

Overview of Frequency Diverse Array in Radar ECCM Applications

Ahmed Abdalla, Hisham Abdalla, Mohammed Ramadan, Suhad Mohamed, Tang Bin

School of Electronic Engineering, University of Electronic Science and Technology of China,

Chengdu 610054, P.R. China

ahmed.baoney6@hotmail.com

Abstract—Necessities of newer radar systems are becoming even more demanding in modern electronic warfare ECM (Electronic Countermeasures) scenarios; therefore, ECCM (Electronic counter-countermeasure) technology has become one of the essential functions of the radar system evaluation. This paper provides an outline of the current research status, developments, achievements of frequency diverse array (FDA) radar, and it is appropriate to ECCM demands. We address some issues concerning FDA radar design, concepts, and key features that making the FDA protects itself from all types of jamming, with a plan to look for further investigations on the FDA ECCM aspects. Furthermore, in this review, several perspectives relevant to FDA opportunities to ECCM processing are pointed out, and numerical simulations verify the available results.

Index Terms—Frequency diverse array (FDA), Radar, electronic counter-countermeasure (ECCM), ECM, range dependent.

I. INTRODUCTION

Generally, the original function of a radar system is to detect the existence of the desired objects (targets) and to measure their positions by using radio waves [1],[2]. Radars can detect objects by emitting out and receiving radio waves. They decide the range position by measuring the transmission and receiving time of radio waves. They can measure the target velocity and differentiate between moving and stationary targets by using the property of the Doppler Effect. Also, radars can estimate both the angle and elevation of the targets by setting the reference point, and then measuring the direction in which the antenna is pointing when the echo is received. The goal, of course, is to search the desired area rapidly, yet with some level of reliability, which leads to mechanical motion of the antennas to steer the radiation beam.

It is, therefore, desirable that the radar can be able to steer the beam with high efficiency electronically. Electronic scanning is the most attractive feature of highly developed radar systems. Since, with electronic scanning, it is viable to steer the main beam of an array antenna instantaneously into a preferred direction where no mechanical mechanism is occupied in the scanning process. An extensive amount of effort has been expended in the research of the methods for electronic scanning of antenna systems. Techniques that have been studied in this connection include frequency variation, phase shift scan and in a minor way, the ideas of space-time

equivalence [3]. Phased-array radars (PAR) are known for their capability to steer a beam with high effectiveness electronically. The directional gain offered by a PAR is useful for detecting/tracking weak targets and nulling interferences from other directions [4]-[8]. However, a limitation of a PAR is that the beam steering is independent of the range, and therefore, fixed at an angle for all the range cells. As results, PARs cannot effectively suppress the interferences and jamming signals that have the same direction angle but a different range of the targets. Moreover, PARs need high phase shifters for beam steering. To overcome these disadvantages, a flexible array called frequency diverse array (FDA) is proposed in recent years [9]-[12]. FDA radar introduces frequency increment across each antenna element to provide the electronic beam steering capability in angle as well as range dimension. This enables the array beam to scan without the need of phase shifters or mechanical steering. The idea of FDA radar was presented recently to show that it has the capability of range dependent beamforming [13]. It is observed that the beam change as a function of the range, angle and time.

With the ability of all-day and all-weather surveillance, radar has got a wide variety of applications and plays a significant role in Earth observation, environment monitor, and military reconnaissance fields. However, in a hostile environment radar is likely to be subjected to the electronic countermeasures (ECM) to avoid target detection and classification. ECM techniques^{[14]-[16]} are aimed at denying information (detection, position, track initiation, etc., of one or more targets) that the victim radar seeks, or at surrounding desired radar echoes with so many false targets that the true information cannot be extracted. Therefore ECM techniques have been widely used in modern electronic warfare. On the other hand, nowadays radar systems are equipped with the so-called electronic counter-countermeasures (ECCM) which are aimed at countering the effects of the enemy's ECM and eventually succeeding in the intended mission [17],[18].

FDA radar has received increasing attention in recent years; however, limited paper on the subject of FDA in ECM scenarios has been published.

This paper aims to study and outline the current research status, developments, and achievements of FDA radar. Moreover, we introduce why FDA radar could be appropriated for ECCM demands with brief explanations of ECM and ECCM types, with an objective to call for more investigations.

This paper can be a roadmap in understanding the basic concepts of FDA radar, properties, and their contributions to guarantee better ECCM electronic warfare capabilities than existing radars, at the price of system and computation complexity. The remainder of this paper is organized as follows. Section 2 summarizes the research achievements in the field of ECM and ECCM. Section 3 introduces the basic FDA scheme, and describes the FDA beampattern characteristics, with the advantages of FDA radar over PAR. Next, Section 4 discusses the new opportunities that provided by the FDA radar to yield a robust ECM signals counteracting ability. Finally, the conclusion is made in Section 5, with an objective to call for more considerations.

II. ECM AND ECCM OVERVIEW

In the modern warfare of achieving mastery of the sky, to destroy enemy's weapon system, and make sure own weapons work well, combat aircraft often use multiple ECM, including suppressive jamming and deceptive jamming [19]. Suppressive jamming is generally generated by noise jammers which transmit high-energy noise-like waveforms to the radar to mask the signal of interest. False target generator (FTG) is usually utilized to create the deceptive jamming. The FTG senses incoming radar signals and regenerates replicas that simulate target echoes to confuse radar, hindering it from classifying true targets from false ones.

ECM techniques against radars are often improved by using digital radio frequency memory (DRFM) systems [20]-[24]. The DRFM is a tool in which high-speed sampling digital memory is exploited for storage and regeneration of radio frequency signals to mislead hostile radar systems. In a DRFM system, the input RF signals are commonly first downshifted in frequency and then sampled with a high-speed analog-to-digital converter (ADC). The samples are stored in a memory and then manipulated in amplitude, frequency, and phase to generate a broad range of deception signals. The stored samples are recalled, processed by the digital-to-analog converter (DAC), up-converted and transmitted back to the victim radar. As results, different kinds of jamming may degrade the radar operation performance. Based on the concepts above, we can see that jamming radar systems are possible, resulting in a great challenge to the survival and operation performance of radar systems in electronic warfare.

Under these circumstances, if one wants its radar work normally, some ECCM should be taken. Since radar without ECCM is regarded as valueless and incapable of deploying in the hazard zones. The primary purpose of radar ECCM is to counter the jamming signals and protect the desired signals, therefore, it is necessary to evaluate the effect of ECCM techniques to weaken the jamming-signal-ratio (JSR) output of the radar receiver after adding anti-jamming techniques and measure the enhancement of the overall system.

Generally speaking, ECCM techniques can be classified as antenna-based, transmitter-based, receiver-based, and signal-processing-based according to the main radar subsystem where they take place [25]. The research of radar's ECCM

focused on spatial domain, time domain, frequency domain, modulation domain, energy domain and joined multiple domains. The essence of ECCM techniques against deception jamming is to discriminate false targets from actual targets based on their differences. Predominately, the deceptive jamming signals are difficult to be suppressed or identified as compared to the suppressive jamming. To combat deceptive jamming signals, several ECCM approaches have been proposed. For example, pulse diversity^{[26]-[30]}, polarization character^{[31]-[34]}, motion feature^{[35],[36]}, clustering analysis^[37], and DRFM quantization error^{[38],[39]}.

Recently, the idea of adaptive detection and discrimination (data fusion-based) between the target signals and ECM signal has been addressed in [40]-[42]. The discrimination is attained by deriving a class of detectors resorting to a generalized likelihood ratio test (GLRT) based implementation of a generalized Neyman-Pearson rule. Adaptive beamformer orthogonal rejection test (ABORT) like detection strategies to combat deceptive ECM Signals in a network of radars have been addressed in [43]-[45]. Whatever the used technique, the response of the radar must be instant to prevent the ECM action.

It is worth remarking that, developing ECCM should consider several aspects. These include not only ECCM techniques themselves, but the identification of specific ECCMs for use against specific ECMs, and assessment of the effectiveness of ECCMs.

III. BASIC FDA RADAR SCHEME

FDA radar has recently gained increasing attention among radar engineers due to its unique range-angle-dependent beam pattern, in contrast to angle-dependent beam pattern of PARs. The pioneering work of Antonik *et al.*^{[46]-[48]} opened the door of this challenging research field. Since then, several papers, based on different design criteria and assumptions have been proposed and assessed.

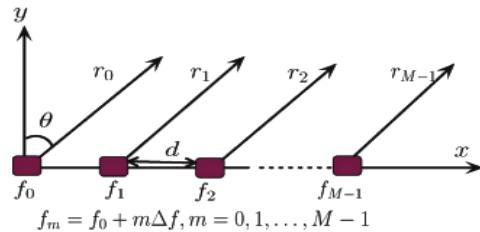


Fig. 1. ULA FDA with frequency increment Δf

Fig.1 demonstrates a uniform linear array (ULA) FDA. Each FDA element radiates an incremental carrier frequency. Thus, the monochromatic signal transmitted by the m-th element is expressed as^[49]

$$s_m(t) = \exp(-j2\pi f_m t) \quad (1)$$

where radiation frequency f_m is

$$f_m = f_0 + m\Delta f, \quad m = 0, 1, \dots, M - 1 \quad (2)$$

where f_0 is the carrier frequency (also the radiation frequency of the first element), Δf is the frequency increment and M is the number of array elements. The signal arriving at a given far-field point target (R, θ) (R and θ denote the slant range and the azimuth angle of the first element, respectively) can then be expressed as

$$s_m(t - \frac{R_m}{c_0}) = \exp\left\{(-j2\pi f_m(t - \frac{R_m}{c_0})\right\} \quad (3)$$

Where c_0 denotes the speed of light. The distance between the m th element and the target is

$$R_m = R - md \sin \theta, \quad m = 1, 2, \dots, M-1 \quad (4)$$

with d being the element spacing. It is worth remarking that, to prevent aliasing effects uniform array spacing is maintained as a function of the maximum transmit frequency and therefore d is

$$d = \frac{1}{2} \frac{c_0}{f_0 + (M-1)\Delta f} \quad (5)$$

Since $\Delta f \ll f_0$, if the amplitude weights are all equal to one, the array factor is seen at the target position (R, θ) , $AF(t; R, \theta)$, can be expressed as^[50]

$$\begin{aligned} AF(t; R, \theta) &= \sum_{m=0}^{M-1} \exp\left\{-j2\pi f_m(t - \frac{R_m}{c_0})\right\} \\ &= \exp\{j\Phi_0\} \sum_{m=0}^{M-1} \exp\left\{-j2\pi \left(m\Delta ft - m\frac{\Delta f R}{c_0} + m\frac{df_0 \sin \theta}{c_0} + m^2 \frac{\Delta f d \sin \theta}{c_0}\right)\right\} \end{aligned} \quad (6)$$

where the phase term Φ_0 has the form

$$\Phi_0 = -2\pi f_0 \left(t - \frac{R}{c_0} \right) \quad (7)$$

When $(M-1)\Delta f \ll f_0$, the phase term $\frac{m^2 \Delta f d \sin \theta}{c_0}$ can be approximated as $\frac{m \Delta f d \sin \theta}{c_0}$. In this case, (6) can be rewritten in a closed-form as

$$\begin{aligned} AF(t; R, \theta) &\approx \exp\{j\Phi_0\} \sum_{m=0}^{M-1} \exp\left\{-j2\pi \left(m\Delta ft - m\frac{\Delta f R}{c_0} + m\frac{df_0 \sin \theta}{c_0} + m\frac{\Delta f d \sin \theta}{c_0}\right)\right\} \\ &= \exp\{j\Phi_0\} \frac{\sin\left[M\pi \left(\frac{\Delta f t}{c_0} - \frac{\Delta f R}{c_0} + \frac{df_0 \sin \theta}{c_0} + \frac{\Delta f d \sin \theta}{c_0}\right)\right]}{\sin\left[\pi \left(\frac{\Delta f t}{c_0} - \frac{\Delta f R}{c_0} + \frac{df_0 \sin \theta}{c_0} + \frac{\Delta f d \sin \theta}{c_0}\right)\right]} \end{aligned} \quad (8)$$

where Φ_1 is

$$\Phi_1 = \Phi_0 + \pi(M-1) \frac{\Delta f R}{c_0} - \pi(M-1) \frac{f_0 d \sin \theta}{c_0} - \pi(M-1) \frac{\Delta f d \sin \theta}{c_0} \quad (9)$$

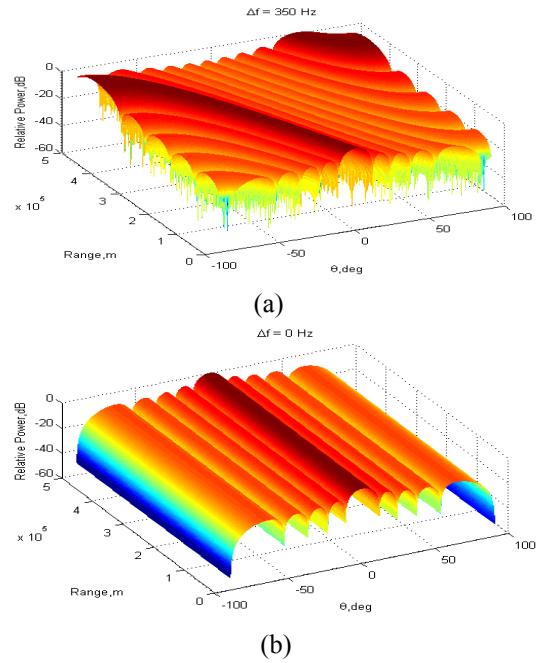


Fig. 2. The transmitted beam pattern comparisons between FDA radar and PAR. (a) FDA radar. (b) PAR.

According to the derived transmit beampattern of [51], it is worth pointing out the following characteristics

- If the frequency increment Δf is fixed, the FDA beampattern demonstrates range-angle-dependent peak gain. As shown in Fig. 2a.
- If the frequency increment across the array is not concerned (i.e., $\Delta f = 0$), the FDA radar reduces to a ULA PAR as shown in Fig. 2b.

The difference in the transmitted beampatterns of the conventional PAR and FDA radar are shown in Fig. 2, where 10 element uniform linear FDA with inter-element spacing denoted $d = \lambda/2$ with λ being the signal wavelength and the carrier frequency $f_0 = 1$ G Hz. $\Delta f = 0$ and 350 Hz for PAR and FDA respectively.

As per the simulation result from Fig. 2, the transmit beampattern of the traditional PAR is angle dependent whilst that of the FDA radar is range-angle-dependent, and hence the FDA provides better control over modulation and beam synthesis when compared to the conventional phased array. More precisely, PAR beam is fixed at one angle for all the ranges and hence there is no range information, while is unfixed and changeable in FDA ranges. As results, FDA with uniform inter-element frequency increment (Fig.1) generates an S-shaped beam pattern (Fig 2a), which generates maxima at multiple ranges and angle values^[50].

Basically, space time adaptive processing (STAP) is a basic technique to detect slowly moving targets in strong clutter background in PAR^{[52]-[58]}. However, the range ambiguity and

range dependence will lead to severe performance degradation of the traditional STAP methods. Therefore, FDA moves further step to circumvent the range ambiguity problem in STAP radar.

IV. WHY FDA RADAR IS THE FUTURE OF ECCM

Several investigations have been carried out on FDA radars. FDA was investigated in [59],[60] as a range dependent beam with applications in suppressing range ambiguous clutter. The time and angle periodicity of FDA beampattern were described by Secmen *et al.* in [61]. A linear FDA is tackled in [62],[63] for forward-looking radar ground moving target indication. Pioneering studies to exploit FDA range-dependent beampattern characteristics were reported in [64]-[66]. Wen-Qin proposed new phased- multiple-input and multiple-output (MIMO) radar with frequency diversity for range-dependent beamforming in [67]. Then, several papers in FDA-MIMO radar have been published [68]-[72]. It is worth highlighting that, FDA structures can either use same waveform [60] or different waveforms [73]. This provides several new potential radar and navigation applications [74]-[81].

Accordingly, FDA can be quite useful in ECCM applications. In ECM scenario the jammer needs to precisely simulate the jamming signals in order to mislead the victim radars. Thus, FDA radar with frequency diversity across the elements will remarkably confuse the jammer. Furthermore, by combining the range and angle information the FDA radar can distinguish the true and false targets. If multiple waves impinge on a linear array from the same direction, but different ranges than it is not feasible for a PAR to discriminate the targets and suppress the unwanted signals. To show the FDA advantages over PAR, we consider the case with one target and two interferences. The target and interferences have the same angle but different ranges. The target is assumed to replicate a plane-wave that impinges on the array from the direction angle of $\theta_t = 0^\circ$ and slant range of $R_t = 10\text{ km}$. The two interferences are positioned at the direction angle of $\theta_1 = \theta_2 = 0^\circ$ and the slant ranges of $R_1 = 9\text{ km}$ and $R_2 = 12\text{ km}$. The target power is fixed to 0 dB while the interference power is fixed to 30dB and SNR is fixed to 10 dB. Fig. 3(a) illustrates the overall transmit receive beampattern profile cut at the target's range. It can be observed that the FDA and conventional PAR have similar overall transmit-receive beampattern profile in the angle dimension; nevertheless, they have different beampattern profile in the range dimension, as shown in Fig. 3(b). The PAR has no resolution ability in the range dimension. On the contrary, the FDA has resolution ability in the range dimension. Since FDA was first developed to provide the range-angle-dependent beampattern [82], it has seen many versions, developed to overcome the shortcomings of the original version due to the range-angle coupling response of

the received target signals.

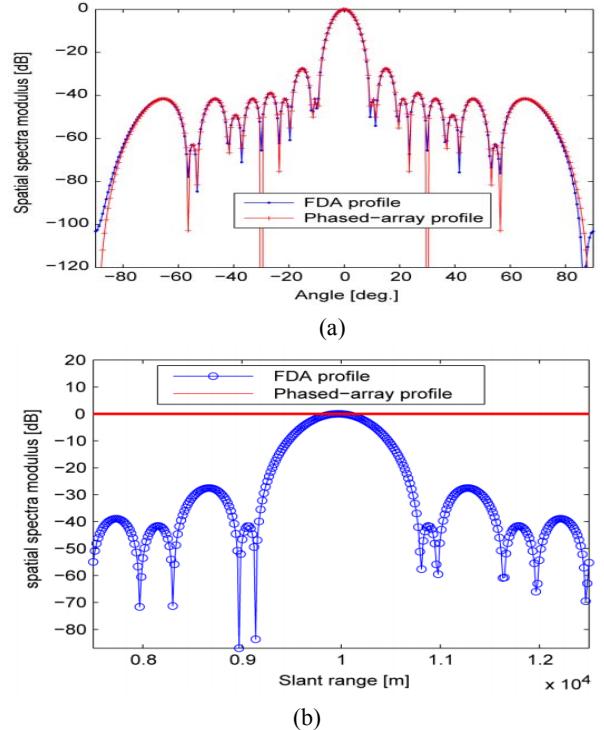


Fig. 3. Comparative transmit-receive beampatterns in one dimension. (a) Angle profile at the target's range. (b) Range profile at the target's angle.

In [83] nonuniform FDA as the transmitter and the uniform phased array as the receiver is used to achieve high-resolution range-angle imaging of targets. Huaizong *et.al*[84] proposed a symmetrical FDA using multi-carrier frequency increments and convex optimization, named convex multi-log-FDA, to achieve dot-shaped transmit beampatterns. In [85] two nonlinearly increasing frequency offsets, namely, square increasing and cubic increasing, to decouple FDA transmit beampattern for range–angle localization of targets is proposed. To estimate the angle and range of targets directly from the beamforming output peaks, Wen-Qin and Huaizong [86] explored double-pulse FDA radar which transmits two pulses with zero and non-zero frequency increments, respectively. In [87] a novel framework of STAP radar which applies frequency diversity in the vertical of a planar array, named as vertical-FDA STAP radar has been described and analyzed. Waseem *et.al*[88] proposed FDA with logarithmically increasing frequency offset to accomplish a beampattern with a single maximum at the target location. In [89], instead of transmitting the signals with the same frequency increment, the frequency increment can adaptively adjust to control the transmit beam direction. With the plan to localize the target in the range-angle domain, Wen-Qin proposed subarray-based FDA radar in [90]. The essence is to divide the FDA array into multiple subarrays, which employ different frequency increments. As results, the target's range and angle are estimated directly from the transmit-receive beamforming output peak with high accurateness.

TABLE I. COMPARISONS BETWEEN THE METHODS

Methods	The frequency offset (Δf) style	Computational complexity	More robustness against which ECM and interference types	Main advantages and discussions
Pawan <i>et.al</i> ^[5]	$\Delta f = 0$ (PAR)	Low	Clutter.	Simple, Angle-dependent. But Range independent.
Wen-Qin ^[82]	$f_m = f_0 + m\Delta f$	Standard	Clutter, weak interference.	Range-Angle is dependent, But Δf is fixed and thus difficult to decouple the range and angle. Also, high technology DRFM can recognize the frequency Δf and blind the victim radar.
Wen-Qin <i>et.al</i> ^[83]	Non-uniform	Medium	Clutter, Strong interference Suppressive jamming.	Simple because the transmitter is non-uniform FDA, but the receiver is uniform PAR. Only stationary targets are considered.
Huaizong <i>et.al</i> ^[88]	Logarithmic	High	Clutter, Strong interference Suppressive jamming.	Allowing focusing multiple targets present at different ranges. Used different subarrays. But, the receiver has not yet investigated.
Huaizong <i>et.al</i> ^[84]	Symmetrical (positive and negative)	High	Clutter, Strong interference Suppressive jamming.	Generating both single dot and multi-dot shaped beampatterns at the desired locations outperforms the existing log-FDA significantly in suppressing undesired sidelobe interferences and focusing range-angle resolution.
Kuandong <i>et.al</i> ^[85]	non-linearly (Square increasing and cubic increasing)	Very High	Clutter, Strong interference Suppressive jamming, deceptive jamming.	This approach suggested two new non-linearly increasing frequency offsets decouple the range–angle-dependent beampattern response for a uniform linear FDA. Thus, it achieves excellent performance in both focusing the transmit energy to the desired target position and efficient range–angle localization of targets.
Wen-Qin and Huaizong ^[86]	double-pulse (zero and non-zero Δf , respectively)	Very High	Clutter, Strong interference Suppressive jamming, deceptive jamming.	This approach can be interpreted as detecting the targets in angle dimension and then localizing them in range dimension by appropriately choosing the frequency increment. Thus, it is excellent for anti-jamming applications.
Jingwei <i>et.al</i> ^[87]	Vertical Frequency in a planer array	Very High	Clutter, Strong interference Suppressive jamming, deceptive jamming.	In this approach, both problems of range ambiguity and range dependence are solved. Thus, it is good for anti-jamming applications.
Wen-Qin ^[90]	different frequency increments at each subarray	Very High	Clutter, Strong interference Suppressive jamming, deceptive jamming.	The range and angle of the target are jointly estimated from the transmit-receive beamforming output peak. Therefore, this method is suitable for anti-jamming applications.
Huaizong <i>et.al</i> ^[89]	adaptively	Very High	Clutter, Strong interference Suppressive jamming, deceptive jamming.	This method can adaptively adjust the beam direction to match the current target angle and range sector. In addition, this approach achieves better performances with an optimal beampattern in a few pulse repetition intervals. Therefore, enables a better anti-jamming capability.

In order to compare the aforementioned methods, identify their ECCM capability, and analyze their advantages, we will exploit different properties in the form of a table. Table I shows the comparison between the schemes where the basic FDA computational complexity is taken as reference (standard). Also, we will consider the clutter as one division of ECM signals.

From table1 it is evident that there is an unavoidable relationship between computational complexity and higher performance. However, good ECCM scheme needs to perform better than others in making this tradeoff. Since, the method with greater capability and reliability require higher system complexity and more additional equipment, which leads to huge cost and is time-consuming.

The main principle of radar ECCM is to counter the jamming signals and protect the desired signals, therefore, it is

necessary to evaluate the effect of ECCM techniques to weaken the jamming-signal-ratio (JSR), the output of the radar receiver after adding anti-jamming techniques and measure the enhancement of the overall system.

FDA provides promising ECCM application potentials. The important FDA feature is that actually every point in space can be scanned in a discrete way by altering the carrier frequency and frequency increment. The scanning properties can be effectively adapted for a new scenario by applying a different frequency regime. Focusing in space is also feasible by choosing unique frequency intervals. Through increasing the total frequency increments, some points in space can be scanned with more than one frequency component and this diversity enhances the resistance to multi-path jamming/interferences.

The advantages of cognitive radar with situational awareness due to closed-loop control and FDA [91] can be quite helpful for mitigating the ECM influences.

In summary, FDA with different design concept has drawn much attention in the antenna array and radar signal processing societies as it provides promising application potentials. However, more investigations should be carried out to exploit FDA ECCM perception in radar for improved its performance. In another hand, several remaining technical challenges need to be solved.

There is a different way for the frequency increments. However, the best solution for ECCM applications is not described yet. The impacts of frequency increment errors in FDA radar and FDA-MIMO radar are analyzed in [92],[93], respectively. Nevertheless, more investigations should be carried out to optimally design FDA frequency increments. Moreover, most of current FDA concept is focusing in transmitting FDA, therefore receiving FDA remains a severe dilemma and requires further awareness. Furthermore, it is essential to decrease the computation complexity in FDA receiver by optimal array signal processing. Thus, implementation of perfect signal processing ability, artificial intelligence, adaptive signal processing and neural network which are meaningful in an FDA responsibility are noteworthy.

V. CONCLUSION

In this paper, we describe some aspects of the FDA radar. Jamming techniques have been seriously developed in the past years, and they formed threats for normal work of radar systems. Thus, to suit today and future electronic warfare combat environment, the radar systems must develop their ECCM ability on several aspects. From the investigations in this paper, we concluded that FDA might be the future direction of ECCM of radar systems.

It may be observed that no matter how the development of the ECM techniques, the FDA radar can always seek a fitting ECCM due to the different style of the frequency increments. The competition between ECCM and ECM lies in who will concern the newest technique on the electronic skill first for the means of protecting itself and attacking the other party effectively, who will get the active situation in electronic warfare.

Out of all, radar ECCM is a technology involving different fields, so it requires further consideration and awareness while considering reliability.

REFERENCES

- [1] Schleher, D.C.: "LPI radar: fact of fiction", *IEEE Aerosp. Electron. Syst. Mag.*, 21, (5), pp. 3–6, 2006.
- [2] Lawrence, D.E.: "Low probability of intercept antenna array beamforming", *IEEE Trans. Antennas Propag.*, 58, (9), pp. 2858–2865, 2010.
- [3] C W. L. Melvin, "A STAP overview," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 19, no. 1, pp. 19–35, Jan. 2004.
- [4] Alaa E, K Assaleh, and H Mir, "Space-Time Adaptive Processing Using Pattern Classification", *IEEE Trans. Signal Process.* vol.63, no. 3, pp. 766-779. Feb.2015.
- [5] Pawan S, Muralidhar R, "Waveform Design for Radar STAP in Signal Dependent Interference", *IEEE Trans. Signal Process.* vol.64, no. 1, pp. 19-34. Jan.2016.
- [6] Diego C , Ingo W, "Joint Monostatic and Bistatic STAP for Improved SAR-GMTI Capabilities" , *IEEE Trans. Geosci. Remote Sens.*,vol. 54, no. 3, pp. 1834-1848, Mar.2016.
- [7] Z Wang, Yongliang W, Keqing D, Wenchong X, " Subspace-Augmented Clutter Suppression Technique for STAP Radar" , *IEEE Trans. Geosci. Remote Sens Letters.*,vol. 13, no. 3, pp. 462-466, Mar.2016.
- [8] H Wang, G Liao, Jun L, W Guo, "Robust waveform design for MIMO-STAP to improve the worst-case detection performance", *EURASIP J. Adv. Signal Process.* 2013 (52), 1-8.
- [9] Wen-Qin Wang, "Overview of frequency diverse array in radar and navigation applications", *IET Radar Sonar Navig*, Vol. 10, Iss. 6, pp. 1001–1012, 2016.
- [10] Antonik, P., Wicks, M.C., Griffiths, H.D., et al.: 'Frequency diverse array radars'. *Proc. of the IEEE Radar Conf.*, Verona, NY, April 2006, pp. 215–217.
- [11] Antonik, P.: 'An investigation of a frequency diverse array'. PhD dissertation, University College London, 2009.
- [12] Aytun, A.: 'Frequency diverse array radar'. Master's thesis, Naval Postgraduate School, 2010
- [13] Wang, W.-Q., Shao, H.Z., Cai, J, "Range-angle- dependent beamforming by frequency diverse array antenna", *Int. J. Antennas Propag.*, 2012, pp. 1–10, article id 760489, 2012.
- [14] D.C.Schleher, Electronic Warfare in the Information Age. Norwood, MA, USA: Artech House, 2000.
- [15] R.A.Poisel, Information Warfare and Electronic Warfare Systems.Norwood, MA, USA: Artech House, 2013.
- [16] N.-J. Liu and Y.-T. Zhang, "A survey of radar ECM and ECCM," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 31, no. 3, pp. 1110–1120, Jul. 1995.
- [17] A. Farina, "Electronic Counter-countermeasures," in Radar Handbook,M. Skolnik, Ed., 3rd ed. New York, NY, USA: McGraw-Hill, 2008.
- [18] R. Schroer, "Electronic warfare. [A century of powered flight:1903–2003]," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 18, no. 7,pp. 49–54, Jul. 2003..
- [19] D. DiFilippo, G. Geling, and G. Currie, "Simulator for advanced fighter radar EPM development," *IEE Proc.-Radar, Sonar Navigat.*, vol. 148, no. 3, pp. 139–146, Jun. 2001.

- [20] Pace, P.E., Fouts, D.J., Ekestorm, S.,et al.: ‘Digital false-target image synthesizer for countering ISAR’, *IEE Proc.-Radar Sonar Navig.*, 149, (5), pp. 248–257, 2002.
- [21] S. J. Roome, “Digital radio frequency memory,” *IET Electron. Commun. Eng. J.*, vol. 2, no. 4, pp. 147–153, Aug. 1990.
- [22] S. D. Berger, “Digital radio frequency memory linear range gate stealer spectrum,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 39, no. 2, pp. 725–735, Apr. 2003
- [23] Wang, X., Liu, J., Zhang, W., et al.: ‘Mathematical principles of interrupted-sampling repeater jamming (ISRJ)’, *Sci. China F Inf. Sci.*, 50, (1), pp. 1–12, 2007.
- [24] Olivier, K., Cilliers, J.E., Plessis, M.D.: ‘Design and performance of wide band DRFM for radar test and evaluation’, *Electron. Lett.*, 47, (14), pp. 824–825, 2011.
- [25] Stephen L. Johnston, , “Radar Electronic Counter – Countermeasures”, *IEEE Trans. Aerosp. Electron. Syst.*, vol. 14, no. 1, pp. 109–117, Jan. 1978.
- [26] N. Liu, S.-S. Zhao, and L.-R. Zhang, “A radar ECCM scheme based on full-rate orthogonal pulse block,” *J. Comput. Inf. Syst.*, vol. 9, no. 24, pp. 9771–9779, 2013.
- [27] J. Akhtar, “Orthogonal block coded ECCM schemes against repeat radar jammers,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 45, no. 3, pp. 1218–1226, Jul. 2009.
- [28] J. Zhang, D. Zhu, and G. Zhang, “New antivelocity deception jamming technique using pulses with adaptive initial phases,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 49, no. 2, pp. 1290–1300, Apr. 2013.
- [29] Ahmed Abdalla, Zhao Y, Mohammed R, T Bin, “An Improved Radar ECCM Method Based on Orthogonal Pulse Block and Parallel Matching Filter”, *Journal of Communications* 10, no. 8 (2015).
- [30] Ahmed Abdalla, Zhao Y, J R, T Bin, “A Study of ECCM Techniques and their Performance”, ICSPCC2015 IEEE press , 2015.
- [31] C. Huang, Z. Chen, and R. Duan, “Novel discrimination algorithm for deceptive jamming in polarimetric radar,” in Proc. ICITSE, Berlin, Germany, pp. 359–365, 2013.
- [32] Wei X, G Zhang,Yu Z , J Yin, “Trilinear decomposition – based spatial polarisation filter method for deception jamming suppression of radar”, *IET Radar Sonar Navig.*, Vol. 10, Iss. 4, pp. 765–773, 2016.
- [34] Dai, H., Wang, X., Li, Y.,et al.:‘Main-lobe jamming suppression method of using spatial polarization characteristics of antennas’, *IEEE Trans. Aerosp. Electron. Syst.*,48, (3), pp. 2167–2179,2012.
- [35] Li, J., Zhou, M.: ‘Improved trilinear decomposition-based method for angle estimation in multiple-input multiple-output radar’, *IET Radar Sonar Navig.*,7, (9), pp. 1019–1026, 2013.
- [36] B. Rao, Y.-L. Zhao, S.-P. Xiao, and X.-S. Wang, “Discrimination of exoatmospheric active decoys using acceleration information.”, *IET Radar, Sonar Navigat.*, vol. 4, no. 4, pp. 626–638, 2010.
- [37] B. Rao, S. Xiao, X. Wang, and T. Wang, “Maximum likelihood approach to the estimation and discrimination of exoatmospheric active phantom tracks using motion features.” *IEEE Trans. Aerosp. Electron. Syst.*,vol. 48, no. 1, pp. 794–819, Jan. 2012.
- [38] S Zhao, N Liu, L Zhang, Y Zhou, and Q Li., “Discrimination of Deception Targets in Multistatic Radar Based on Clustering Analysis”, *IEEE Sensor J*, v. 16, no. 8, Apr 15, 2016.
- [39] M. Greco, F. Gini, and A. Farina, “Radar detection and classification of jamming signals belonging to a cone class,” *IEEE Trans. Signal Process.*, vol. 56, no. 5, pp. 1984–1993, May 2008.
- [40] F. Bandiera, A. De Maio, and G. Ricci, “Adaptive CFAR radar detection with conic rejection,”*IEEE Trans. Signal Process.*, vol. 55, no. 6, pp. 2533–2541, Jun. 2006.
- [41] F. Bandiera, A. Farina, D. Orlando, and G. Ricci, “Detection algorithms to discriminate between radar targets and ECM signals,” *IEEE Trans. Signal Process.*, vol. 58, no. 12, pp. 5984–5993, Dec. 2010.
- [42] S. Buzzi, M. Lops, L. Venturino, and M. Ferri, “Track-Before-Detect Procedures in a Multi-Target Environment,” *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 44, No. 3, pp. 1135–1150, July 2008.
- [43] A. Coluccia and G. Ricci, “Detection strategies for a network of radars in presence of ECM signals,” International Radar Conference 2014, Lille, France, 13-17 2014.
- [44] N. B. Pulsone and C. M. Rader, “Adaptive Beamformer Orthogonal Rejection Test,” *IEEE Trans. on Signal Processing*, Vol. 49, No. 3, pp. 521-529, March 2001.
- [45] F. Bandiera, O. Besson, and G. Ricci, “An ABORT-like detector with improved mismatched signals rejection capabilities,” *IEEE Trans. Signal Process.*, vol. 56, no. 1, pp. 14–25, Jan. 2008.
- [46] A Coluccia, and G Ricci, “ABORT-Like Detection Strategies to Combat Possible Deceptive ECM Signals in a Network of Radars”, *IEEE Trans. Signal Process.* vol.63, no. 11, pp. 2904-2914, Jun.2015.
- [47] P. Antonik, M. C. Wicks, H. D. Griths, and C. J. Baker, “Multi-mission multi-mode waveform diversity”, inProc. IEEE Radar Conf., Verona, Italy, pp. 580-582, Apr. 2006.
- [48] P. Antonik and M. C. Wicks, “Method and apparatus for simultaneous synthetic aperture and moving target indication”, U.S. Patent 0 129-584, Jun 2008.
- [49] Antonik, M. C. Wicks, H. D. Gri ths, and C. J. Baker, “Range dependent beamforming using element level waveform diversity”, inProc. Int. Waveform Diversity Des. Conf., Las Vegas, NV, USA, pp. 14, Jan. 2006.
- [50] Wen-Qin Wang,: ‘Frequency diverse array antenna: new opportunities’, *IEEE Antennas Propag. Mag.*, 57, (2), pp. 145–152, 2015.
- [51] P. F. Sammartino, C. J. Baker, and H. D. Griffiths, “Frequency diverse MIMO techniques for radar,”*IEEE Trans. Aerosp. Electron. Syst.*, vol. 49, no. 1, pp. 201–222, Jan. 2013.
- [52] Wen-Qin Wang, “Range-angle dependent transmit beampattern synthesis for linear frequency diverse arrays,” *IEEE Trans. Antennas Propag.*, vol. 61, no. 8, pp. 4073–4081, Aug. 2013.
- [53] Lapierre, F.D., Ries, P., Verly, J.G.:‘Foundation for mitigating range dependence in radar space-time adaptive processing’, *IET Radar Sonar Navig.*, 2009, 3, (1),pp. 18–29,2009.
- [54] Zhou, S.H., Liu, H.W., Wang, X.,et al.: ‘MIMO radar range-angular-Doppler sidelobe suppression using random space-time coding’, *IEEE Trans. Aerosp. Electron. Syst.*, 2014, 50, (3), pp. 2047–2060,2014.
- [55] Meng, X., Wang, T., Wu, J.,et al.: ‘Bistatic clutter analysis and range ambiguity resolving for space time adaptive processing’, *IET Radar Sonar Navig.*, 2009, 3, (5), pp. 502–511,2009.
- [56] Xu, J.W., Zhu, S.Q., Liao, G.S.: ‘Space-time-range adaptive processing for airborne radar systems’, *IEEE Sens. J.*, 2015, 15, (3), pp. 1602–1610,2015.

- [57] J. Guerci, Space-Time Adaptive Processing for Radar, ser. Artech House Radar Library. Norwood, MA, USA: Artech-House, 2002.
- [58] W. Melvin, "A STAP overview," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 19, no. 1, pp. 19–35, Jan. 2004.
- [59] D. Madurasinghe and A. P. Shaw, "Mainlobe jammer nulling via tsi finders: A space fast-time adaptive processor," *EURASIP J. Appl. Signal Process.*, vol. 2006, pp. 221–221, Jan. 2006.
- [60] Mustafa, S., Simsek, D., Taylan, H.A.E.: 'Frequency diverse array antenna with periodic time modulated pattern in range and angle'. Proc. of the IEEE Radar Conf., Boston, April 2007, pp. 427–430, 2007.
- [61] Huang, S., Tong, K.F., Baker, C.J.: 'Frequency diverse array: Simulation and design'. Proc. of the LAPS Antennas and Propagation Conf., Loughborough, UK, May 2009.
- [62] Secmen, M., Demir, S., Hizal, A., et al.: 'Frequency diverse array antenna with periodic time modulated pattern in range and angle'. Proc. of the IEEE Radar Conf., Boston, MA, April 2007, pp. 427–430,2007.
- [63] P. Baizert, T. B. Hale, M. A. Temple, and M. C. Wicks, "Forwardlooking radar GMTI benefits using a linear frequency diverse array," *Electron. Lett.*, vol. 42, no. 22, pp. 1311–1312, Oct. 2006.
- [64] T. Eker, S. Demir, and A. Hizal, "Exploitation of linear frequency modulation continuous waveform (LFMCW) for frequency diverse arrays," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3546–3553, Jul. 2013.
- [65] Higgins, T., Blunt, S.: 'Analysis of range-angle coupled beamforming with frequency diverse chirps'. Proc. Fourth Int. Waveform Diversity & DesignConf., Orlando, FL, February 2009, pp. 140–144,2009.
- [66] Zhuang, L., Liu, X.Z.: 'Precisely beam steering for frequency diverse arrays based on frequency offset selection'. Proc. of the Int. Radar Conf., Bordeaux, France, October 2009.
- [67] Wen-Qin Wang,, 'Two-dimensional imaging of targets by stationary frequency diverse array', *Remote Sens. Lett.*, 2013, 4, (11), pp. 1067–1076 ,2013.
- [68] Wen-Qin Wang, 'Phased-MIMO radar with frequency diversity for range-dependent beamforming', *IEEE Sens. J.*, 2013, 13, (4), pp. 1320–1328,2013.
- [69] Huleihel, W., Tabrikian, J., Shavit, R.: 'Optimal adaptive waveform design for cognitive MIMO radar', *IEEE Trans. Signal Process.*, 2013, 61, (20), pp. 5075–5089,2013.
- [70] Ahmed, S., Alouini, M.-S.: 'MIMO-radar waveform covariance matrix for high SINR and low side-lobe levels', *IEEE Trans. Signal Process.*, 62, (8), pp. 2056–2065, 2014.
- [71] Cui, G.L., Li, H.B., Rangaswamy, M.: 'MIMO radar waveform design with constant modulus and similarity constraints', *IEEE Trans. Signal Process.*, 2014, 62, (2), pp. 343–353,2014.
- [72] Qian, K., Wang, W.-Q., Shao, H.Z.: 'Low-complexity transmit antenna selection and beamforming for large-scale MIMO communications', *Int. J. Antennas Propag.*, 2014, pp. 1–11.
- [73] Zhou, S.H., Liu, H.W., Wang, X.,et al.: 'MIMO radar range-angular-Doppler sidelobe suppression using random space-time coding', *IEEE Trans. Aerosp. Electron. Syst.*, 2014, 50, (3), pp. 2047–206,2014.
- [74] Wang, W.-Q., Shao, H.Z.: 'Aflexible phased-MIMO array antenna with transmit beamforming', *Int. J. Antennas Propag.*, 2012,pp. 1-10 , article id 609598 , 2012.
- [75] T. Sjogren et al., "Suppression of clutter in multichannel SAR GMTI," *IEEE Trans. Geosci. Remote Sens.*, vol. 52, no. 7, pp. 4005–4013, Jul. 2014.
- [76] W. Khan, I.M. Qureshi, A. Basit, M Zubair, "A double Pulse MIMOFDA radar for improved range-angle localization of target," *Wireless Personal Communication*, Vol. 82 , no. 4, pp. 2199–2213, Feb. 2015.
- [77] J. Xu, G. Liao,S. Zhu, L. Huang, and H. C. So, "Joint Range and Angle Estimation Using MIMO Radar With Frequency Diverse Array" *IEEE Transactions on Signal Processing*, vol. 63, no. 13, July 1, 2015.
- [78] Ding, Y., Zhang, J., Fusco, V.: 'Frequency diverse array OFDM transmitter for secure wireless communications', *Electron. Lett.*, 2015, 51, (10), pp. 5319–5324,2015.
- [79] Cetinepe, C., Demir, S.: 'Multipath characteristics of frequency diverse arrays over a ground plane', *IEEE Trans. Antennas Propag.*, 2014, 62, (7),pp. 3567–3574,2014.
- [80] Xu, Y., Shi, X., Xu, J.,et al.: 'Range-angle-dependent beamforming of pulsed frequency diverse array', *IEEE Trans. Antennas Propag.*, 2015, 63, (7),pp. 3262–3267,2015.
- [81] Wang, Y.B., Wang, W.-Q., Shao, H.Z.: 'Frequency diverse array radar Cramér-Rao lower bounds for estimating direction, range and velocity', *Int. J. Antennas Propag.*, 2014, pp. 1–15, article id 830869 , 2014.
- [82] W.-Q. Wang, "Mitigating range ambiguities in high PRF SAR with OFDM waveform diversity," *IEEE Geosci. Remote Sens. Lett.*, vol. 10,no. 1, pp. 101–105, Jan. 2013.
- [83] Y Wang, Wen-Qin W, Hui C "Linear Frequency Diverse Array Manifold Geometry and Ambiguity Analysis", *IEEE Sensors J*, vol. 15, no. 2,pp.984-993, Feb 2015.
- [84] Wen-Qin Wang, So, H.C., Shao, H.Z.: 'Nonuniform frequency diverse array for range-angle imaging of targets', *IEEE Sens. J.*, 2014, 14, (8), pp. 2469–2476, 2014.
- [85] Shao, H., Li, J., Chen, H.,et al.: 'Dot-Shaped Range-Angle Beampattern Synthesis for Frequency Diverse Array', *IEEE Antennas Wirel. Propag. Lett.*, 13, (1),pp. 1405–1408,2013.
- [86] K Gao, Wen-Qin W, J Cai, Jie X., "Decoupled frequency diverse array range– angle- dependent beampattern synthesis using non-linearly increasing frequency offsets", *IET Microw. Antennas Propag.*, Vol. 10, Iss. 8, pp.880–884, 2016.
- [87] Wen-Qin W., Shao, H.Z.: 'Range-angle localization of targets by a double-pulse frequency diverse array radar', *IEEE J. Sel. Top. Signal Process.*, 2014 , 8, (1), pp. 106–114. 2014.
- [88] J Xu, G Liao,d Hing C., "Space-Time Adaptive Processing With Vertical Frequency Diverse Array for Range-Ambiguous Clutter Suppression," *IEEE Trans. Geosci. Remote Sens.*, 2016.
- [89] Khan, W., Qureshi, I.M., Saeed, S.: 'Frequency diverse array radar with logarithmically increasing frequency offset', *EEE Antennas Wirel. Propag. Lett.*, 14, pp. 499–502, 2015.
- [90] Shao, H., Li, J., Chen, H.,et al.: 'Adaptive frequency offset selection in frequency diverse array radar', *IEEE Antennas Wirel. Propag. Lett.*, 2014, 13, (1),pp. 1405–1408,2013.
- [91] Wen-Qin Wang,: 'Subarray-based frequency diverse array radar for target range-angle estimation', *IEEE Trans. Aerosp. Electron. Syst.*, 2014, 50, (4),pp. 3057–1076,2014.
- [92] Wen-Qin Wang,, "Decoupled frequency diverse array range– angle- dependent beampattern synthesis using non-linearly increasing frequency offsets",*JET Radar Sonar Navig.*, 2016, Vol. 10, Iss. 2, pp. 359–369,2016.

[93] Gao, K.D., Chen, H., Shao, H.Z.,et al. “Impacts of frequency increment error on frequency diverse array beampattern”,

EURASIP J. Adv. Signal Process., 2015, (34), pp. 1–12, 2015.