = (e^{\Delta f} - 1)\Delta f \)) to locate the true target and jammer after identifying the signal of true and false target. Then the location of the jammer is fed back to other radars in the net, which can take corresponding anti-jamming measures such as sector silence to suppress jamming. And FDA-MIMO radar can suppress dense false target interference in the two-dimensional transmit-receive frequency domain.

Sector silence does not mean that no signal is received at all in the direction of the jammer, but the radar does not actively transmit signals in that direction. However, it should be pointed out that when the radar scans outside the sector silence area, there will still be signals entering the radar through the side lobes in the silent area of the sector.

The normalized pattern gain of spatial matched filtering in the beam pointing direction \( \theta_0 \) is

\[
G(\theta) = \left| \frac{\sin[\pi d N (\sin \theta - \sin \theta_0) / \lambda]}{N \sin[\pi d (\sin \theta - \sin \theta_0) / \lambda]} \right|^2 \tag{14}
\]

When the main lobe of the radar antenna is scanned, only the side lobes are scanned in the sector silence area. The farther the sector silence area is from the antenna main lobe, the lower the antenna side lobe level. Which means that the larger the radar sector silence area, the lower the jamming power entering the radar.

Specific steps are as follows:

1) FDA-MIMO radar adopts linear frequency interval and directly estimates the spatial spectrum of the received signal on the space-time two-dimension (angle + time range) to estimate the angle and range information of the received target and jamming;

2) According to the estimated angle and range information, calculate the distribution of the target and jamming in the transmit-receive two-dimensional spatial frequency domain;

3) Directly perform spectrum estimation on the received signal in transmit-receive two-dimensional spatial frequency domain and compare it with the position obtained in step (2). If the two positions are consistent, it can be judged as true targets. In contrast, if the two positions are inconsistent, it can be judged as a false target. Then output the real target position (angle + airspace range);

4) Change the frequency interval of the FDA-MIMO radar to be non-linear. Then perform spatial spectrum estimation in the range-angle domain (such as MUSIC algorithm) and estimate the spatial position of the target and jammer. And remove the target position calculated in step (3), the remaining positions are the jammer positions;

5) The location of the jammer is fed back to other radars in the information sharing network and anti-jamming measures such as sector silence are taken to suppress dense false target jamming. FDA-MIMO radar adapts beamforming in transmit-receive two-dimensional frequency domain to suppresses the jamming.

4. Simulation analysis

4.1. FDA-MIMO radar true and false target identification and jamming source location simulation analysis

The parameters are set as follows: the radar element number of FDA-MIMO is 10. The carrier frequency is 3GHz. The frequency interval is set to 3kHz and the true target located on the 100th range gate position is \( (0°,180km) \). The signal-to-noise ratio is 5dB and there are 3 jammers. The positions are \( (2°,450km),(15°,300km),(25°,200km) \), respectively. And each jammer releases 3 false target jams, which are located at the 40th, 100th, 160th, 70th, 100th, 130th, 20th, 100th, and 180th
range gates, respectively. 3 jammers release the jamming signal-to-jamming-noise ratio is 15dB, 25dB, and 30dB. When locating the true target and the jamming source, the frequency interval in exponential form is adopted, and the bottom of the exponent is 1.2. The simulation diagram is shown below.

![Figure 3. Range-angle gate two-dimensional power spectrum](image3)

![Figure 4. True and false target’s distribution on transmit-receive two-dimensional frequency domain](image4)

It can be seen from figure 3 that there are 9 false targets and 1 true target in the range-angle two-dimensional domain, since there is no prior information about the position of the true target. It is impossible to distinguish which signal for the FDA-MIMO radar is a true target, so the FDA-MIMO radar cannot distinguish false targets and true targets in the range-angle gate two-dimensional domain. Since the false targets generated by the same jammer will be superimposed, the position is the location of the jammer, rather than the position of the false target jamming in the transmit-receive two-dimensional frequency domain, so when comparing the positions which are converted from signals on two-dimensional range-angle gate to the position estimated directly in the two-dimensional transmit-receive frequency domain, only the true target position calculated coincides with the position estimated by the direct spatial spectrum, as shown in figure 4. The true target position outputted accurately is (0,180km), as shown in figure 5, which is consistent with the true target position parameter settings.

![Figure 5. True target space position](image5)

![Figure 6. Range-angle two-dimensional power spectrum](image6)

It can be found from figure 6 that when the signal is spectrum estimated in the range-angle two-dimensional domain, the position of the true target and the jammer can be clearly estimated. After
removing the true target position, the rest is the jammer position and the estimated value is same as the parameter settings basically.

4.2. Simulation Analysis of Suppressing False Targets on Networking Radar with sector silence

Suppose there is a network of S-band, L-band radar and FDA-MIMO radar. The working frequency of L-band radar is 1.2GHz and the working frequency of S-band radar is 2.7GHz. The carrier frequency and frequency interval of FDA-MIMO radar are respectively 3GHz and 3kHz. The L-band radar is located in north by east 60° of the FDA-MIMO radar with a range of 250km and the S-band radar is located in north by west 80° of the FDA-MIMO radar with a range of 150km. The three radar antennas are linear arrays and the number of array elements all are 20. The network center uses a unified rectangular coordinate system with FDA-MIMO radar as the origin for calculation. And the deflection angle in the counterclockwise direction as the azimuth. Assuming that a true target is located at (0′, 180km). The peak of the echo is located at the 180th range gate of the FDA-MIMO radar and the signal-to-noise ratio is 5dB. A jammer is located at the (2°, 450km) of FDA-MIMO radar. Here 2° is the degrees north by east of the FDA-MIMO radar (north by east is positive, north by west is negative). The jammer releases dense false target jamming to three radars and the echo peaks are located on the 40th, 60th, 100th, 120th, 140th, 160th, 180th, 200th, 220th, 240th, 260th, 280th, 300th, 320th, 340th, 360th, 380th range gates of the three radars. The jamming-to-noise ratio is 25dB. The positional relationship among the three radars, jammers and targets is shown in figure 7. As mentioned in the previous section, the FDA-MIMO radar can identify and locate the target and the jamming source. Considering the positioning error, assuming the location of the jammer is (1°, 470km), and then sending the jamming source location information to other radars through the netted radar. The L-band and S-band radars use their own coordinate system as a reference to estimate the location of the jammer, as shown in figure 8 and figure 9.

Figure 7. Distribution of networked radars, targets and jammers
It can be found from figure 8 and figure 9 that the position of the jammer and true target located by the L-band radar are respectively at \((-59',403\text{km})\) and \((-14',223\text{km})\), the position of the jammer and true target located by the S-band radar are respectively at \((19',470\text{km})\) and \((44',213\text{km})\). The jammer is far away from the true target. The L-band radar and S-band radars are different from the FDA-MIMO radar, their beam direction is not related to the range, but only related to the angle. Therefore, the angle difference between the jammer and the true target can be used for jamming suppression, such as sector silence at the location of the jammer.

Considering the possible existing range and angle errors of the jammer’s position estimated by the L-band and S-band radars, as well as the robust performance of sector silence, it is better to take the azimuth of the jammer as the center and the azimuth area deviated by 5° up and down and a total of 10° is the sector silence area. The sector silence area of the L-band radar is \((-64',-54')\) and the sector silence area of the S-band radar is \((14',24')\). Considering the worst case, the highest side lobe level in the sector silence area during the radar scanning process is used as the radar antenna gain when the jamming enters the radar. The simulation diagrams of FDA-MIMO radar before and after filtering, and L-band and S-band radars before and after sector silence are shown below.
From figure 10 and figure 11, it can be found that the L-band and S-band radars adopt the sector silence method to suppress dense false targets jamming, so that the jamming can only enter the radar from the antenna sidelobe. Through time domain filtering, the L-band radar is basically removed the dense false targets jamming. Because the S-band radar is close to the jammer, although the jamming is not completely filtered out, it weakens the energy of jamming and increases output SINR. It can be seen from figure 12 and figure 13, the FDA-MIMO radar uses the range-angle correlation characteristics of its beam pointing to direct beam to the target location in the transmit-receive two-dimensional frequency domain. At the same time a null at the position of the jammer is adaptively formed, so that false target jamming can be directly suppressed during time domain filtering, which greatly improves the radar network's ability to detect true targets.

According to the previous analysis, it can be known that the division of the angular range of the silent sector directly affects the jamming energy entering the L-band and S-band radars, which affects the anti-jamming effect of the networked radars. Here we study the settings of silent azimuth range of the L-band and S-band radars sectors (the two sector silence azimuth range settings are the same) has an impact on the evaluation of the anti-jamming effectiveness of the networking radar. The main indicators include network jamming suppression ratio and target discovery probability. The network jamming suppression ratio is the ratio of the sum of the output SINR before and after all radars in the network taking anti-jamming measures. The target discovery probability refers to the probability of finding correctly the target under jamming from the networking radar. The influence of the sector silence range on the anti-jamming performance of the network is shown in table 1.
It can be further seen from table 1, because FDA-MIMO radar can identify and locate false target jamming sources and true targets, when it is networked with L-band and S-band radars, the information of the located jamming sources can be sent to other radars of the network and then sector silence on the location of the jamming source is taken, which can effectively suppress the dense false targets jamming. And along with the azimuth range of the sector silence becoming larger, the number of radars found targets in the network becomes more, the probability of L-band and S-band radars networking finding targets is increased dramatically and the three radar networks jamming suppression ratio and target discovery probability are also getting larger.

Table 1. Influence of sector silence range on the anti-jamming performance of networking radars

| L, S band radar sector silent azimuth range (°) | 1  | 5  | 10 | 15 | 20 | 25 | 30 |
|-----------------------------------------------|----|----|----|----|----|----|----|
| The number of radars found the target          | 1  | 2  | 2  | 3  | 3  | 3  | 3  |
| Netted radar jamming suppression ratio         | 22.2 | 26.97 | 27 | 28.17 | 28.19 | 29 | 29.93 |
| L,S band radar networking target detection probability | 0.1218 | 0.4034 | 0.4061 | 0.5491 | 0.5534 | 0.6641 | 0.7842 |
| Probability of target detection for netted radar | 0.9903 | 0.9934 | 0.9934 | 0.9949 | 0.9951 | 0.9963 | 0.9976 |

5. Conclusion
In the case of suppressing dense false target jamming, the existing literature hardly simultaneously considers the problems of true and false target identification and position estimation, a method of dense false target jamming suppression is proposed based on FDA-MIMO radar network. FDA-MIMO radar first transmits linear frequency interval signals and identifies true and false targets in the transmit-receive two-dimensional frequency domain. Then the signals in the form of nonlinear frequency intervals are transmitted to decouple their beams, remove range dimension ambiguity and locate targets and jamming sources. Finally other radars in the information sharing network are instructed to silence sector at the location of the jamming source to reduce the jamming power into the radar. The simulation results show that this method has a great effect in identifying true and false targets and locating jammer. After adopting the sector silence method, the ability of other radars to suppress false targets and detect true targets is significantly improved and the sector silence range becomes larger, the greater radar network jamming suppression ratio and target discovery probability.

![Figure 13. FDA-MIMO radar time domain before and after filtering](image)
However, the proposed method has not comprehensively considered the problems of hardware implementation, which is the direction to be discussed in the next step.

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