1 Introduction

Frequency diverse array (FDA) utilizing a small frequency increment across each antenna element was proposed by [1] to steer the beam electronically in angle and range dimensions. The FDA concept has range dependent beamforming capability. It was observed that frequency increment makes the array beampattern changes as a function of the range, angle and time [1-3]. In [3], FDA applications for various modes of operations in radar systems has been presented. The periodicity of beam pattern in time, range and angle was investigated in [5]. In [6], a linear FDA was proposed to address the range ambiguous clutters and improves the detection ability in a relatively slow moving targets. The radiation capabilities of FDA was presented in [7] to show its beam scanning features. Also it was proven that the scanning speed was related to frequency offset employed between two neighboring antenna elements. In [8], the range and angle coupled beamforming with frequency diverse chirp signals was presented. In addition, [9] investigated FDA range-angle dependent beamforming to suppress interferences at different ranges and directions.

FDA has alot of promising application [10] which has sparked many interesting investigations in finding a suitable frequency offset to provide range-angle dependent. It is important to mention that frequency offset across the FDA elements plays essential role in improving the overall performance of an FDA radar, especially in controlling range-angle dependency and spatial distribution of generated beam pattern [11,12]. Hence, researchers have shown great interest to investigate frequency offset between the adjacent elements of FDA to improve it performance. Since FDA offers a range-angle-dependent beampattern, it is of great significance as this provides a potential for range-angle localization of targets, however, the beampattern of the conventional FDA is coupled in range-angle dimension. In this regards, a nonuniform linear array was proposed in [13] to decouple the FDA transmit beampattern, however, the carrier frequency and/or frequency increments cannot be altered in real-time because it requires relocating the elements mechanically. In [14] and [15], logarithmically increasing frequency offsets and time-dependent frequency offsets, respectively are reported to decouple the

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range-angle beampattern. However, these methods resulted in poor beamforming performance in the range dimension. Note that the best decoupling way is to form a dot-shaped beampattern rather than S-shaped beampattern.

In this paper, transmit/received beamforming FDA radar with symmetrical frequency offset to decouple range and angle beampattern in order to produce a single maxima is investigated. The idea is to use the symmetrical frequency offset to provide extra degree of freedom in terms of producing single maxima for a particular target of interest in a given region. Due to single maxima the received signal at the receiver array will be better than the signal for the conventional FDA. Furthermore, the proposed transmit/received beamforming are evaluated by the signal-to-interference-plus-noise ratio (SINR) and detection probability. Results shows the superiority of the proposed method.

The remaining sections are organized as follows: Section II presents the signal model of the conventional FDA, followed by the proposed symmetrical frequency offset FDA radar. Section III derives the SINR and detection probability. Section IV presents results and discussions and concluding summaries are drawn in Section V.

2 Background

2.1 Conventional FDA Range-Angle Dependent Transmit Beampattern

Figure 1 shows the conventional FDA antenna array structure.

The narrow-band monochromatic signal radiated from each element is identical but with a frequency increment $\Delta f$. The radiated frequency of the $m$th element can be expressed as

$$f_m = f_0 + m\Delta f, \quad m = 0, 1, \ldots, M - 1$$

(1)

where $f_0$ is the carrier frequency and $M$ is the number of array elements. Then, the signal transmitted by the $m$th element can be represented by

$$s_m(t) = \exp(-j2\pi f_m t).$$

(2)

The signal arriving at a far-field point $(r, \theta)$ can be expressed as

$$s_m(t - \frac{r_m}{c_0}) = \exp\left\{-j2\pi f_m\left(t - \frac{r_m}{c_0}\right)\right\}.$$ 

(3)

where $c_0$ is the speed of light and $r_m \approx r - md \sin \theta$, with $d$ being the element spacing, is the target slant range for the $m$th element. If uniform weights (all ones) are applied, the array factor can be approximately derived as

$$AF(t; r, \theta) = \sum_{m=0}^{M-1} \exp\left\{-j2\pi f_m\left(t - \frac{r_m}{c_0}\right)\right\}$$

$$\approx e^{-j\Phi_0} \sin\left\{M\pi\left(\Delta f t - \frac{\Delta fr}{c_0} + \frac{df_0\sin \theta}{c_0} + \frac{\Delta fd \sin \theta}{c_0}\right)\right\}$$

(4)

where $\Phi_0 = 2\pi f_0(t - r/c_0) - \pi(M - 1)\Delta f r/c_0 + \pi(M - 1)\Delta fd\sin \theta/c_0$.

Equation (4) implies that FDA has range, angle and time dependent transmit beampattern. However, the beampattern is coupled in the range and angle dimensions and consequently it will have multiple maxima. To avoid the dependence of range gain on the angle, the FDA parameters should be properly designed.

2.2 Proposed Symmetrical Frequency Offset FDA for Transmit/Received Beamforming

In this paper, the symmetrical frequency offsets is proposed to decouple range and angle beampattern in order to localize a target in a given region. In designing symmetrical frequency offset, the central element is chosen as the symmetrical point depicted in Figure 2.

In this paper, odd number of elements are assumed, namely, $M = 2M_s - 1$. The frequency offset for the $k$th element can be expressed as

$$\Delta f_k = |k|\Delta f, \quad k = -M_s + 1, \ldots, 0, 1, \ldots, M_s - 1.$$ 

(5)

Note that in order to show distinct representations, a new element index $k \in [-M_s + 1, \ldots, 0, \ldots, M_s - 1]$ instead of $m$ defined in (1) is adopted. Reformulate (4) as

$$AF(\theta, r, t) = \sum_{k=-M_s}^{M_s} \frac{1}{r_k} \exp\left\{-j2\pi\left(f_0 + |k|\Delta f\right)\left(t - \frac{r_k}{c_0}\right)\right\}$$

$$\approx \sum_{k=-M_s}^{M_s} \frac{1}{r} \exp\left\{-j2\pi\left(f_0 - k\Delta f\right)\left(t - \frac{r_k}{c_0}\right)\right\}$$

$$+ \sum_{k=1}^{M_s} \frac{1}{r} \exp\left\{-j2\pi\left(f_0 + k\Delta f\right)\left(t - \frac{r_k}{c_0}\right)\right\}$$

(6)

Similarly, $r_k \approx r - kd \sin \theta$ is used, where $r$ denotes here as the reference range to the central element. Equation (6) can be rewritten as a general vector formulation:

$$AF(\theta, r, t) \approx \mathbf{w}^H \mathbf{a}(\theta, r, t)$$ 

(7)
where $^H$ is the conjugate transpose operator, $\mathbf{w}$ is the $M \times 1$ weighting vector, and transmit steering vector $\mathbf{a}(\theta, r, t)$ is

$$
\mathbf{a}(\theta, r, t) = \frac{1}{r} \left[ e^{-j\Phi, t}, \cdots, 1, \cdots, e^{-j\Phi, t}, \cdots, e^{-j\Phi, t} \right]^T
$$

with $^T$ being the transpose operator and

$$
\Phi_k = 2\pi (f_0 + k|\Delta f|) \left( t - \frac{R_k}{c_0} \right).
$$

The $\mathbf{w}$ can be optimally designed to synthesize the desired transmit beampattern.

3 Transmit / Received Beamforming for Symmetrical frequency offset FDA

In this section transmit and received beamforming for proposed method is presented. The transmit beamforming can be expressed as

$$
B_T(\theta, r) = \frac{|\mathbf{w}^H \mathbf{a}(\theta, r)|^2}{|\mathbf{w}^H \mathbf{a}(\theta, r, t)|^2}
$$

(10)

The normalized received beampattern can be written as

$$
B_r(\theta, r) = \frac{|\mathbf{w}_r^H \mathbf{v}(\theta, r)|^2}{|\mathbf{w}_r^H \mathbf{v}(\theta, r, t)|^2}
$$

(11)

where $\mathbf{v}(\theta, r) = (\mathbf{w}^H \mathbf{a}(\theta, r)) \mathbf{b}(\theta)$ denotes the virtual steering vector $\mathbf{v}(\theta, r)$ and $\mathbf{b}(\theta)$ being the receive steering vector due to the propagation delays from a source to the receive elements.

4 Performance Analysis

4.1 SINR

The performance analysis of the proposed method are evaluated by signal-to-interference-plus-noise ratio (SINR) and probability of detection. First of all all SINR can be expressed as

$$
SINR = \frac{\sigma_d^2 |\mathbf{w}_r^H \mathbf{v}(\theta, r, t)|^2}{\sigma_n^2 Q_{i+n} \mathbf{w}_r^H \mathbf{w}_r}
$$

(12)

where $\sigma_d^2$ is the variance of the target reflection coefficient and $Q_{i+n}$ denotes the interference-plus-noise covariance matrix which is given as

$$
Q_{i+n} = \sum_{i=1}^F \sigma_i^2 \mathbf{v}(\theta_i, r_i) \mathbf{v}^H(\theta_i, r_i) + \sigma_n^2 I
$$

(13)

where $\sigma_i^2$ is the variance of the $i^{th}$ interference reflection coefficient, $F$ is the number of interferences and $\sigma_n^2 I$ is the covariance matrix with $I$ being an identity matrix. Plugging in (13) and $\mathbf{w}_r = \mathbf{v}(\theta_d, r_d)$ into (12) for any radar system, will yields SINR for that radar system.

4.2 Probability of Detection (Pd)

In this section, the probability of detection (Pd) is employed to evaluate the performance of a radar system. For the proposed method, the hypothesis problem can be written as

$$
\begin{cases}
H_0: & x(t)=n(t) \\
H_1: & x(t)=h(t)+n(t)
\end{cases}
$$

(14)

The noise process is assumed to be Gaussian and independent and identically distributed (i.i.d). The probability density function (PDF) can be expressed as

$$
p(x(t); H_0) = e^{-\frac{|x(t)|^2}{2\sigma_n^2}}
$$

(15)

$$
p(x(t); H_1) = e^{-\frac{|x(t)|^2}{2\sigma_t^2}} e^{-\frac{|x(t)-h(t)|^2}{2\sigma_d^2}}
$$

(16)

The likelihood ratio test can be given as

$$
\gamma = \frac{p(x(t); H_1)}{p(x(t); H_0)} > \xi
$$

(17)

The probability of detection $p_d$ and probability of false alarm $p_{fa}$, respectively, is expressed as in [17]

$$
p_d = p(\gamma > \xi | H_1) = 1 - S_{\psi(2)} \left( \frac{\sigma_d^2 S_{\psi(2)}^{-1} (1-p_{fa})}{M^2 \sigma_n^2 + \sigma_d^2} \right)
$$

(18)

$$
p_{fa} = p(\gamma > \xi | H_0) = 1 - S_{\psi(2)} \left( \frac{2\xi}{\sigma_n^2} \right)
$$

(19)

where $S(\cdot)$ denotes the cumulative distributive function, $\psi(2)$ being the chi-square distribution.

5 Results and Discussions

In the simulations, the carrier frequency $f_0 = 10GHz$, frequency offset $\Delta f = 3KHz$. Both the transmit and receive arrays $M$ and $N$, respectively, have 8 antenna elements spaced by half wavelength $d = \frac{\lambda}{2}$. The target is assumed to be located at $(\theta_d, r_d) = (50^o, 50km)$. Gaussian noise is utilized as additive noise with zero mean spatially and temporally white random sequence having same variance on each array elements.

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5.1 Transmit Beampattern

First, normalised transmit beampattern for FDA and the proposed symmetrical FDA is presented to show the effectiveness of symmetrical FDA. Note that the two arrays are steered to instantaneous angle $\theta = 0^\circ$ and the beam direction ranges are also normalised to zero-range.

Figure 3(a) illustrates the conventional FDA beampattern which is coupled in the range-angle dimension. In contrast, Figure 3(b) shows the proposed symmetrical FDA which has decoupled range-angle beampattern. And this is beneficial for targets localization.

As shown in Figure 4(a), the conventional FDA beampattern shows the problem of periodic maxima. These maxima are undesirable for proper target localization. On the other hand, Figure 4(b) shows the proposed method beampattern which produce exactly one maxima at target location and no other maxima is seen in the entire region of observation.

5.2 Received Beampattern

In Figure 5(a) and 5(b) both radars produce maxima at the intended range-angle pair, but the conventional FDA has more serious ambiguity problem shown by the arrow in Figure 5(a). It is important to mention that because the conventional FDA has larger total frequency offset, it achieved higher range resolution than the proposed method. In the case of the proposed method shown in Figure 5(b), the target is better localized than the conventional FDA. It can be noticed that there is no spread of beampattern in both range and angle dimensions.

Finally, SINR and probability detection performance of the proposed method and the conventional FDA have been plotted. It can be observed that in Figure 6, the SINR of proposed symmetrical FDA is better than the conventional FDA. Thus proposed method has better robustness against the interferences. Figure 7 shows the detection probability versus SNR for the proposed method and the conventional FDA radar. Proposed method exhibits better detection performance compared to the conventional FDA radars. Improvement in performance in terms of SINR and detection probability can be attributed to single maxima due to symmetrical frequency offset employed across the transmit antenna array.

6 CONCLUSION

A symmetrical frequency offset base FDA has been presented. The proposed method avoids the periodic maxima presented in conventional FDA radar and focus the target with multiple beams to get single maxima for better target localization. Numerical results shows that the proposed method exhibits better robustness against interference as well as better detection performance than the conventional FDA radar due to the employment of symmetrical frequency offset across the transmit antenna array. Overall,
Figure 5: Comparisons of received beampattern when the target is present at \((\theta_d, r_d) = (50^\circ, 50\text{ km})\): (a) Conventional FDA, (b) Proposed symmetrical FDA.

Figure 6: SINR versus SNR performance.

Figure 7: Probability of detection versus SNR performance.
the proposed method received beampattern show a reasonable improvement compared to the conventional FDA.

Conflict of Interest The author declare no conflict of interest.

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