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Radar Signal Design for Improved Target Detection in HRR

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Abstract— *In this paper an attempt has been made to evaluate the detection ability of mono-alphabetic sequences for the application to high resolution radar in presence of high dense additive noise environment. The performance of these sequences is evaluated in terms of their noise robustness, multiple target discrimination through coincidence detection and range resolution ability. Asymptotic figure of merit of proposed serially uncorrelated mono-alphabetic sequence are determined by employing exhaustive search algorithm rather than by analytical design. Hamming back-track algorithm is designed and used for optimization. The simulation results based on the outcomes of this design algorithm for poly-semantic sequences give improved noise robustness in HRR target detection compared to conventional pulse compression sequences.*
Keywords—*Hamming Backtrack Algorithm, High Range resolution Radar, Poly-Semantic Sequences, Optimal Binary Codes, Target detection.*

I. INTRODUCTION

The inadequacy of optimal binary codes including Barker sequence for obtaining peaky autocorrelation properties with good discrimination or merit factor at larger sequence lengths can overcome by employing poly-phase alphabetic sequences [1], [2]. In poly-phase alphabetic sequence the elements are chosen such that

$$\{b_n\} \in \exp(i2\pi k / p); k = 0,1...p-1,$$

where p is the size of alphabet in the sequence. For a binary sequence; $p = 2, k = 0,1$.

The binary sequence consists of alphabet $\{b_n\} \in (-1,+1)$. When $p = 4$; then $\{b_n\} \in (1, i, -1, -i)$ results into quaternary alphabetic sequence. In principle this can be enlarged to any alphabetic sequence of alphabetic size p, but practical constraints would arise.

In poly-alphabetic radar [1] the bipolar phase coded sequence transmitted can be processed as binary sequence as received as well as four phase sequence of alphabet size *four* and an eight phase sequence of alphabet size *eight.* The transmitted binary sequence is so chosen that each of these interpretations lead to a peaky joint non-periodic autocorrelation. This facilitates an efficient implementation of coincidence detection strategy as the central peak of the auto-correlation function in three channels align while their time side lobes may not. Thus, the coincidence detection scheme reduces the degree of false alarm due to time side lobes of the autocorrelation function. The detection ability of poly-alphabetic radar improves at the larger sequence lengths [1] while maintaining the low-range side lobes. Eventually, the main purpose of the pulse compression is to raise the central peak to maximum side lobe level known as discrimination factor (D) which is defined in [3]. The discrimination factor and figure of merit (F) are monotonic function of each other. The difference between these quantitative measures of goodness is that the figure of merit also takes into the account of bit errors in the received sequence due to synchronization / decoding errors at the receiver [3]. Also, for a good pulse compression sequence the detection performance should be evaluated by considering the noise rejection at different signal to noise ratios.

Further, the earlier investigation on poly-alphabetic sequence design shows that the improved detection performance can be achieved over binary sequence at larger code lengths $N > 5200$. The work presented in [2] did not discuss about noise rejection ability of these sequences for detecting a target in noise environment conditions. Also, the enlarged alphabet obtained by multiple interpretations in terms of poly-alphabetic sequences, if theoretically accepted, it is difficult for practical implementation. The design of such sequences with enlarged number of phases at larger length is a difficult and time consuming process. Further, the question of whether or not phases can be maintained with such a precision also remains unanswered as the phase become continues variable. In order to overcome these problems poly-semantic sequences [4] with restricted alphabet were considered. It was argued that the central idea to the poly-alphabetic sequence design is poly-semantism which was achieved through poly-alphabetism. The multiple interpretations of poly-phase alphabetic sequence can even be achieved using mono-alphabetic interpretation. The work presented in this paper is an attempt to evaluate the detection ability of poly-semantic mono-alphabetic sequences for the application to high resolution radar in the presence of noise environment.

Given a complex sequence $\{b_n\}$ with $n = 0,1,...N-1$, the aperiodic autocorrelation function $\{r_k\}$ is defined as

$$r_k = \sum_{n=0}^{N-k} b_n^* b_{n+k} ; k = -(N-1)...+(N+1) \qquad ...1$$

For mono alphabetic sequence, $|b_n| = 1$ and the bi-phase sequence is represented with alphabet chosen from $\{b_n\} \in (1,-1)$. In our study, optimal binary codes (OBC) and randomly generated codes are considered to design poly-semantic mono-alphabetic sequences of larger lengths up to $N = 5200$. Problem formulation and the design algorithm of poly-semantic sequences for application in high resolution radar target detection are discussed in sec II. The rest of this paper is organized as follows. In section III, we present the detection performance of poly-semantic sequences to obtain noise rejection with respect to figure of merit for the application of high resolution radar. Conclusions are made in section IV.

II. DESIGN OF POLY-SEMANTIC SEQUENCES

Consider, optimal binary codes or randomly generated binary codes of length N, given by

$$S_1 = A = [a_i] \qquad ... 2$$

$$B = [b_i] \qquad ... 3$$

and $$C = [c_i] \qquad ... 4$$

where, $i = 0,1,2,3...N-1$.

The elements of this sequence are drawn from alphabet $\{-1,+1\}$. The sequences S_2 and S_3 are given by

$$S_2 = [a_i b_i] \qquad ... 5$$

and $$S_3 = [a_i b_i c_i] \qquad ... 6$$ where, $i = 0,1,2,3...N-1$.

A selective Hamming scan algorithm is applied on the sequences S_2 and S_3, so that the figure of merit of the sequence is optimized.

The binary sequence S_3 is transmitted as a waveform. As S_3 is interspersed by binary sequences S_1 and S_2, it is equivalent to three sequences with good autocorrelation properties being transmitted in the form of S_3. On reception, the received waveform is decoded into binary sequence (R) and the cross correlation is computed in discrete mode. The decoded sequence R is cross correlated in the receiver with three predesigned sequences, given by

$$T_1 = [a_0, 0, 0, a_1, 0, 0, a_2, 0, 0...a_{N-1}, 0, 0] \qquad ... 7$$

$$T_2 = [a_0, b_0, 0, a_1, b_1, 0, a_2, b_2, 0...a_{N-1}, b_{N-1}, 0] \qquad ...8$$

$$T_3 = S_3 = [a_0, b_0, c_0, a_1, b_1, c_1, a_2, b_2, c_2...a_{N-1}, b_{N-1}, c_{N-1}] \qquad ... 9$$

The Hamming scan algorithm is applied on T_1, T_2 and T_3 for optimizing the joint asymptotic figure of merit F of the cross correlated of sequences S_3 & T_1, S_3 & T_2 and S_3 & T_3. The good figure of merit properties of these three interpretations are jointly used through coincidence detection for the detection of target.

The poly-semantic radar signal in which the received binary sequence R is cross correlated with three embedded sequences T_1, T_2 and T_3 (or S_3) in three channels separately. The three cross correlation peaks in three channels are coinciding, which simultaneously indicates the presence of the target. It is also interesting to observe from the results obtained in sec. III that the time sidelobes in three channels do not align. This in turn reduces the degree of false alarm because of time sidelobes in the return signal.

A. Measure of detectability and figure of merit of PSS:

The figure of merit is defined [3] as,

$$F^{(m)} = \frac{\overline{C^{(m)}(0)} - \max_{k \neq 0} \overline{C^{(m)}(k)}}{\overline{C^{(m)}(0)}} \qquad \ldots 9$$

Here 'm' represents the number of bit errors obtained in the sequence. Thus, the figure of merit is defined in this context, when known number decoding errors are added in the detected signal. It is assume that distortion due to propagation delay is ignored. Also, the additive noise is independent with transmitted signal. But in real time situation, the received signal R is corrupted by additive noise with unknown noise strength. If the additive noise exceeds the threshold level, the received sequence is not true replica of transmitted signal. The resulting signal at the output of the detector will undergo any number of bit errors. Then the optimal waveform design problem is solved by redefining the measure of performance in Eq. (9) by taking into the effect of additive noise at any given signal to noise ratio η as discussed in Sec. III. The over head bars in Eq. (9) denote the averaging over the ensemble of R. In this study we have considered the ensemble of R has 100 runs of additive noise signals with transmitted sequence in order to obtain more accurate performance. The return signal R is triply processed to exploit the goodness at three different stages of construction. The criterion of goodness, which is used for design, takes into account the interaction of the three interleaved sequences T_1, T_2 and T_3.

B. Hamming backtrack algorithm for mono-alphabetic PSS:

The Hamming scan algorithm has been applied successfully to design of poly-alphabetic [1] and Bi-alphabetic [5] sequences with good aperiodic autocorrelation properties. To determine the poly-semantic mono-alphabetic sequences with low autocorrelation sidelobes, a modified Hamming scan algorithm known as Hamming backtrack algorithm is developed in the present study.

The Hamming backtrack scan algorithm starts with the binary sequence S_3 and derives three sequences T_1, T_2 and T_3 for finding the asymptotic figure of merit F_1, F_2 and F_3. The F_1, F_2 and F_3 are obtained by cross correlation of the sequences S_3 & T_1, S_3 & T_2 and S_3 & T_3 respectively. The asymptotic figure of merit is monotonic function of discrimination D of the correlated function of the given sequence. The mono-alphabetic poly-semantic Hamming scan induces mutations in the elements of S_3, Viz., + → -, - → + and looks at the first order Hamming neighbours of all the elements in the sequences. A mutation in the element of S_3, in turn induces mutation in the corresponding element of the sequences T_1, T_2 and T_3. The algorithm computes the sum of asymptotic figure of merit F_1, F_2 and F_3 of all the first order Hamming neighbours of S_3 and picks up the mono-alphabetic sequence which results in largest value of $F = (F_1 + F_2 + F_3)/3$. The autocorrelation due to each perturbation of the binary sequence is calculated merely taking into account the changes required in the original autocorrelation instead of calculating the aperiodic autocorrelation of the Hamming neighbour *ab initio*. This expedites the process of mono-alphabetic Hamming scan algorithm. Table.1 gives the figure of merit of poly-semantic sequences of length, N=585 to 5100. These results provide evidence that the figure of merit is high at larger lengths and become stable as length increases further.

TABLE I
Figure of merit and discrimination for poly-semantic sequences

Sequence Length N	Figure of Merit (F)	Discrimination in dB (D)
585	0.9368	23.9791
633	0.9400	24.4324
825	0.9479	25.6597
1071	0.9486	25.7885
1173	0.9497	25.9689
1377	0.9528	26.5204
1575	0.9600	27.9588
2250	0.9613	28.2533
3159	0.9655	29.2425
3645	0.9668	29.5782
4092	0.9663	29.4411

4293	0.9695	30.3098
4743	0.9694	30.2937
4890	0.9701	30.4991
5100	0.9694	30.2889

III. Performance Evaluation of PSS

To evaluate the noise performance, the poly-semantic sequences, which are perturbed by Gaussian noise at different SNR, are considered as input sequence. Fig. 1 gives the measure of detectability of poly-semantic sequences when the echo is received from a single target at different SNR (η). For range resolution ability, consider a target model when a dispersed echo is reflected from two targets located at sub-pulse delay apart (SPDA) of zero to $(N-1)$. Fig. 2 gives the coincidence detection of poly-semantic sequences due to single target with η = -15 dB. Fig. 3 (a) shows the output waveforms of poly-semantic sequences when two targets are at 50 SPDA and η = -15 dB. The targets can be detected even if the SNR falls to -30dB as shown in Fig. 3 (b). This is not possible with conventional sequences. Simulation results show that for HRR systems, poly semantic sequences show better noise robustness when compared to conventional binary sequences [02].

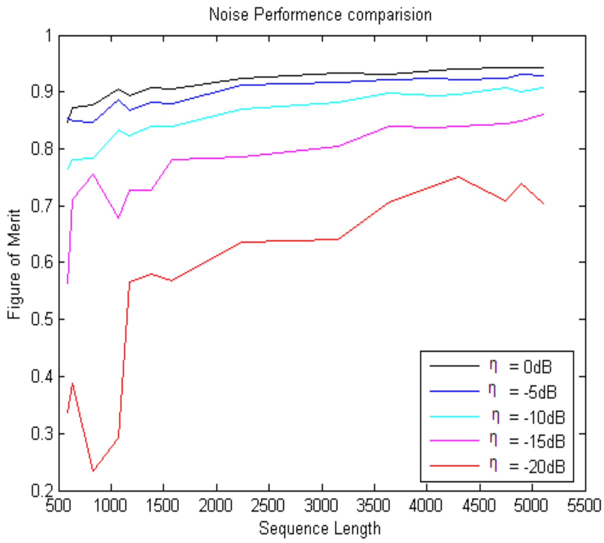


Fig. 1 Noise performance of poly semantic signal

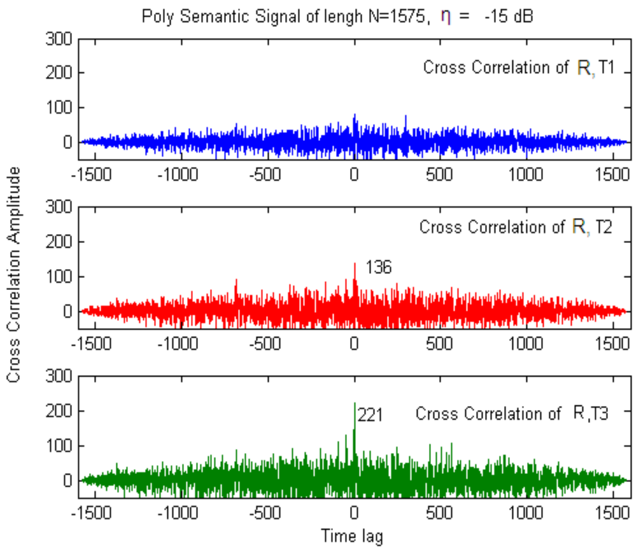
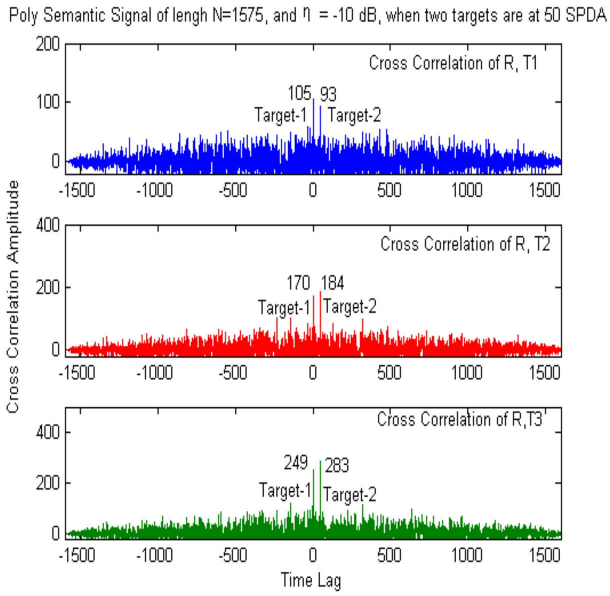
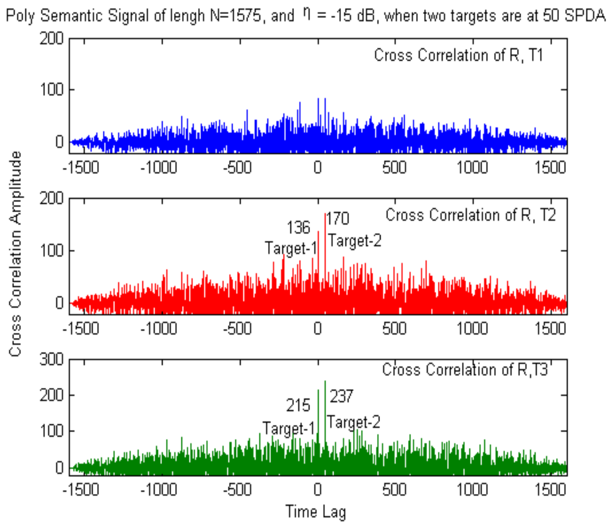


Fig.2 Coincidence detection of the poly-semantic sequence at length N=1575 at η = -15 dB for single target



(A)



(B)

Fig.3 Coincidence detection of the poly-semantic sequence at length N=1575 (a) when η = 0 dB and (c) η = -15 dB

IV. CONCLUSIONS

The signal design problem for high resolution radar systems is solved by the notion of poly-semantic sequences which are generated and transmitted with the existing transmission technology. In this paper poly-semantic sequences (PSS) are analyzed for the detection of multiple target in high density additive noise environment for the application of high resolution radar system. The poly-semantic sequences are optimized by using Hamming backtrack algorithm. The received signal is subjected cross-correlation with reference poly-semantic sequences T_1, T_2 and T_3. The transmitted binary sequence is optimized such that each of the poly-semantic interpretations lead to maximum discrimination/figure of merit. These sequences are processed separately to setup a coincidence detection scheme. Table.1 shows that the discrimination and figure of merit values of PSS at larger lengths, N > 500 in noise free environment. These results provide the evidence that the PSS with larger pulse compression ratios can achieve the range side lobe level below 14.78 dB. This is significance improvement over conventional pulse compression sequences [4] and poly-phase alphabetic sequences [2], which provide side lobe level of 13.42 dB at length N >1638 under noise free environment. The simulation results indicate that the multiple target detection using mono-alphabetic poly-semantic sequences could be achieved in high dense noise condition up to SNR of -15 dB when two targets are at 50 SPDA with coincidence detection (Fig. 5). This advantage arises because when the binary sequence is designed using 2nd order HBT algorithm, it performs recursive search such that the multiple interpretations of PSS of larger length reinforce each other through matched filtering and coincidence detection. These results show improved noise robustness in HRR target detection which is achieved by coincidence detection when compared to conventional poly-alphabetic sequences [2].

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