

NEW ANTI-ARM TECHNIQUE BY USING RANDOM PHASE AND AMPLITUDE ACTIVE DECOYS

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Abstract—This paper presents a new method to counter Anti Radiation Missile (ARM) threats, which is effective against advanced ARM. By using random phase and amplitude active decoys in the specified optimum positions and network implementation we show that ARM threats will be removed profoundly. Also, iterative methods are presented to cancel the internal interference effects in the proposed structure.

1. INTRODUCTION

Radar and its related researches have gone through a history for more than a century. In recent years, new techniques are applied in various radar systems [1–10]. The threat of electronic jamming to military radar is well known. But in the event of future wars, there are two serious threats to radar: stealth and antiradar missiles (ARM). Stealth is similar to electronic jamming, that is a “soft” opposing technique which makes radar vulnerable but ARM is a “hard” opposing technique which destroys radar.

Since the emergence of this threat in Vietnam battlefield in 1965, Anti Radar Missiles have been rapidly developed, especially after the

seventies with the advent of SHRIKE and other types of new generation of ARM such as AGM-88E and ALARM which are fatal threats to the radar. Hence, countermeasure techniques against ARM become an urgent matter at present and lots of the methods are presented in literature [11–13]. Active decoys are the only reasonable option for the radar to counter ARM threats [14–17]. These decoys are, in general, designed to radiate synchronously pulse-by-pulse with the radar, covering both leading and trailing edges of the radar pulses. In this paper, we propose a new decoy structure which introduces better performance while reducing production cost by transmitting random phase and amplitude signals. The problem is that if the number of decoys increases or they are used in a network system the interference caused by these transmitters (radar and decoy) reduces the detection ability of the main radars.

In section two, we review some aspects and parameters of ARM homing. According to these parameters, in section three we find the optimum distance between decoys. The proposed method is introduced in section four and iterative methods for reducing the interference is discussed in section five. Finally, we summarize our results in section six.

2. ARM GUIDANCE HEAD: TRACKING OF THE DECOYS OR RADAR NETWORK

Before tracking the target, ARM locks on frequency, direction of arrival and sometimes repetition frequency of target signal through gate circuits. Then the guidance head tracks the source of the power until hitting it. Angle tracking for the desired target is a common radar problem. Statistics of the measured angle can vary significantly for the guidance head of the ARM. A commonly used expression for the apparent angle of two point-sources in the same resolution cell (Figure 1) is given in the following equation [18]:

$$\theta = (a^2 + a \cos \vartheta) / (1 + a^2 + 2a \cos \vartheta) \quad (1)$$

where the measured angle θ is a function of the amplitude ratio “ a ” and the relative phase ϑ between the two radars. Here the angle separation of the two radars is normalized to unity in this equation. Typically this equation is used to illustrate the nature of target glint and how the apparent measured angle from this glint can appear outside of the physical extent of the two sources. It was shown by Dunn and Howard [20] that this equation represents the phase front distortion of the returning signal for the dual source, and is independent of the radar system parameters.

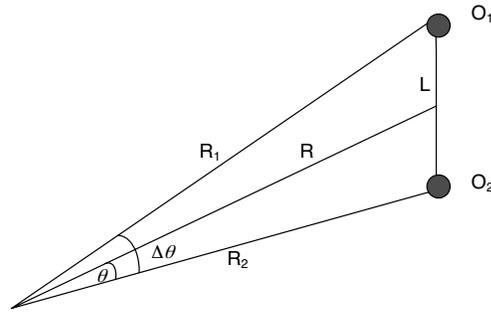


Figure 1. The ARM response in the presence of two point sources.

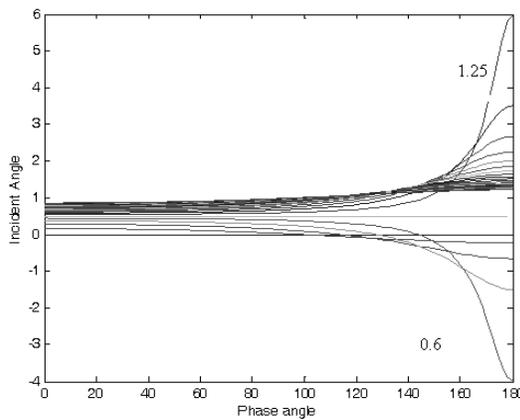


Figure 2. Indicated angle as a function of amplitude and phase for two point-sources.

The hitting angle can range from the midpoint between the two sources ($\theta = 0.5$) to large values that physically fall outside of the two point sources. It is a well documented phenomenon and is the basis for target glint at close range [19]. Taking $\vartheta = 180$ degree (which is ideal as shown in Figure 2) ARM will hit somewhere away from two points statistically. But it is not simple to implement and sometimes cause problems. According to the fact that we use magnetrons as radar transmitters in the network or we use random phase and amplitude for the pulse compression techniques the phase and/or amplitude will be random.

It is possible to evaluate the mean and variance of the indicated angle for two point-sources whose amplitudes and/or phases are random. First, we use only random phase for both sources, the mean

and variance of the indicated angle can be evaluated for a single or multiple measurements. The maximum likelihood estimator (MLE), commonly used in seeker systems for multiple measurements, has been used here. It has been shown [20] that the MLE for a single Gaussian source in Gaussian receiver noise is a power weighted combination of the measured angles. Equation (2) depicts how the MLE angle is determined from the individual indicated angles.

$$\theta = \frac{\sum P_i \theta_i}{\sum P_i} \quad (2)$$

Equation (2) takes each individual measured angle θ_i and weights each with the measured power P_i . From the denominator of (1),

$$P_i = (1 + a_i^2 + 2a_i \cos \vartheta_i) \quad (3)$$

The mean of the indicated angle for the MLE detector becomes:

$$\theta = \left(a^2 + (a/N) \sum \cos \vartheta_i \right) / \left(1 + a^2 + \frac{2a}{N} \sum \cos \vartheta_i \right) \quad (4)$$

Let Y be the Gaussian random variable that approximates the summation of cosines divided by N . Then Applying the Central Limit Theorem for large N , $E[Y]$ for large N becomes:

$$E[Y] = \frac{1}{\sigma\sqrt{2\pi}} \int ((a^2 + aY) / (1 + a^2 + 2aY)) e^{(-Y^2/2\sigma^2)} (dY) \quad (5)$$

where σ is the variance of Y . Since the expected value of the second moment for each cosine is 0.5, the variance of Y is $1/(2N)$. It is now possible to make an approximation of the above integral and solve for $E[\theta]$ in the limit as N becomes large. Let the Gaussian be approximated by a uniform random variable over the interval $-\sigma$ to $+\sigma$:

$$E[\theta] = \frac{1}{2\sigma} \int_{-\sigma}^{\sigma} \int ((a^2 + aY) / (1 + a^2 + 2aY)) dY \quad (6)$$

This can be evaluated as:

$$E[\theta] = 1/2 - \frac{(1 - a^2)}{8a\sigma} [\ln(1 + a^2 + 2a\sigma) - \ln(1 + a^2 - 2a\sigma)] \quad (7)$$

By the use of Taylor series of ln function one can easily see that:

$$E[\theta] = 1/2 - \frac{(1-a^2)}{8a\sigma} 2 \left[\frac{2a\sigma}{1+a^2} + \frac{(2a\sigma)^3}{3(1+a^2)^3} + \dots \right] \quad (8)$$

In the limit as N becomes large, σ goes to zero, thus (8) becomes:

$$E[\theta] = a^2 / (1 + a^2) \quad (9)$$

According to this result we can conclude that by the use of sources which are random in phase, ARM will hit the center of these sources. For considering the consistency of this estimation we calculate the variance of this parameter, Equation (10) is a modified version of (4) when Y is allowed to replace the summation of cosines:

$$\theta[Y] = (a^2 + aY) / (1 + a^2 + 2aY) \quad (10)$$

Since the mean of Y is zero, we use Taylor expansion of (10) to estimate the variance centered at $Y = 0$. The first order Taylor expansion for $\theta[Y]$ at $Y = 0$ is:

$$\theta'(0) = \frac{a}{1+a^2} - \frac{2a^3}{(1+a^2)^2} = \frac{a(1-a^2)}{(1+a^2)^2} \quad (11)$$

If one defines a new variable $X = Y \times \theta'(0)$ then the variance is estimated by:

$$\sigma_x^2 = [\theta'(0)]^2 \sigma_y^2 \quad (12)$$

Since the Gaussian variable Y becomes increasingly centered on zero for increasing values of N , the linear approximation about zero becomes more accurate as N becomes large. Using the previous result that the variance of Y is $1/(2N)$, the approximated variance is given in (13).

$$\sigma^2 = (a(1-a^2))^2 / (2N(1+a^2)^4) \quad (13)$$

which becomes zero as $a = 1$, According to this result if the phase of signals used as transmitter in the decoys or radar network is random the guidance head tracks the power center of the sources. The simulations verify these results. If we use two sources which are coherent, the resulting pattern is shown in Figure 3.

In this figure, the distance between two sources are 500 m and the carrier frequency of them is assumed to be 10 GHz. On the other hand,

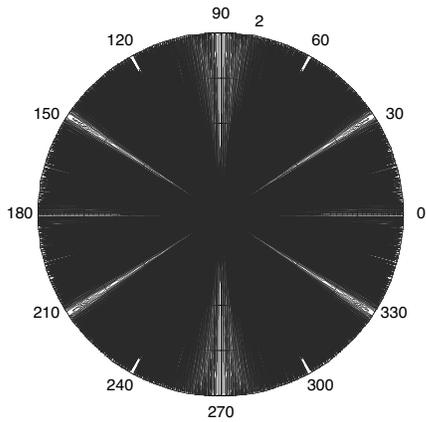


Figure 3. The pattern of two coherent sources.

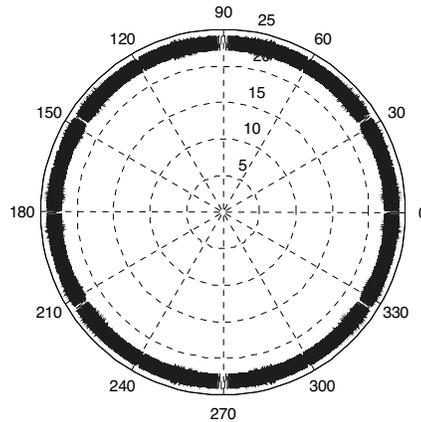


Figure 4. The pattern of two coherent sources with π radian phase difference.

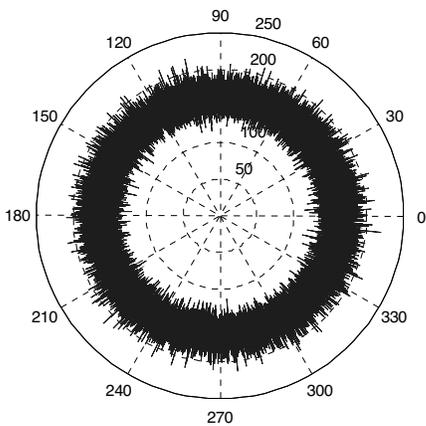


Figure 5. The pattern of two non-coherent sources.

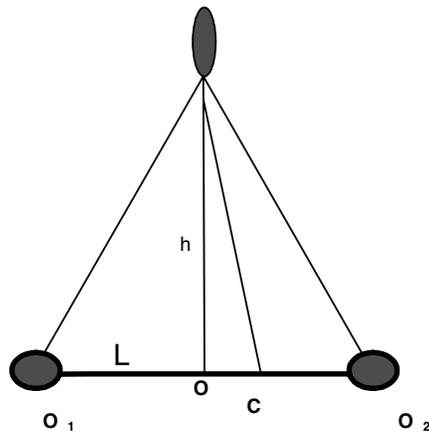


Figure 6. The schematic of the ARM at the vicinity of two decoys.

if we use two coherent sources with the π radian phase difference the result will be as Figure 4.

Finally, we use random phase for these sources and the result are shown in Figure 5.

If the amplitude of these sources is random the problem will be

the same, A Gaussian source is one with Rayleigh random amplitude and uniformly distributed random phase. If we define the ratio p as the normalized power of sources ($p = E[a^2]$), mean and variance of this type is [21–23]:

$$E[\theta] = \frac{p}{1+p} \quad (14)$$

According to the above equation if the sources have the same power ($p = 0.5$), ARM will hit the center of them. Thus if we use random phase and amplitude code for sources the ARM seeker will hit the power center of them.

3. DISTANCE BETWEEN DECOYS AND RADAR NETWORK

With the continuous approach to the target, the included angle of the two sources relative to the guidance head antenna continuously increases; thus the tracking of the guidance head is in the state of indifferent equilibrium. At this time the guidance head begins to discriminate the targets. Since the volume of the missile is finite, the antenna aperture can not be made very large; then the resolving angle of the guidance head is relatively large. For example, for AGM-88 series it is approximately 20 degrees and for Russian ARM (AS-11 (KH-58)) its value is approximately 35 degrees. Thus we must find the optimum distance between the sources, because

- They must be close to each other to be seen as one target by the ARM guidance head.
- They must be away from each other, because if the ARM begins to discriminate the target yet the missile is unable to deflect its direction in time before hitting the center or the power center of the two sources.

Generally, attack by ARM against radar is from overhead. Therefore, the formula for calculating L_{opt} is derived when the missile tracking state is at the vertical bisector of the connecting line of the two-point source, as shown in Figure 5.

Assume that the resolving angle of the guidance head is θ_C , the maximum overloading coefficient of the missile is ng , its effective radius of destruction is R_d ; and the missile flight velocity is v_{rel} .

$$h = \frac{L}{2} \operatorname{ctg} \frac{\theta_C}{2}, \quad \int_0^{t_0} v_1(t) dt = h \quad (15)$$

$$\int_0^{t_0} v_2(t) dt = |OC| \quad (16)$$

$$v_1(t) = v_{rel} \cos q, \quad v_2(t) = v_{rel} \sin q, \quad q = \frac{1}{2}ngt^2 \quad (17)$$

$$\int_0^{t_0} v_{rel} \cos \left(\frac{1}{2}ngt^2 \right) dt = \frac{L}{2} \text{ctg} \left(\frac{\theta_c}{2} \right) \quad (18)$$

$$\begin{aligned} \int_0^{t_0} \cos \left(\frac{1}{2}ngt^2 \right) dt &= \int_0^{t_0} \cos \left(\frac{\pi}{2} \left(\sqrt{\frac{ng}{\pi}} t \right)^2 \right) dt = \int_0^{\sqrt{\frac{ng}{\pi}} t_0} \cos \left(\frac{\pi}{2} u^2 \right) \sqrt{\frac{\pi}{ng}} du \\ &= \frac{1}{k_1} \int_0^{k_1 t_0} \cos \left(\frac{\pi}{2} u^2 \right) du \end{aligned} \quad (19)$$

where $k_1 = \sqrt{\frac{ng}{\pi}}$. Thus:

$$|CO_2| = \frac{L}{2} - \int_0^{t_0} v_{rel} \sin \left(\frac{1}{2}ngt^2 \right) dt \quad (20)$$

$$\frac{\partial |CO_2|}{\partial L} = \frac{1}{2} - v_{rel} \sin \left(\frac{1}{2}ngt^2 \right) \frac{\partial t_0}{\partial L} \quad (21)$$

Then:

$$\cos \left(\frac{1}{2}ngt_0^2 \right) \frac{\partial t_0}{\partial L} = \frac{1}{2v_{rel}} \text{ctg} \frac{\theta_c}{2} \quad (22)$$

If $\frac{\partial |CO_2|}{\partial L} = 0$ then $\frac{1}{2} - \frac{1}{2} \text{tag} \left(\frac{1}{2}ngt_0^2 \right) \text{ctg} \frac{\theta_c}{2} = 0$ thus $ngt_0^2 = \theta_c$ and finally:

$$\begin{aligned} L_{opt} &= \int_0^{\sqrt{\frac{\theta_c}{ng}}} \cos \left(\frac{1}{2}ngt_0^2 \right) dt 2v_{rel} \text{tag} \frac{\theta_C}{2} \\ &= 2v_{rel} \text{tag} \frac{\theta_C}{2} \sqrt{\frac{\pi}{ng}} \int_0^{\sqrt{\frac{\theta_c}{\pi}}} \cos \left(\frac{\pi}{2} u^2 \right) du \\ &= 2v_{rel} \text{tag} \frac{\theta_C}{2} \sqrt{\frac{\pi}{ng}} \text{FresnelC} \left(\sqrt{\frac{\theta_c}{\pi}} \right) \end{aligned} \quad (23)$$

And according to L_{opt} maximum of the CO₂ is equal to:

$$\begin{aligned}
 |CO_2|_{opt} &= \frac{L_{opt}}{2} - v_{rel} \int_0^{t_0} \sin\left(\frac{1}{2}ngt_0^2\right) dt \\
 &= \frac{L_{opt}}{2} - v_{rel} \sqrt{\frac{\pi}{ng}} \int_0^{\sqrt{\frac{\theta_c}{\pi}}} \sin\left(\frac{\pi}{2}u^2\right) du \\
 &= \frac{L_{opt}}{2} - v_{rel} \sqrt{\frac{\pi}{ng}} \text{FresnelS}\left(\frac{\theta_0}{\pi}\right) \quad (24)
 \end{aligned}$$

According to these formula for AS-11 (KH-58) with $\theta_C = 35$ degrees, $v = 3.6$ mach and $ng = 10 \text{ m/s}^2$, we have $L_{opt} = 225$ meters and CO₂ will be 109 meters, which is larger than the destructive radius of AS-11 (KH-58). According to the above discussion by the use of the distances calculated here, ARM is unable to deflect to hit one of the sources.

4. INTEGRATED ANTI-ARM SYSTEM

We use the system which is composed of decoys and radar network, which is called here Radar-Decoy Network (Figure 6). If the transmitted signals of the decoys (and radar if possible) as mentioned in section two are random in phase and amplitude the performance of the system against ARM threat increases dramatically. In other words, networking of more than two radars is needed for more jamming effect on the seeker of ARM. In fact, amplitude and phase of overlapping transmission signals changing continuously, corresponds to introducing white noise to the ARM, so that the tracking error is increased or it loses the tracking capability.

Transmission systems of separated decoys are with the same power, the same frequency and PRF But with codes different in phase and amplitude and changing rapidly. In order to avoid interference among radars and decoys, the transmissive signal of each radar must be modulated with orthogonal codes; on the other hand these codes must be random in phase and amplitude. These two concepts are mutually exclusive. In the next section we use iteration methods for solving this problem

5. ITERATIVE INTERFERENCE CANCELLATION

Interference cancellation (also called Co-channel Interference in some radar applications) is a simple detection technique in which estimates

(or statistics) of other radar transmitter interferences are subtracted from the received signal, in order to improve the estimate for a given radar transmitter. This process can proceed iteratively (sometimes called a multi stage receiver), by repeating the subtraction process. Such iterations may be linear or non-linear. Linear methods use linear estimates of the interference, whereas non-linear methods have no such restriction. We mainly restrict our attention to linear schemes, previously considered in [24] and [25].

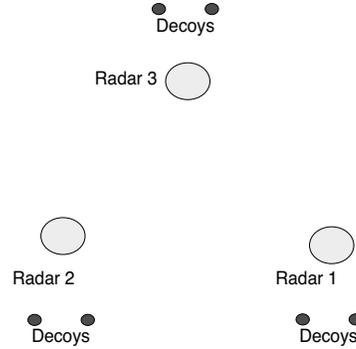


Figure 7. Generalized radar-decoy network structure.

Iterative methods which are used here, have also been successfully applied to coded multi-user systems [26–28], in CDMA applications. In particular, we consider the method of Jacobi and improvements theorem, corresponding to weighted parallel cancellation (such as Chebyshev method). Finally, we also present results concerning the conjugate gradient method, which is a parameter free iteration. Assume that the received signal is modeled as:

$$r = AWd + n \quad (25)$$

where A is a $N * K$ dimension matrix (K transmitters access the channel with a pulse code of N chip, pulse compression also decreases the detection of the radar by the ARM with \sqrt{N}), W is a diagonal matrix of the transmitters amplitude, and d is a vector of binary symbols for transmitter i . The pulse compression section of the radar finds the best estimate of d as:

$$\hat{d} = \arg \min_{d \in R^k} \|r - AWd\|^2 \quad (26)$$

This has the closed form solution as:

$$d = A^{-1}r \quad (27)$$

For linear multi-transmitter detection, we are interested in the iterative solution of $Md = b$ where for the correlator (matched filter) or pulse compression in radar, $M = R = AA^*$, $b = y = A^*r$.

It is shown in [26] that for large systems with $\beta = K/N < 1$ which is very common in coding of the radar, the first order stationary iteration for solving Equation (27) is [23]:

$$d_{k+1} = \frac{1}{1 + \beta}y - \left(\frac{1}{1 + \beta}R - I \right) d_k \tag{28}$$

It was shown that the asymptotic convergence factor is approximately equal to:

$$\rho = \frac{2\sqrt{\beta}}{1 + \beta} \tag{29}$$

Figure 8 shows the implementation of this receiver, with $\tau_i = 1/(1 + \beta)$. This first order stationary method has been suggested in [26], and in simple case is known as PIC method. Given in [28] however is an outline of how to select τ_i to minimize the mean square error for a given number of steps. See also [27].

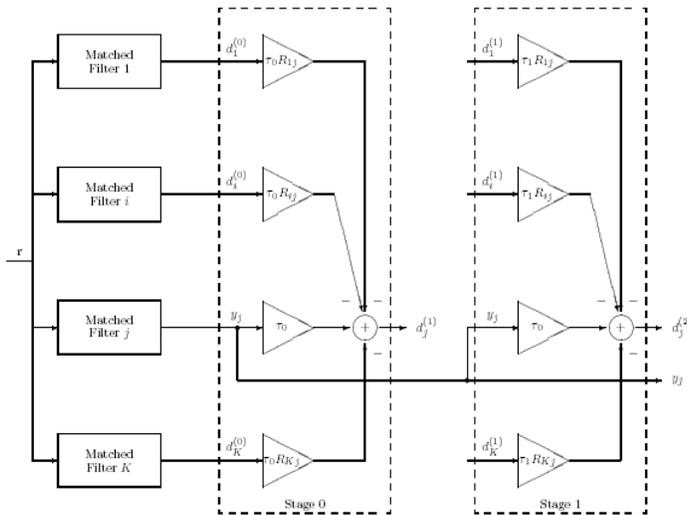


Figure 8. First order iterative implementations of the pulse compressor in the receiver, including: First order and second order stationary system.

For large systems, the second order iteration is given by [28]:

$$d_1 = y - \left(\frac{1}{1 + \beta} R - I \right) d_0 \quad (30)$$

$$d_{k+1} = y - (R - (1 + \beta)I)d_k - \beta d_{k-1}$$

This method converges to the correlator for any given initial guess d_0 , and the parameters chosen are optimal among second order stationary iterations. The asymptotic convergence factor is given by:

$$\rho = \sqrt{\beta} \quad (31)$$

As mentioned above we are willing to use this method to increase radar receiver detection performance in netted radar with decoys having random phase and amplitudes. Figure 9 shows the simulated bit error rate versus iteration for conjugate gradient (CG), Chebyshev, first and second order stationary methods in pulse compression section output. The simulation parameters are K (Number of Transmitters) = 8, N (Number of Chips) = 16, $E_b/N_0 = 10$ dB (SNR) which is equivalent to the detection probability of 0.98 and false alarm probability of 10^{-6} (here we assumed that all transmitters transmit with equal powers). In terms of BER, the Conjugate Gradient method achieves the correlator performance, requiring only three iterations. Note that the convergence of this method is not monotonic. Chebyshev method performs best, both in terms of BER and in terms of providing a

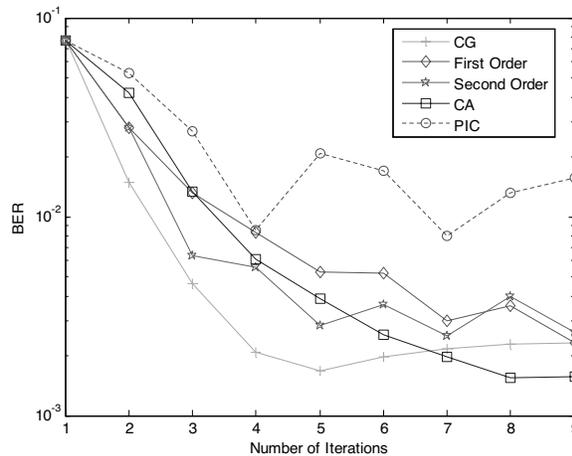


Figure 9. Iterative implementations of the correlator. Simulated BER convergence properties. $K = 8$, $N = 16$, $E_b/N_0 = 10$ dB.

smooth convergence. Similar phenomena have been observed by other researchers in CDMA application, and have been exploited in [28].

6. CONCLUSION

From the analysis mentioned in this paper, we showed that by the use of random pulse coding both in amplitude and phase of the decoy signals we can achieve very good performance while reducing the production cost. Also the optimum distance between decoys and radars was derived. The concept of networking was presented and by the use of the iterative methods the interference was reduced considerably.

REFERENCES

1. Rocca, P., L. Manica, and A. Massa, "An effective excitation matching method for the synthesis of optimal compromises between sum and difference patterns in planar arrays," *Progress In Electromagnetics Research B*, Vol. 3, 115–130, 2008.
2. Lee, K.-C., C.-W. Huang, and M.-C. Fang, "Radar target recognition by projected features of frequency-diversity RCS," *Progress In Electromagnetics Research*, PIER 81, 121–133, 2008.
3. Qu, Y., G. S. Liao, S. Q. Zhu, X. Y. Liu, and H. Jiang, "Performance analysis of beamforming for MIMO radar," *Progress In Electromagnetics Research*, PIER 84, 123–134, 2008.
4. Qu, Y., G. S. Liao, S. Q. Zhu, and X. Y. Liu, "Pattern synthesis of planar antenna array via convex optimization for airborne forward looking radar," *Progress In Electromagnetics Research*, PIER 84, 1–10, 2008.
5. Sabry, R. and P. W. Vachon, "Advanced polarimetric Synthetic Aperture Radar (SAR) and Electro-Optical (EO) data fusion through unified coherent formulation of the scattered EM field," *Progress In Electromagnetics Research*, PIER 84, 189–203, 2008.
6. Zang, W., Z. G. Shi, S. C. Du, and K. S. Chen, "Novel roughening method for reentry vehicle tracking using particle filter," *Journal of Electromagnetic Waves and Applications*, Vol. 21, No. 14, 1969–1981, 2007.
7. Mahanti, G. K., A. Chakraborty, and S. Das, "Design of fully digital controlled reconfigurable array antennas with fixed dynamic range ratio," *Journal of Electromagnetic Waves and Applications*, Vol. 21, No. 1, 97–106, 2007.
8. Shi, Z. G., S. Qiao, and K. S. Chen, "Detection and localization of RF radar pulses in noise environments using

- wavelet packet transform and higher order statistics,” *Progress In Electromagnetics Research*, PIER 58, 301–317, 2006.
9. Soliman, M. S., T. Morimoto, and Z. I. Kawasaki, “Three dimensional localization system for impulsive noise sources using ultra wideband digital interferometer technique,” *Journal of Electromagnetic Waves and Applications*, Vol. 20, No. 4, 515–530, 2006.
 10. Singh, A. K., P. Kumar, T. Chakravarty, G. Singh, and S. Bhooshan, “A novel digital beamformer with low angle resolution for vehicle tracking radar,” *Progress In Electromagnetics Research*, PIER 66, 229–237, 2006.
 11. Li, N., “Radar ECCM’s new area: Anti-STEALTH and anti-ARM,” *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 31, No. 3, July 1995.
 12. Lian, W., “Discussion of radar anti anti-radiation missile technology — Alarming plus decoy system,” *International Radar Conference, CIE 2001*, 2001.
 13. Wang, F., R. He, and X. Sha, “Anti-ARM technique: Feature analysis of ARM warning radar,” *International Radar Conference, CIE 2001*, 2001.
 14. Schindler, J. K., “Netted search radar system,” U. S. Pat. No. 4347513, Aug. 31, 1982.
 15. Manoogian, D. V., B. H. Labitt, J. R. Wood, “Transmitter peak power efficient pseudo-blink ARM decoy system,” U. S. Pat. No. 4433333, Feb. 21, 1984.
 16. Atar, D., “Operation of a decoy against threats,” U. S. Pat. No. 6833804, Dec. 21, 2004.
 17. Manoogian, D. V., “Missile decoy system,” U. S. Pat. No. 4990919, Feb. 5, 1991.
 18. Rougas, J. A., “Anti-Radar Missile (ARM) countermeasure method,” U. S. Pat. No. 6414622, July 2, 2002.
 19. Skolnik, M. I., *Introduction to Radar Systems*, McGraw-Hill, New York, 2002.
 20. Dunn, J. H. and D. D. Howard, “Radar target amplitude, angle, and Doppler scintillation from analysis of the echo signal propagation in space,” *IEEE Trans. on Microwave Theory and Techniques*, Vol. 6, No. 9, 715–728, Sept. 1968.
 21. Kanter, I., “Varieties of average monopulse responses to multiple targets,” *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 17, No. 1, 25–28, Jan. 1981.
 22. Kanter, I., “Multiple Gaussian targets: The track-on-jam

- problem," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 13, No. 6, 620–623, Nov. 1977.
23. Patel, P. and J. Holtzman, "Analysis of a simple successive interference cancellation scheme in a DS/CDMA system," *IEEE J. Select. Areas Commun.*, Vol. 12, No. 5, 796, June 1994.
 24. Elders-Boll, H., M. Herper, and A. Busboom, "Adaptive receivers for mobile DS-CDMA communication systems," *Proc. of IEEE Vehicular Technology Conference*, Vol. 3, Phoenix, AZ, May 1997.
 25. Elders-Boll, H., A. Busboom, and H. D. Schotten, "Spreading sequences for zero-forcing DS-CDMA multiuser detectors," *Proc. of 8th IEEE International Symposium, PIMRC'97*, Helsinki, Finland, Sept. 1997.
 26. Guo, D., L. K. Rasmussen, S. Sumei, T. J. Lim, and C. Cheah, "MMSE-based linear parallel interference cancellation in CDMA," *Proc. of IEEE International Symposium Spread Spectrum Techniques and Appl.*, Sun City, South Africa, Sept. 1998.
 27. Rasmussen, L. K., Y. Ma, D. Guo, and T. J. Lim, "Aspects on linear parallel interference cancellation in CDMA," *Proc. of IEEE International Symposium Information Theory*, 37, Cambridge, USA, Aug. 1998.
 28. Grant, A. and C. Schlegel, "Iterative implementation for linear multiuser detectors," Dept. of Electrical Engineering University of Utah, 1999.