Eight -phase Sequence Sets Design for Radar

S.P SINGH[1] , S.A MUZEER[2] , K SUBBA RAO[3]

[1]MGIT, Gandipet, Hyderabad, INDIA, singh_spgahlot@rediffmail.com

[2]VBIT, Hyderabad, INDIA

[3]ECE Dept, College of Engg, (O.U), Hyderabad, INDIA

Abstract: In this paper a novel Modified Simulated Annealing Algorithm (MSAA) is used as global optimization technique to find the solution of combinatorial optimization problem which is usually difficult to tackle. MSAA combines good methodologies like global minimum converging property of Simulated Annealing algorithm and fast convergence rate of Hamming scan algorithm. Orthogonal Netted Radar System (ONRS) and spread spectrum communication system can fundamentally improve the system performance by using a group of specially designed orthogonal signals. MSAA is used to synthesize orthogonal eight-phase sequence sets with good autocorrelation and cross correlation properties. Some of the synthesized sequence sets are presented, and their properties are better than four-phase sequence sets known in the literature. The synthesized eight-phase sequence sets are promising for practical application to Netted Radar System and spread spectrum communication. The effect of Doppler shift on synthesized sequences set is also investigated using ambiguity function. The convergence rate of the algorithm is shown to be good.

Key Words:- Hamming Scan, Netted Radar, Polyphase code, Radar signal design, Simulated annealing.

1 Introduction

Polyphase signals have been widely used in radar and communication. But the synthesis of polyphase coded radar signal with good correlation properties is a nonlinear multivariable optimization problem, which is usually difficult to tackle. The Simulated Annealing Algorithm (SAA), introduced by Kirkpatrick etal [1, 2] proved to be an efficient and powerful tool to find optimal or near optimal solutions for complex multivariable nonlinear functions. The Hamming Scan Algorithm (HSA) is a traditional greedy optimization algorithm, which searches in the neighborhood of the point in all directions to reduce the cost function and has fast convergence rate [3, 4]. The proposed algorithm has fast convergence property of HSA and global minimum capability of SAA [5, 6]. The suggested algorithm preserves the analogy between the search for a minimum cost function and physical process by which a material changes state while minimizing its energy. This algorithm is used to design orthogonal eight-phase coded sequence sets that can be used in netted radar systems / multiple radar systems and spread spectrum communication. The radar used orthogonal signal can be termed as Orthogonal Netted Radar Systems (ONRS). The several authors have worked in the design the coded signal with good correlation properties which are widely used in communication and radar. [7-10]

2. Orthogonal eight-phase signal design

Assuming that an orthogonal eight-phase code set consists of L signals with each signal containing N subpulses represented by a complex number sequence, one can express the signal set as follows[11]:

$$\left\{ s_l(n)=e^{j\phi_l(n)}, n=1,2,...,N \right\}, l=1,2,3,.....L \quad .. (1)$$

where $\phi_l(n)$ is the phase of bit n of signal l in the signal set and lies between 0 and 2π. If the number of the distinct phases available to be chosen for each subpulses in a code sequence is M, the phase for a sub pulse can only be selected from the following admissible alphabets:

$$\phi_l(n) \in \left\{0, \frac{2\pi}{M}, 2\frac{2\pi}{M}, ..., (M-1)\frac{2\pi}{M}\right\} = \{\psi_1, \psi_2, ..., \psi_M\} \quad ..(2)$$

For example, if M = 4, then values of $\psi_1, \psi_2, ..., \psi_4$ will be 0, π/2, π and 3π/2 respectively. Considering a eight-phase code set S with code length N, set size L, and distinct phase number M, one can concisely represent the phase values of S with the following L by N phase matrix:

$$S(L,N,M)=\begin{bmatrix} \phi_1(1) & \phi_1(2) & \phi_1(3) & .... & \phi_1(N) \\ \phi_2(1) & \phi_2(2) & \phi_2(3) & .... & \phi_2(N) \\ & \vdots & & & \\ \phi_l(1) & \phi_l(2) & \phi_l(3) & .... & \phi_l(N) \\ \phi_L(1) & \phi_L(2) & \phi_L(3) & .... & \phi_L(N) \end{bmatrix} \quad . \; . \; (3)$$

where the phase sequence in row l $(1 \le l \le L)$ is the eight-phase sequence of signal l and all the elements in the matrix can only be chosen from the phase set in eq (2). The autocorrelation and crosscorrelation properties of orthogonal eight-phase codes should satisfy or nearly satisfy the following:

$$A(s_l,k)=\begin{cases} \frac{1}{N}\sum_{n=1}^{N-k} s_l(n)s_l^*(n+k) = 0, \; 0<k<N \\ \frac{1}{N}\sum_{n=-k+1}^{N} s_l(n)s_l^*(n+k) = 0, \; -N<k<0 \end{cases}$$
$$l = 1,2,.....L. \quad ...... \quad (4)$$

and,

$$C(s_p, s_q, k) = \begin{cases} \frac{1}{N}\sum_{n=1}^{N-k} s_p(n)s_q^*(n+k) = 0, \; 0 \le k<N \\ \frac{1}{N}\sum_{n=-k+1}^{N} s_p(n)s_q^*(n+k) = 0, \; -N<k<0 \end{cases}$$
$$p \ne q, \quad p,q = 1,2,...L \quad .... \quad (5)$$

where $A(s_l, k)$ and $C(s_p, s_q, k)$ are the aperiodic autocorrelation function of eight-phase sequence s_l and the crosscorrelation function of sequences s_p and s_q respectively, the asterisk denotes the complex conjugate, and k is the discrete time index. The design of an orthogonal eight-phase code set is equivalent to the construction of a eight-phase matrix S(L,N,M) in eq (3) with the autocorrelation and crosscorrelation constraints in eq (4) and eq (5). It seems to be very difficult to algebraically design a set of three or more sequences with low crosscorrelation between any two sequences in the set. Alternatively, a more practical approach to design a eight-phase code set with properties in eq (4) and eq (5) is to numerically search the best eight-phase sequences by minimizing a cost function that measures the degree to which a specific result meets the design requirements. For the design of orthogonal eight-phase code sets used in ONRS, the cost function is based on the sum of the square of maximum autocorrelation sidelobe peaks and the square of maximum crosscorrelation peaks. Hence, from eq (4) and eq (5), the cost function can be written as

$$E = \sum_{l=1}^{L}(\max_{k \ne 0} |A(s_l,k)|)^2 + \lambda \sum_{p=1}^{L-1} \sum_{q=p+1}^{L} (\max_{k} |C(s_p,s_q,k)|)^2 \quad ....(6)$$

where λ is the weighting coefficient between autocorrelation function and crosscorrelation function in the cost function. With given values of N, M, and L, the minimization of cost function in eq (6) generates a group of eight-phase sequences that are automatically constrained by eq (4) and eq (5). In other words, the objective is that the autocorrelation sidelobe peaks and the crosscorrelation peaks for all lags of S must be as small as possible.

3. Simulated Annealing Algorithm

The simulated annealing technique, introduced by Kirkpatrick et al [1] proved efficient and powerful tool to find optimal or near optimal solutions for complex multivariable nonlinear functions the major advantage of the SA algorithm over the traditional "greedy" optimization algorithms is the ability to avoid becoming trapped in local optima during the search process. The algorithm employs a random variable search that not only accepts the changes that decrease the cost function but some changes that increase it with a probability of

$$p = \exp\left(-\frac{\Delta E}{T_i}\right) \quad .... (7)$$

as well, where is the ΔE cost change due to a random research, and T_i is the control parameter, which by analogy is known as the system "temperature." Normally, the temperature T_i slowly decreases from a large value to a very small one during the annealing process. The SA algorithm can find the global optimum of a nonlinear multivariable function by carefully controlling the change rate of the system temperature [12, 14]. As shown in (9), for

SA algorithms, the probability for the system state change due to the random variable search is

$$p = \begin{cases} \exp\left(-\frac{\Delta E}{T_i}\right), & \Delta E > 0 \\ 1, & \Delta E < 0 \end{cases} \quad \ldots. \ (8)$$

Consequently, the system state change probability is decided by the subsequent cost value change only, and the random system state change at a temperature is indeed a Markov chain.

4. Hamming Scan Algorithm

The Hamming scan algorithm is a traditional greedy optimization algorithm, which searches along the directions to reduce the cost function and has fast convergence rate. The basic difference between Genetic algorithm and Hamming scan algorithm is that Genetic algorithm uses random but possibly multiple mutations. The Mutation is a term metaphorically used for a change in an element in the sequence. For example if a phase value of a polyphase sequence is ψ_m ($1 \le m \le M$), i.e., one term in the phase matrix (3), it is replaced with phase ψ_i, i = 1,2,…M, $i \neq m$, and the cost for each ψ_i change is evaluated. If the cost is reduced due to a change in phase value, the new phase value is accepted; otherwise, the original phase value is retained. The same procedure is performed for all phase values of all sequences in a set, i.e., every term of the phase matrix (3). This process is recursively applied to the matrix until no phase changes are made. A single mutation in a sequence results in Hamming distance of one from the original sequence. The Hamming scan algorithm mutates all the elements in a given sequence one by one and looks at all the first order-Hamming neighbors of the given sequence. Thus, Hamming scan performs recursively local search among all the Hamming-1 neighbors of the sequence and selects the one whose objective function value is minimum.[3,4]

5. MSAA for orthogonal eight-phase signal design

The MSAA is a combination of both SA and Hamming scan algorithms. It combines the good methodologies of the two algorithms like global minimum converging property of SA algorithm and fast convergence rate of Hamming scan algorithm. The demerit of Hamming scan algorithm is that it gets stuck in the local minimum point because it has no way to distinguish between local minimum point and a global minimum point. Hence it is sub-optimal [4, 5]. The drawback in SA is that it has a slow convergence rate because even though it may get closer to the global minimum point, it may skip it because of the methodology it employs, generating the sequences randomly and accepting them with probability based on annealing schedule. The MSAA overcomes these drawbacks. The computational cost for searching the best polyphase code set with set size L, code length N, and distinct phase number M through an exhaustive search, i.e., minimizing eq (6), is of the order of $M^{(L.N)}$ and grows exponentially with the code length and the set size. Therefore, the numerical optimization of polyphase codes is an NP-complete problem for which the global optimization methods can be effectively used. Here, the MSAA algorithm is used as global optimization methods. The flow chart of the algorithm is shown in fig (1). Initially, a set of sequences S(L,N,M) is chosen randomly. Here L is taken as 3 and M = 8 and N is varied from 40 to 500. One element of S is randomly chosen and mutated [Mutation means a particular element is replaced with any one of the permissible alphabet given in eq (2)]. With each phase “mutation”, the cost function before and after the phase change are evaluated, and the phase change is accepted with a probability $\exp(-\Delta E/T_i)$. More specifically, the phase values of a polyphase code set S(L,N,M) is “mutated” as follows: First, a polyphase sequence set S(L,N,M) as given in eq (3) is randomly chosen; then the selected phase value is replaced with a phase value randomly chosen from the other M-1 possible distinct phase values that are from $\{\psi_1, \psi_2, \ldots, \psi_M\}$. Now the cost function for the new eight-phase code set is evaluated according to eq (6). If the new cost value is reduced, then accept the new set. Otherwise, accept it with a probability $\exp(-\Delta E/T_i)$. The probability density function for all random selections is a uniform function among all possible values. The next step of the algorithm is to invoke the Hamming scan as shown in the Fig. 1. The success rate of the algorithm is depends on the starting temperature, the decrement rate of temperature, i.e., cooling schedule, the determination of equilibrium condition at each temperature, and the annealing stopping criterion [12, 13]. The starting temperature T_0 is decided based on the standard deviation σ of the initial cost distribution by setting

$$T_0 = 30\,\sigma. \quad \ldots(9)$$

From the initial temperature T_0, the system temperature is systematically reduced according to

$$T_{i+1} = \alpha T_i \quad \ldots\ldots \quad (10)$$

where α is constant and chosen to be 0.90 in this design. At a temperature T_i ($i > 0$), the phase values of the sequence set are constantly "mutated" and accepted with a probability according to (8) until the cost function distribution reaches equilibrium state. Then, the temperature is reduced to T_{i+1} according to eq. (10), and the code "mutations" are repeated until a new equilibrium state is reached at the updated temperature.

The annealing process is stopped if no "mutated" phase is accepted during three consecutive temperature reductions or $T < \varepsilon$, where ε is minimum stopping temperature. The flowchart of MSAA for optimizing the orthogonal polyphase code set is shown in Fig.1.

6 Design results

A variety of eight-phase code sets are designed using the proposed algorithm. The cost function for the optimization is based on eq (6), and the value of λ in the eq (6) is chosen as 1. In this work all the autocorrelation sidelobe peak (ASP) values and crosscorrelation (CP) values are normalized with respect to sequence length, N and all the design examples are single realizations. Some of the synthesized results are presented which have better correlation properties than four- phase sequences available in literature [11]. Tables 1 & 2 show the comparison between our results and the results reported in the reference [11]. In table1&2, columns 2 and 3 show maximum ASP and average of the ASPs respectively, columns 4 and 5 show maximum CP and average of CPs respectively. From table 1, it is observed that normalized value of maximum ASP in literature is 0.182 while synthesized value is 0.111 and maximum CP in literature is 0.212 while synthesized value is 0.199, both are better than the results reported in literature. Similarly, average of ASPs is also better as indicated. Table 2 shows the same correlation properties as table 1 but for different values of L and N. From table 2, it is observed that normalized value of maximum ASP in literature is 0.095 while synthesized value is only 0.073. Similarly average of ASPs and maximum CP are also lower. All the synthesized results are one-time optimization results although better designs might have been obtained by repeatedly applying MSAA.

The proposed optimization algorithm for eight-phase sequence set design is indeed very effective, especially when the code length is large. As expected, the autocorrelation sidelobe energy and the crosscorrelation energy of the sequence sets are nearly uniformly distributed among all possible locations.

The term max(ASP), min(ASP), avg(ASP), max(CP), min(CP), avg(CP) and avg all are defined using eq.(6) and eq. (7) as,

$$\max(\text{ASP}) = \max\{\max_{k \neq 0}(A(s_l, k)\} \quad \ldots \quad (13)$$

$$\text{avg(ASP)} = \frac{1}{L}\sum_{l=1}^{L}\{\max_{k \neq 0} A(s_l, k)\} \quad \ldots \quad (14)$$

$$\max(\text{CP}) = \max\{\max(C(s_p, s_q, k))\} \quad \ldots. \quad (15)$$

$$\text{avg(CP)} = \frac{2}{L(L-1)}\sum_{p=1}^{L-1}\sum_{q=p+1}^{L}(\max \ |C(s_p, s_q, k)|\ ) \quad \ldots \quad (16)$$

Table 1 Comparison between ref [11] values and synthesized values (M = 8, L= 4 & N = 40).

Particulars	Max (ASP)	Avg (ASP)	Max (CP)	Avg (CP)
Literature values(M= 4)	0.182	0.152	0.212	0.198
Synthesized Values	0.111	0.106	0.199	0.189

Table 2 Comparison between ref [11] values and synthesized values (M= 8, L=3 & N=128).

Particulars	Max (ASP)	Avg (ASP)	Max (CP)	Avg (CP)
Literature values (M= 4)	0.095	0.089	0.118	0.111
Synthesized Values	0.073	0.071	0.104	0.103

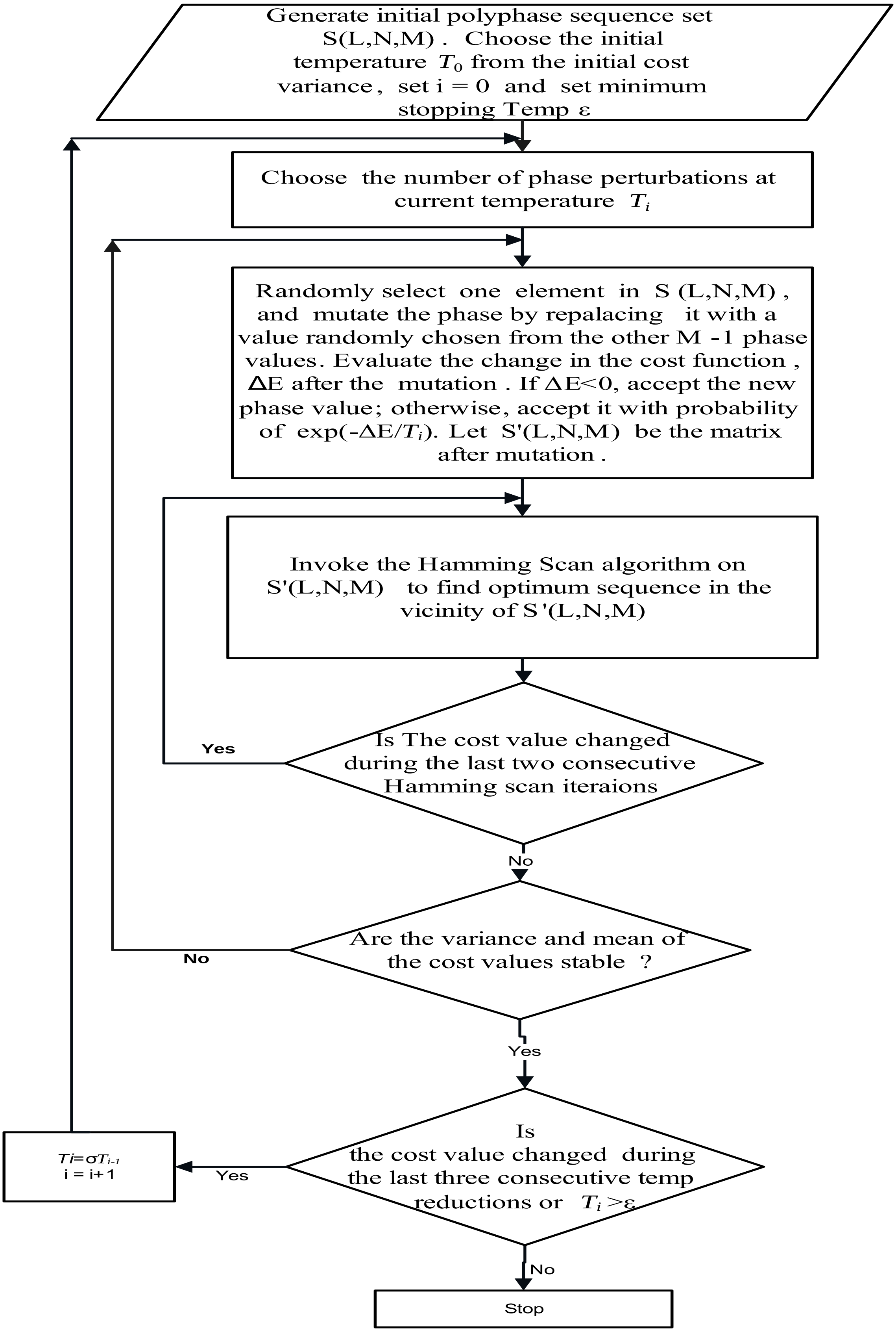


Fig 1 Flow chart of Modified Simulated Annealing Algorithm

Fig.2 shows the comparison of correlation values of synthesized sequence set and values of sequence set reported in the literature with L= 4 and N = 40. Fig.3 shows the comparison of correlation values of synthesized sequence set and values of sequence set reported in the literature with L = 3 and N = 128. Fig. 4 shows the maximum autocorrelation sidelobe peak (ASP) and maximum crosscorrelation peak (CP) of designed eight-phase sequence sets versus sequence length (N), varying from 40 to 500. Fig. 5 shows the average of autocorrelation sidelobe peaks (ASPs) and average of crosscorrelation peaks (CPs) of designed eight-phase sequence sets versus sequence length (N), varying from 40 to 500. sequence length (N), varying from 40 to 500.

Fig. 6 shows the autocorrelation functions of designed sequence set with sequence length, N=350 and number of sequences in the set, L = 3. As shown in the fig. 6 the autocorrelation functions are like impulse in all three cases, which indicate the resolution capability of the signal, is good and generate very less self-clutters. Fig. 7 shows the crosscorrelation between all possible pairs of sequences of S with the L = 3 and N = 350. As shown in the fig. 7 the crosscorrelation functions between possible pairs of sequences are very low which indicate that designed sequences are orthogonal. For conventional radar pulse-compression signals such as polyphase sequences or Frank polyphase sequences, the autocorrelation sidelobe peak decreases at the rate of $1/\sqrt{N}$. Similarly, eight-phase sequence sets designed in this work also decrease at the rate of $1/\sqrt{N}$. The design sequence sets are practically very useful for ONRS. It can be demonstrated by taking one design sequence set (i.e., L = 3 and N = 300), these design sequences are applied to an ONRS with three radar stations (L = 3) for detection of a target. The processing results at the three radar stations using Sequence 1 (S_1), Sequence 2 (S_2) and Sequence 3 (S_3) are shown in Fig.8(a)–(c), respectively. The simulated results are achieved with assumptions that the target radar cross section (RCS) is the same for each radar station, and the distances from the target to all radar stations are identical. The result at each radar station includes the autocorrelation function of its own transmitted signal and the crosscorrelation functions between the matched filter and the waveforms transmitted by the other radar stations in the ONRS. The target responses are clearly distinguishable from interference in the output at each radar station as shown in Fig.8

However, if the numbers of radar stations in an ONRS are very large, the interference between the radar stations might degrade the target detection, and additional processing, such as the CLEAN algorithm, may be needed for inference removal [11]. The effects of Doppler on the designed ONRS polyphase signals are also study.

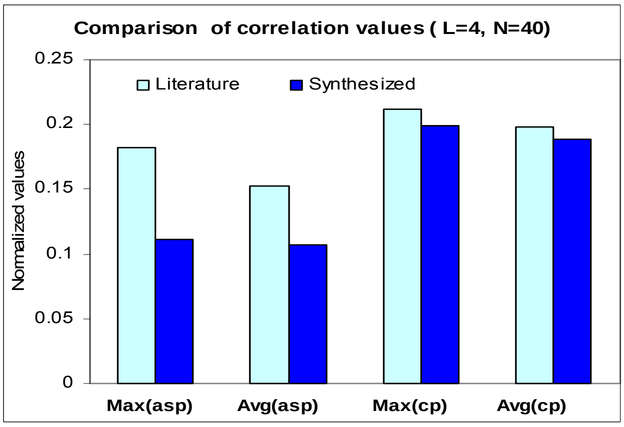


Fig.2 Comparison of correlation values of synthesized sequence set and values of sequence set reported in the literature with L= 4 and N = 40.

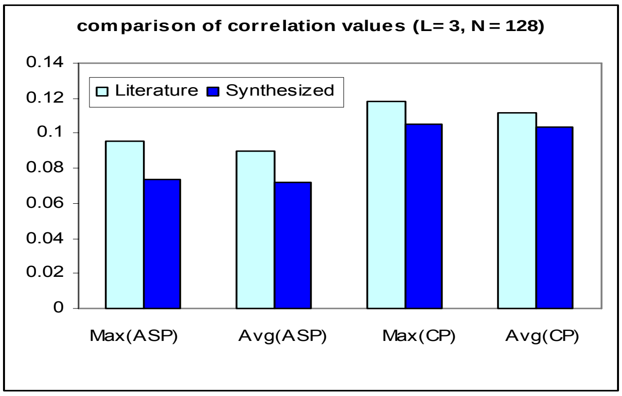


Fig.3 Comparison of correlation values of synthesized sequence set and values of sequence set reported in the literature with L = 3 and N = 128.

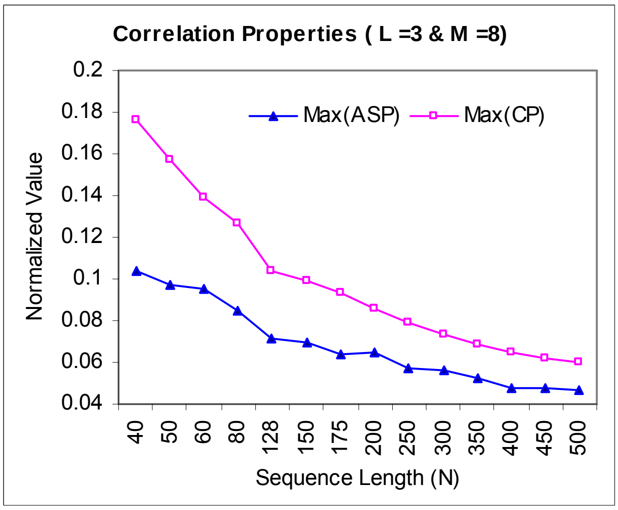


Fig 4 Max (ASP) and max (CP) values of 8-phase designed sequence sets, with L = 3 and sequence length, N varying from 40 to 500.

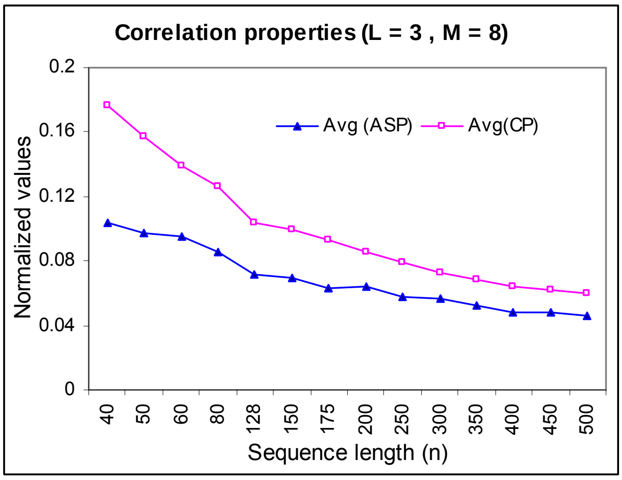


Fig 5 Avg(ASP) and Avg (CP) values of 8-phase designed sequence sets, with L = 3 and sequence length, N varying from 40 to 500.

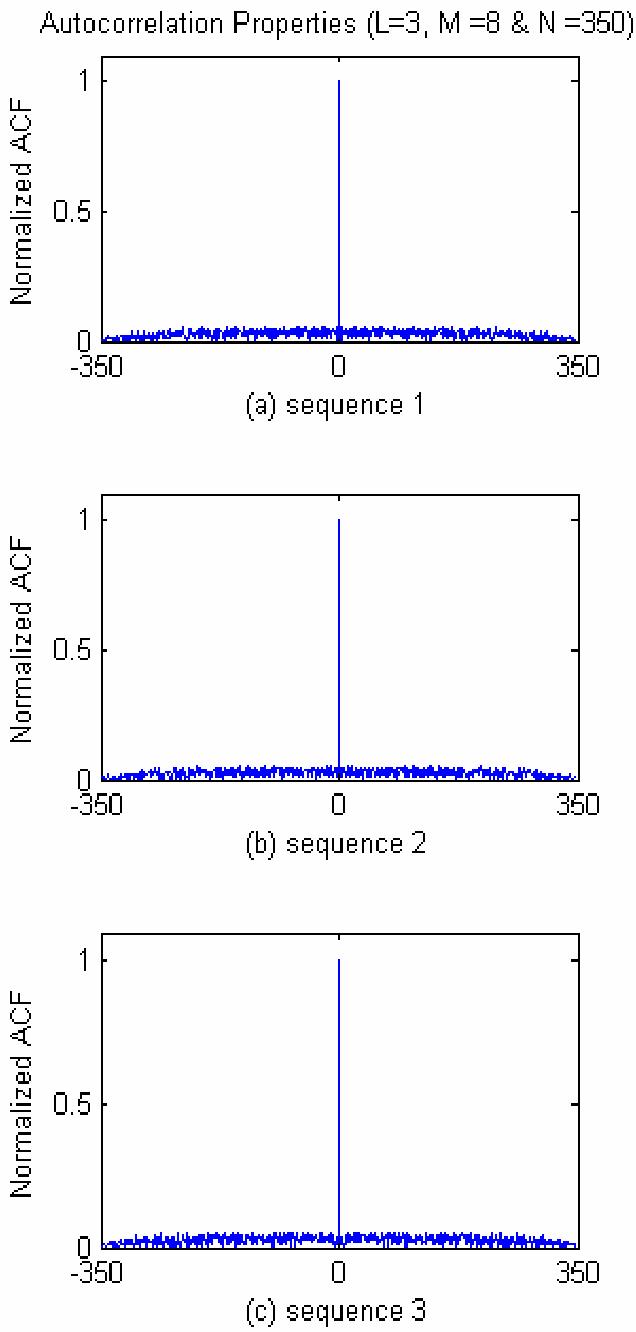


Fig.6 Normalized autocorrelation functions of (a) sequence 1, (b) sequence 2, and (c) sequence 3 of the designed 8-phase sequences of set with L = 3 and N = 350.

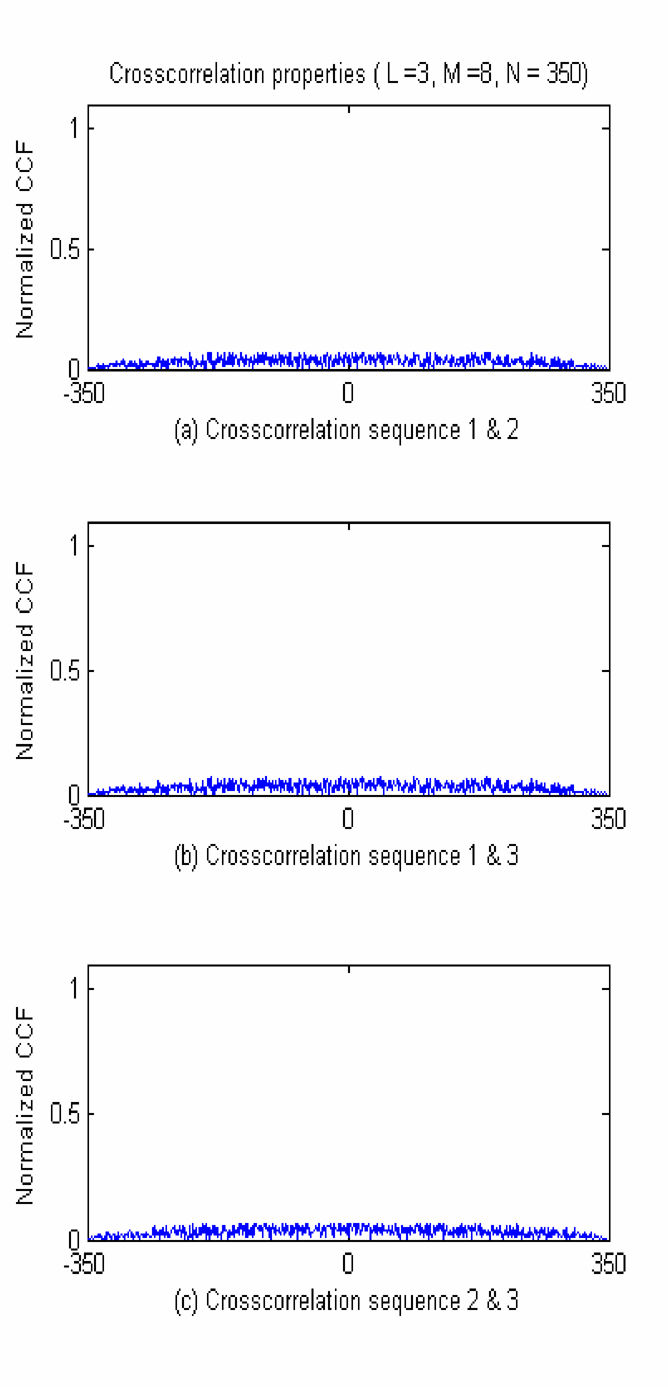


Fig. 7 Normalized crosscorrelation functions of (a) sequences 1 & 2 (b) sequences 1 & 3, and (c) sequences 2 & 3, of 8-phase designed sequences of set L = 3 and N = 350.

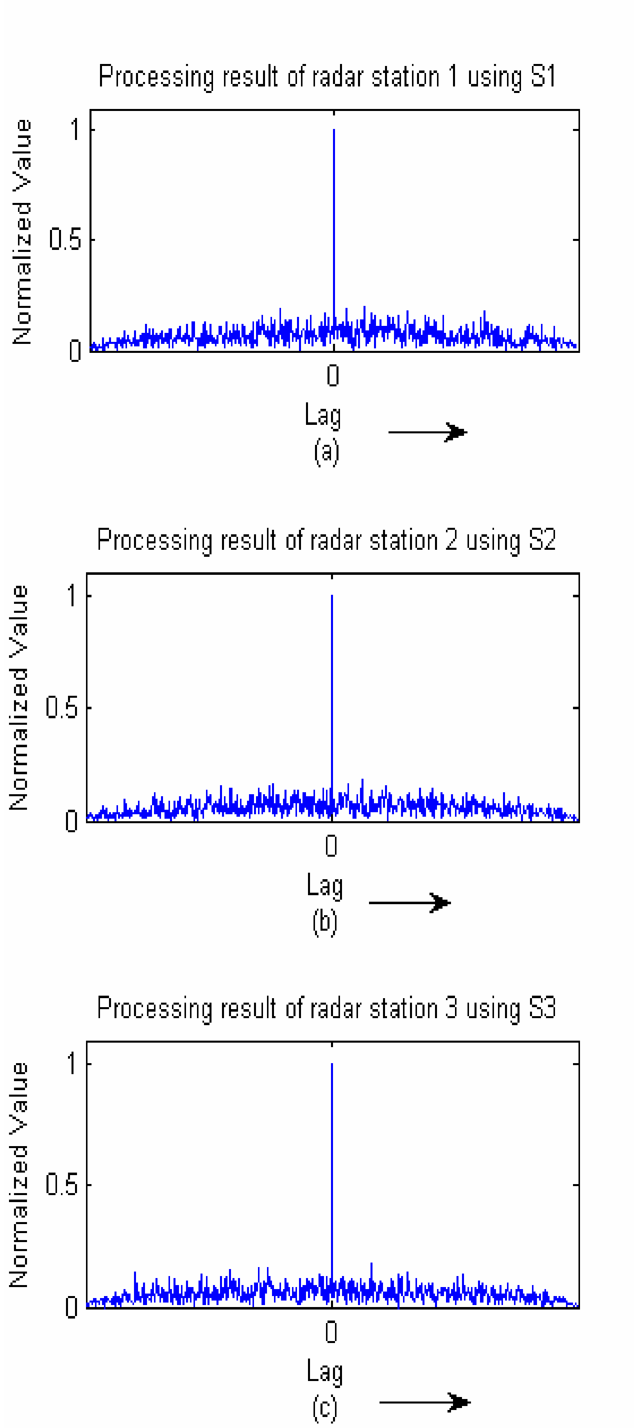


Fig. 8 Processing results of (a) Radar 1, (b) Radar 2, and (c) Radar 3 of a netted radar system that uses Sequences 1 to 3 of the designed polyphase sequences of set with L = 3, M = 8 and N = 300, as the signal, respectively.

7 - Ambiguity function and ONRS

The radar signal design is actually based on the ambiguity function and cross ambiguity function rather than autocorrelation and crosscorrelation functions. The ambiguity function of transmit waveform specifies the ability of the sensor to resolve targets as a function of delay (τ) and Doppler (ν). The ideal transmit signal would produce an ambiguity function with zero value for all non-zero delay and Doppler (i.e., a "thumbtack"), indicating that the responses from dissimilar targets are perfectly uncorrelated. It is well known that if the ambiguity function is sharply peaked about the origin, then simultaneous range and velocity resolution capability is good.

Ambiguity function $|\chi(\tau,\nu)|$ can be defined as[19]

$$|\chi(\tau,\nu)| = \left| \int_{\infty}^{\infty} \mathrm{u(t)}\, \mathrm{u}^*(\mathrm{t}-\tau)\exp(\mathrm{j}2\pi\nu t)\, \mathrm{dt} \right| \quad .. \qquad (17)$$

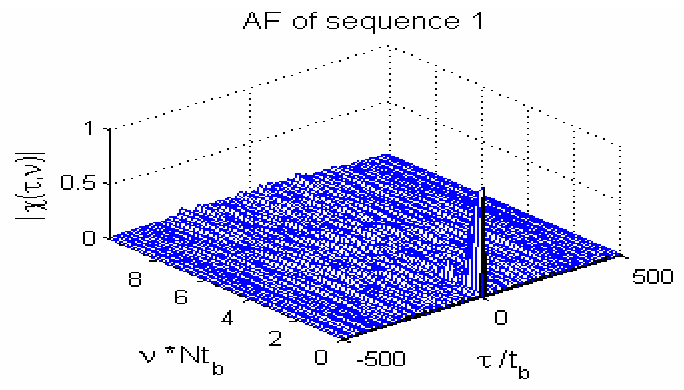
where u(t) is the transmitted signal.

Ambiguity Function has been used to assess the properties of the transmitted waveform of each ONRS as regards to its target resolution, measurement accuracy, ambiguity, and response to clutter and effect of Doppler.

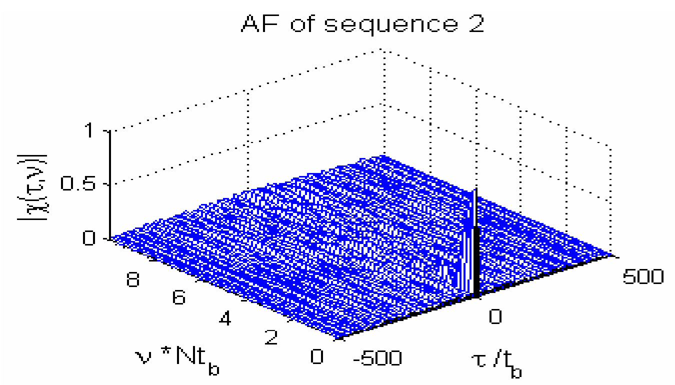
If the designed Eight- phase sequence set is applied to an ONRS with three radar stations for detection of a target, the effect of Doppler on the performance of the ONRS can be investigated using ambiguity function at the three radar stations using Sequences 1–3 (i.e, s_1-s_3) as shown in Fig. 9(a)–(c), respectively. Synthesized sequences have thumbtack ambiguity diagrams which indicate that simultaneous range and velocity resolution capability of the sequences are good.

The simulated results are achieved with assumptions that the target radar cross section (RCS) is the same for each radar station, and the distances from the target to all radar stations are identical. It is assumed that waveform is normalized to get unity height ambiguity function.

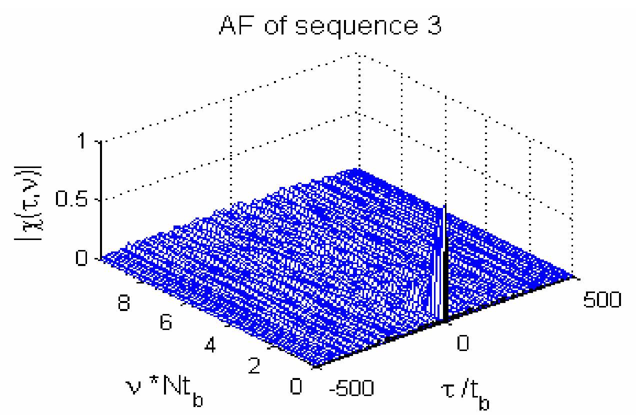
Unlike the Frank codes or the polyphase sequences which are derived from linear frequency modulation (LFM) signals (like P1, P2, & P3 codes etc)[20-22], the numerically designed eight-phase sequences have thumbtack ambiguity diagram, and thus, the matched filtering results are very sensitive to the Doppler frequency (ν) in the radar echoes due to target movement. It can be seen that the output signal amplitude is not significantly reduced (signal loss < 3 dB) if the Doppler frequency is less than 0.5/T, i.e.,



(a)

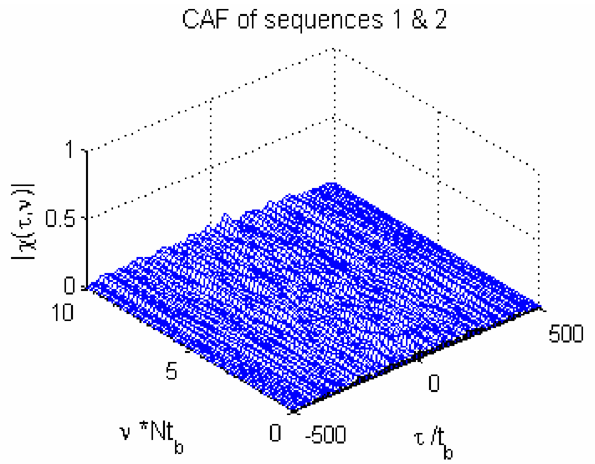


(b)

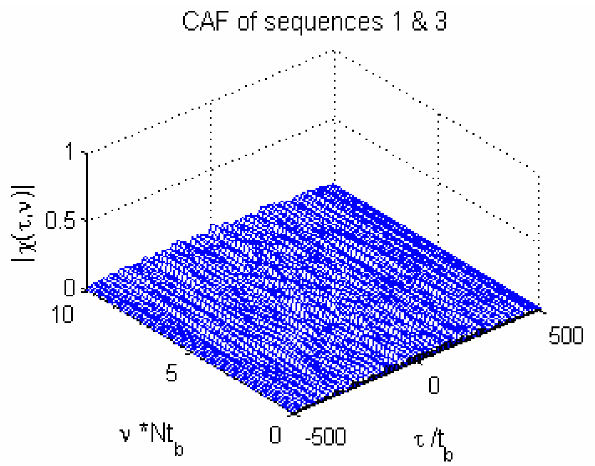


(c)

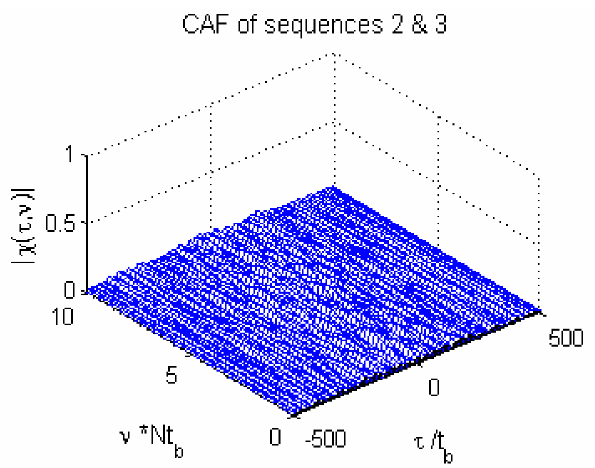
Figs. 9(a) -(c) Ambiguity Function (AF) of Sequence s_1, s_2, and s_3 respectively Sequences s_1-s_3 are the designed 8-phase coding sequences for L=3, M=8, and N = 500.



(a)



(b)



(c)

Figs 10 (a)–(c) Cross Ambiguity Function (CAF) of Sequences s_1 & s_2, s_1 & s_3, and s_2 & s_3 respectively Sequences s_1-s_3 are the designed 8-phase coding sequences for L = 3, and N = 500.

$$|\nu|T < 0.5 \quad \ldots\ldots \quad (18)$$

where T is the signal time duration equal to Nt_b, where t_b is the duration of sub pulse. Therefore, if eq (18) is satisfied, the Doppler effect on the processing result is negligible; otherwise, the correction processing must be conducted. A simple way to minimize the Doppler effect is to select the signal time duration such that eq (18) is satisfied for all expected target speeds. Another approach for overcoming the Doppler Effect is to use a bank of Doppler-matched filters for every signal. Each of the Doppler-matched filter is designed to match a different Doppler-shifted version of the signal. Target detection is based on the maximum output from the Doppler-matched filter bank. The Doppler shift frequencies and the number of the matched filters are chosen such that the signal loss is limited to a tolerable level (such as 3 dB) for all possible target speeds. The effect of Doppler on cross ambiguity diagrams for the eight phase sequences (s_1-s_3), are shown in Fig. 10(a)-(c), the cross ambiguity function of the designed eight-phase sequence set are uniformly distributed on the surface of the ambiguity diagram which indicates cross ambiguity diagram is very less sensitive to Doppler frequency shift.

8. Conclusions

An effective MSAA has been developed for the design of eight-phase code sets used in radar and spread spectrum communication for significantly improving performance of the system. This new approach includes the SAA and HSA and provides a powerful tool for the design of Orthogonal Eight-phase Sequence Sets for Radar Systems with requirements imposed on both autocorrelation and crosscorrelation functions. From the design results, it is found that for large code lengths, both average autocorrelation side lobe peak and average crosscorrelation peak approximately decrease at the rate of $1/\sqrt{N}$ with code length N. This property conforms to those of other well-known polyphase sequences designed through algebraic methods. In addition to the applications to ONRS, the orthogonal polyphase signal sets can be used by monostatic radar to counter the Coherent Repeater Jamming (CRJ) interferences [18]. CRJ retransmits a delayed radar signal to the radar receiver to interfere with the current echoes from the targets. However, if a radar continuously transmits different waveforms from an orthogonal polyphase signal set for consecutive transmitted pulses, most likely, the received jamming signal is the radar signal transmitted for one period or even a few periods earlier that will not correlate with the current matched filter. Therefore, the CRJ interference generates a near-zero output and will have very little effect on target detection. Hence we can conclude that the design results are very useful for multiple radar as well as monostatic radar systems. The effect of Doppler shift on design sequence are also investigated using ambiguity function and cross ambiguity functions. The synthesized sequence sets have correlation properties better than four-phase sequences reported in the literature.

References:

[1] S. Kirkpatrick, C. D. Gelatt, and M. P. Vecchi, "Optimization by simulated annealing," *Science,* May 1983, vol. 220, pp 671–680.

[2] S. Salcedo-Sanz, A. Portilla-Figueras, S. Jiménez-Fernández, J. A. Martínez Rojas**,** "A Hybrid Greedy-Simulated Annealing algorithm for the optimal location of controllers in wireless networks", *Proceedings of the 5th WSEAS Int. Conf. on Artificial Intelligence, Knowledge Engineering and Data Bases, Madrid, Spain,* February 15-17, 2006, pp159-164.

[3] Moharir,P.S, Singh,R.and Maru ., "S-K-H algorithm for signal design", *Electronic letter*, 18 Aug 1996, vol 32, pp1642-1649.

[4] Moharir,P.S and Maru,V.M and Singh.R, "Bi-parental Product algorithm for coded waveform design in radar", *sadhana*, Oct. 1997, vol.22, pp 589-599.

[5] S.P.Singh, and Dr K. Subba Rao, "A Modified Simulated Annealing Algorithm for Binary Coded Radar signal design" *IRSI 2005*, Bangalore, Dec 2005, pp 693-697.

[6] Singh. S.P, and K. Subba Rao., "Modified simulated Annealing Algorithm for Polyphase Code Design**",** *Proc of IEEE ISIE -06, Canada,* 09-13 July, 2006, pp 2961-2971,

[7] K. Raja Rajeswari etal "A New Sidelobe Reduction Technique", *Proceedings of the 7th WSEAS International Conference on Multimedia Systems & Signal Processing,* Hangzhou, China, April 15-17, 2007 152

[8] Jalal Jamal Hamad-Ameen, "Proposed sets of Polyphase Spreading Sequences for DS-CDMA System" , *Proceedings of the 5th WSEAS International Conference on Telecommunications and Informatics,* Istanbul, Turkey, May 27-29, 2006, pp 371-376

[9] Hideyuki Torii and Makoto Nakamura, "New ZCZ Sequence Sets Composed of Two Subsets", *Proceedings of the 6th WSEAS Int. Conference on Telecommunications And Informatics, Dallas, Texas, USA,* March 22-24, 2007, pp 1-6.

[10] José Barahona Da Fonseca, "Code Design as an Optimization Problem: from Mixed Integer Programming to a High Performance Simplified Randomized Algorithm", *Proceedings of the 5th WSEAS Int. Conf. on Artificial Intelligence, Knowledge Engineering and Data Bases, Madrid, Spain,* February 15-17, 2006 , pp 47-52.

[11] Hai Deng "Polyphase Code Design for orthogonal Netted Radar Systems" *IEEE Trans. Signal processing,* Nov 2004, vol. 52, pp 3126-3135.

[12] S. White, "Concept of scale in simulated annealing," in *Proc. IEEE Int. Conf. Computer. Design,* 1984, pp. 646–651.

[13] M. D. Huang, F. Romeo, and A. Sangiovanni-Vincentelli, "An efficient general cooling schedule for simulated annealing," in *Proc. IEEE Int. Conf. CAD*,1986, pp 381–384.

[14] E. H. L. Aarts and P. J. M.Van Laarhoven, "Statistical cooling: A general approach to combinatorial optimization problems," *Philips J. Res*., vol. 40, no. 4, 1985, pp. 193–226.

[15] Bo Liu, Zishu He, Jiankui Zeng, Benyong Liu " Polyphase orthogonal code design for MIMO radar system" *proceeding of IEEE 2006*.

[16] Nadav Levanon and Eli Mozeson '*Radar Signals' IEEE Press, John Wiley & sons, Inc Hoboken*, New Jersey, 2004.

[17] Dilip V. Sarwate " Bounds on Crosscorrelation and autocorrelation of sequences", *proceeding of IEEE,* 1963, pp 720-724.

[18] W. Melvin, R. Brown, and M.Wicks, "Effects of coherent repeater jamming on space-time adaptive radar," in *Proc. Joint Electronic Warfare Conf.*, Monterey, CA, May 1996.

[19] Nadav Levanon and Eli Mozeson 'Radar Signals' *IEEE Press, John Wiley & sons, Inc Hoboken,* New Jersey, 2004

[20] Peter Browein and Ron Fergusion, "Polyphase sequence with low autocorrelation", *IEEE Trans, Inf. Theory,* 2005, IT -51, No 4, pp1564-1567.

[21] B. L. Lewis and F. F. Kretschmer, "Linear frequency modulation derived polyphase pulse compression codes," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-18, pp. 637–641, Sept. 1982

[22] A W Rihaczek, "Principles of high resolution Radar", *McGRAW-Hill,* New York.,1969.