ADAPTIVE RF STEALTH BEAMFORMING FOR FREQUENCY DIVERSE ARRAY RADAR

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ABSTRACT

This paper proposes an adaptive radio frequency (RF) stealth beamforming for frequency diverse array (FDA) radar using spoiled frequency increments. Since active radars are highly visible to intercept receivers, traditional high-gain phased-array antenna beam is replaced by a series of low-gain FDA beam with nonlinear frequency increments to reduce the system visibility, and it achieves the same performance as the original high-gain by jointly exploiting the spoiled beams. Equivalently the detection performance is not degraded. Numerical simulation results verify the proposed method.

Index Terms— RF stealth, frequency diverse array, transmit beamforming, low probability of intercept.

1. INTRODUCTION

Active phased-array has the ability to steer high-gain beam towards any desired direction. However, the high-gain active beam is often highly visible to intercept receivers and consequently the capability of the surveillance system may be degraded and destroyed [1]. It is thus necessary to develop radio frequency (RF) stealth or low probability of intercept (LPI) radar systems.

Numerous techniques have been proposed to reduce radar visibility and enhance its LPI capability [2]. These techniques are often jointly applied to ensure LPI property; However, the energy cannot be spread unlimitedly. For instance, frequency hopping, orthogonal frequency division multiplexing (OFDM) and random waveforms have been suggested for LPI radars [3]. An antenna hopping approach is proposed in [4] to improve the LPI performance. It uses irregular scan patterns to reduce the susceptibility to receivers. Although the probability of being detected in sidelobe region can be reduced by specific beamforming technique, the high-gain main beam is still easily detected. It is thus necessary to reduce the instantaneous transmit peak power to possible interceptors. A novel LPI transmit beamforming approach is proposed in [5], where phased array antenna is employed. Although phased-array has been employed for various applications, its beam steering is fixed in an angle for all ranges.

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In recent years, a flexible antenna array named frequency diverse array (FDA) has received much attention [6–8]. The most important FDA difference from conventional phased-arrays is that a small frequency increment, compared to the carrier frequency, is applied across the elements. The frequency increment results in that the beam direction changes as a function of the range, angle and time. It can be considered as a specific transmit beamforming applied on phased-array. Nevertheless, FDA provides new degrees-of-freedom in range, angle, and time for designing and controlling the array factor. This enables the array beam to scan without the need of phase shifters or mechanical steering because the array factor depends on the range and time variables. The auto-scanning property of FDA has been investigated in [9]. To decouple range and angle response of targets, we proposed a transmit subaperturing FDA radar [10] and a double-pulse FDA radar [11] for target range and angle estimation.

Moreover, the radar should learn from its experience on how to deal with different targets in an effective and robust manner. Cognitive radar is considered as an intelligent active sensing system that utilizes adaptive radar waveforms and machine learning techniques to achieve improved performance for radar tasks such as target recognition, sensor scheduling and scene analysis [12]. In [13], Haykin formalized the notion of cognitive radar to be a technological solution for performance optimization in resource-constrained and interference-limited environments. From this statement it is clear that a radar system to be cognitive, it must operate such that it can mitigate and exploit various interference sources [14].

Inspired by the fact that FDA transmit beampattern and energy spatial distribution can be controlled by jointly exploiting the frequency increments and transmit beamforming, along with that radar performance can be improved by cognitive exploiting its environment to update current probabilistic understanding of the channel, we propose a FDA transmit beamforming with spoiled frequency increments and spoiled phases. The traditional high-gain beampattern is spoiled into a series of low-gain basis patterns covering the desired surveillance region. In receiver, these basis beampatterns are coherently combined using beamforming to synthesize an ensemble of the original high-gain beampatterns scanned across the prescribed surveillance field for unaffected FDA detection performance. In doing so, the FDA radar detectable range remains unchanged while limiting the area detectable for intercept receivers. Moreover, the cognitive radar technique is also applied for the LPI FDA radar to formulate a cognitive FDA radar for improved target localization performance.

The rest of this paper is organized as follows: Section 2 proposes the adaptive RF stealth beamforming, which is verified in Section 3 with numerical results. Section 3 concludes the paper.

2. ADAPTIVE RF STEALTH BEAMFORMING

Different from the stepped frequency increments used in the literatures [15], this paper makes an judicious choice of the spoiled frequency increments, namely, optimized nonlinear frequency increments. Consider an M-element FDA and suppose the spoiled frequency increments used for the mth element is Δf_m, i.e., the radiation frequency of the mth LPI FDA element is

$$f_m = f_0 + \Delta f_m, \qquad m = 0, 1, \ldots, M-1. \tag{1}$$

Specially, when $\Delta f_m = m\Delta f$, it simplifies to the basic FDA. Consider also a far-field position with slant range r and azimuth angle θ, the phase of the mth element transmitted signal can be expressed as

$$\psi'_m(r,\theta) = (f_0 + \Delta f_m)(r - md\sin\theta)\beta. \tag{2}$$

Accordingly, the phase difference between the signals transmitted by the mth and first elements is

$$\begin{aligned}\Theta'_m(r,\theta) &= \psi'_m(r,\theta) - \psi'_0(r,\theta)\\ &= -\beta f_0 md\sin\theta + \beta\Delta f_m r - \beta m\Delta f_m d\sin\theta.\end{aligned} \tag{3}$$

To achieve also a "spoiled" low-gain beampattern, a set of range-dependent spoiled frequency Δf_m and phases $\{\alpha_m(r)\}$ are applied in the array and thus, the transmit array factor can be expressed as

$$\begin{aligned}a'_0(r,\theta) = \sum_{m=0}^{M-1} & e^{-jm\beta f_0 d\sin\theta} e^{j\beta\Delta f_m r}\\ & \times e^{-j\alpha_m(r)} e^{-jm\beta\Delta f_m d\sin\theta}\end{aligned} \tag{4}$$

where $\{\Delta f_m\}$ and $\{\alpha_m(r)\}$ can be designed by computer optimization of a quadratic phase shift variation across the elements. Eq. (4) can be seen as the fundamental basis pattern.

Additional basis patterns can be formed by applying a linear phase progression to the fundamental basis pattern in increments of $\gamma = 2\pi/N$ for 1st basis pattern, 2γ for the 2nd basis pattern and so on. In doing so, we can get $N-1$ additional basis patterns:

$$\begin{aligned}a'_n(r,\theta) = \sum_{m=0}^{M-1} & e^{-nm\gamma} e^{-jm\beta f_0 d\sin\theta}\\ & \times e^{j\beta\Delta f_m r} e^{-j\alpha_m(r)} e^{-jm\beta\Delta f_m d\sin\theta}\end{aligned} \tag{5}$$

where $n = 1, 2, \ldots, N$. These N steered versions of the fundamental pattern are linearly independent and more importantly, they all exhibit low-gain and broad beamwidth and thus their peak power in any directions are significantly reduced to ensure LPI property.

To make the array radar performance remain unchanged, while ensuring LPI property at the same time, we synthesize a high-gain beampattern towards the desired direction by linearly combinging these basis spoiled beams. Assuming the weight using for the nth basis pattern is $w_{0,n}$, the N transmit beampatterns can be written as [5]

$$\begin{bmatrix} A_0(r,\theta)\\ A_1(r,\theta)\\ \cdots\\ A_{N-1}(r,\theta)\end{bmatrix} = \begin{bmatrix} w_{0,0} & w_{0,1} & \cdots & w_{0,N-1}\\ w_{1,0} & w_{1,1} & \cdots & w_{1,N-1}\\ \vdots & \vdots & \ddots & \vdots\\ w_{N-1,0} & w_{N-1,1} & \cdots & w_{N-1,N-1}\end{bmatrix} \begin{bmatrix} a'_0(r,\theta)\\ a'_1(r,\theta)\\ \cdots\\ a'_{N-1}(r,\theta)\end{bmatrix} \tag{6}$$

This implies that we can form high-gain beampatterns by linearly combinations of the N basis patterns.

In the case when a signal source is received in the background of white Gaussian noise, according to the minimum variance distortionless response (MVDR) beamforming principle, the weighter $\mathbf{w}$ for the steering vector $\mathbf{a}(r,\theta)$ should be satisfactory with

$$\mathbf{w}^H \cdot \mathbf{a}(r,\theta) = 1 \tag{7}$$

where ^{H} denotes the conjugate transpose operator. In doing so, the target range-angle can be estimated by jointly exploiting the multiple signal classification (MUSIC) and Kalman filter techniques, and the receiver output signal-to-interference plus noise ratio (SINR) can be calculated.

Since the FDA creates a range-dependent beampattern whose amplitude and spatial distribution can be controlled by tuning the frequency increments and the range-dependent spoiled control phases, we feedback the estimated range and DOA information in the receiver to the transmitter to update the frequency increments in a closed-loop way. Once the estimated DOA and range are known to the transmitter, the task is to get the appropriate spoiled frequency increments, spoiled phases and weights to control the transmitted energy distribution to suppress range-angle-dependent interferences.

This cognitive process can be implemented in the following procedure:

1) The FDA transmitter transmits the pulse signals with initial frequency increments and spoiled phases.
2) At first, we get the starting target range and angle estimation.
3) The receiver measures the output performance index such as target localization errors and SINR, and updates the best output performance index.
4) The receiver sends feedback information to the transmitter to tell the newest performance index is better or worsen than the previous ones.
5) Accordingly the transmitter updates its operating parameters until the decision threshold is arrived.
6) Finally, the target range and angle are estimated by using the optimized system parameters.

3. SIMULATION RESULTS

In the simulations, we assume the FDA radar operating at a carrier frequency of $f_0 = 10$ GHz. An 32-element uniform linear array (ULA) FDA is used for transmitting the baseband waveform and 32-element phased-array at the receiver is assumed. Both the transmit and receive array interelement spacings are designed to be $d = c_0/2f_0$. The additive noise is modeled as a complex Gaussian zero-mean spatially and temporally white random sequence that has identical variance in the array.

According to the proposed RF stealth beamforming scheme, low-gain basis pattern can be implemented by selecting spoiled frequency increments to provide a broad, spoiled beampattern. Since a linear phase variation across the array will result in a high-gain beampattern steered in angle proportional to the slope of the phase variation and alternatively, a quadratic phase variation may defocus the beampattern and reduce the array gain. Therefore, the set of spoiled frequency increments Δf_m is calculated using a quadratic phase variation where the constraint is to minimize the gain [5].

Figures 1 and 2 show the low-gain transmit basis pattern for the 32-element LPI FDA radar in azimuth angle domain and range domain, respectively. It is noticed that the peak gain is only about 1 dB (otherwise, the peak gain for conventional methods using unspoiled frequency increments is about 15 dB). Using the weighter coefficients calculated in (6), we can form high-gain (about 14 dB)) beampatterns by linear combinations of the 32 basis beampatterns, as shown also in Figures 1 and 2. They assume the target range $r_0 = 20$ km and azimuth angle $\theta_0 = 0°$, respectively. Any of other high-gain scanning beampatterns can be similarly formed.

To evaluate the cognitive closed-loop control performance, we simulate the cognitive FDA radar target localization in strong interferences with unknown positions by assuming a target located at (76 km, $10°$) and six interferences

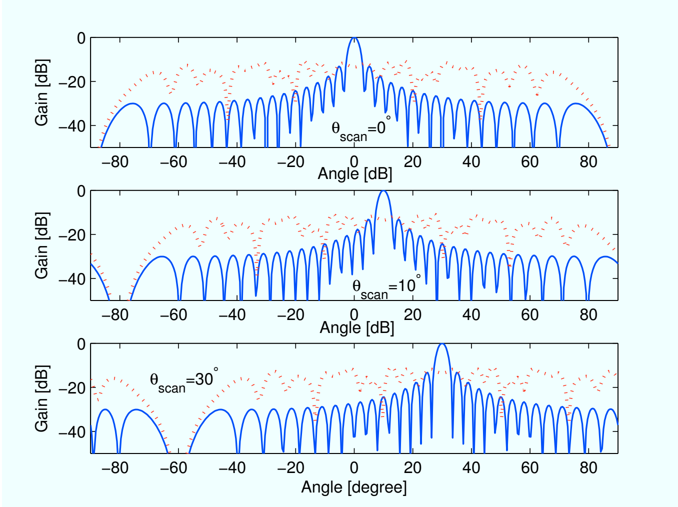

Fig. 1. Comparisons of low-gain transmit basis pattern (dashed line) and formed high-gain scanning beampattern (solid line) in azimuth angle domain, where target range $r_0 = 20$ km is assumed.

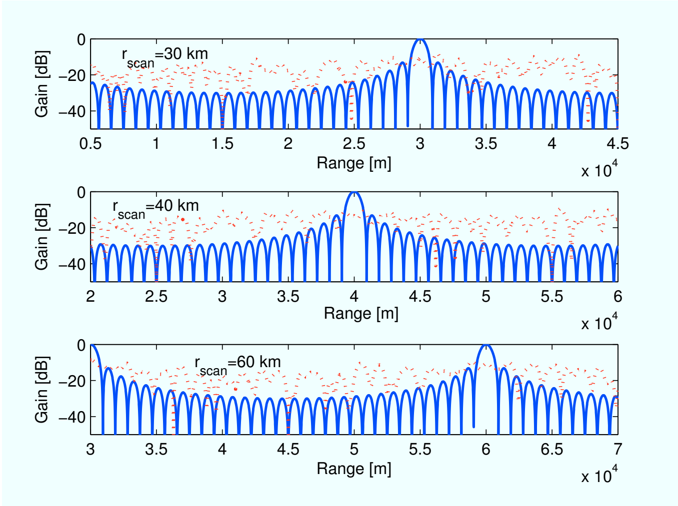

Fig. 2. Comparisons of low-gain transmit basis pattern (dashed line) and formed high-gain scanning beampattern (solid line) in range domain, where target range $\theta = 0°$ is assumed.

located at (140 km, $10°$), (50 km, $10°$), (50 km, $10°$), (76 km, $0°$), (180 km, $40°$) and (182 km, $10°$), respectively. Furthermore, suppose there are inhomogeneous K-distribution clutter.

When the signal-to-clutter ratio (SCR) is fixed to SCR = 5 dB, Figure 3 compares the MUSIC spectra between the cognitive controlled FDA radar and basic FDA radar. It is shown that, since the target and some strong interferences have the same angle, namely, $10°$, the target cannot be effectively de-

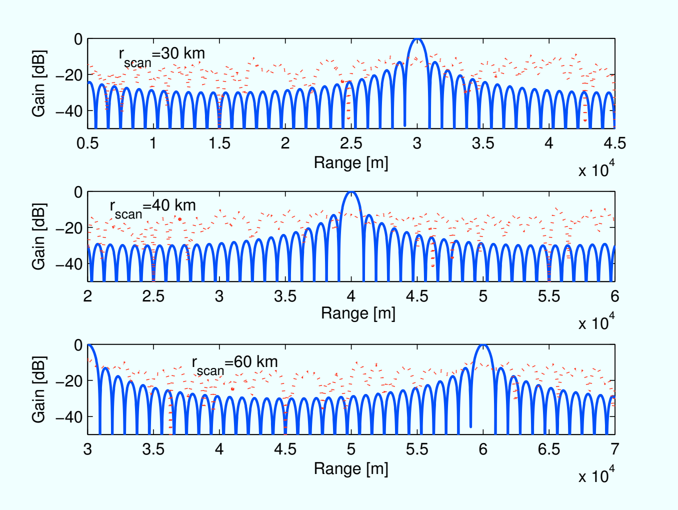

Fig. 3. MUSIC spectra comparisons between without and with applying the cognitive closed-loop controlling in unknown strong interferences and inhomogeneous clutter.

tected by the basic FDA radar. More unfortunately, there will be false detections in the strong interferences angles 0° and 40°. In contrast, by employing the cognitive closed-loop controlled, the target can be effectively detected the MUSIC spectra.

4. CONCLUSION

This paper proposed an adaptive RF stealth beamforming for FDA radar which offers LPI for surveillance systems. It requires no extra scan time when compared to the traditional FDA method for scanning across the same reqion. Numerical results show that, the proposed method enjoys the advantages of both FDA radar and cognitive radar simultaneously, along with the additional LPI property. In this paper, the frequency increments are optimally chosen from a quadratic phase slope across the array to ensure the LPI property. Nevertheless, we think other designs of the frequency increments are also possible. This investigation is planned for future work.

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