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Poly-semantic Coded Waveform Analysis for High Resolution Doppler Radar

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Abstract— *Superiority of poly-alphabetic sequences (PAS) for pulse compression radar over the binary and ternary sequences was established earlier. However, the enlarged alphabets in poly–alphabetic sequences deteriorate the noise and Doppler robustness at higher lengths in High Resolution Radar (HRR) systems. In this paper, poly-semantic sequences (PSS) with restricted alphabets {+1,-1} are considered and their performance is analyzed in order to achieve superior detection performance for high resolution Doppler radar system in presence of high density additive noise and Doppler shift. The poly-semantic sequences are optimized by employing modified Hamming scan algorithm called Hamming Backtrack algorithm (HBT) by taking figure of merit as the measure of goodness. The detection capability of poly-semantic sequences is further improved through coincidence detection of the return signal. The simulation results show that the proposed sequences give improved robustness of noise and Doppler shift for HRR target detection compared to conventional pulse compression sequences.*

I. INTRODUCTION

In high resolution radar (HRR) systems, there is a need to employ sequences of larger lengths to achieve high pulse compression ratios. Optimal binary codes (OBC) including Barker code and Golay codes provide significant advantages in terms of detection and sidelobe suppression [1], but these codes are available at lower lengths less than 60. The reported largest value of discrimination (D) is +22.27 dB, which is obtained in case of Barker; B13code [2], [3]. Earlier, the generation of optimal sequences at higher lengths up to 5000 is developed for poly-alphabetic sequences (PAS) [4], [5]. Here a binary sequence is transmitted, but through poly-gram reading, it can also be interpreted as quaternary and octal sequences. Thus, it is as if one sequence is physically transmitted, but three sequences are notionally transmitted and received. They can therefore be processes separately at the receiver to set up coincidence detection. A bigram viewed as a quaternary element or a trigram viewed as an octal element is some what of a constrained concept. Quaternary and octal elements as independent entities would have 3 and 7 first order Hamming neighbors but bigrams and trigrams on the substratum of binary monograms, which undergo Hamming scan, have only two and three first order Hamming neighbors. Thus the higher order poly-gram interpretations have a disadvantage in Hamming scan.

In order to overcome this drawback and to restrict the enlarged alphabets of poly- alphabetic sequence to binary, the poly-semantic sequences are proposed [6]. These sequences are mono-alphabetic nature of poly alphabetic sequences. The detection performance of the detected signal in presence of additive noise and Doppler shift will be evaluated in terms of figure of merit.
The figure of merit is defined [7] as,

$$F^{(m)} = \frac{\overline{C^{(m)}(0)} - \max\limits_{k \neq 0} \overline{C^{(m)}(k)}}{\overline{C^{(m)}(0)}} \qquad (1)$$

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 is corrupted by additive noise with unknown noise strength. If the additive noise exceeds the threshold level (at the detector), the receive 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. (1) by taking into the effect of additive noise at any given signal to noise ratio η as discussed in Sec. II.

II. DESIGN ALGORITHM & ASSOCIATED CONCEPTS

The concept of mono-alphabetic poly-semanticism [7] is similar to adaptation of the self-cooperative sequences. A binary sequence S with good autocorrelation properties is designed. It is doubled in length by interleaving another binary sequence whose elements are so chosen that enlarged sequence is good. Yet another sequence is interleaved to triple the length and the elements of former are so chosen that the new enlarged sequence has good autocorrelation.

Let, $$S = [s_0, s_1, s_2, ..., s_{N-1}] \quad (2)$$
be a transmitted signal of length N,

$$R = [r_0, r_1, r_2, ..., r_{N-1}] \quad (3)$$

is received signal. Here, R =S+W; where W is the additive noise signal at given η. Now, Eq. 1 is redefined as

$$F_\eta = \frac{\overline{C_\eta(0)} - \max\limits_{k \neq 0} \overline{C_\eta(k)}}{\overline{C_\eta(0)}} \quad (4)$$

where, F_η is the figures of merit at given η and the cross correlation between S&R at given η is

$$c_\eta(k) = \sum_{i=0}^{N-1-k} s_i r_{i+k}, \; k = 0,1,2,...,N-1 \quad (5)$$

Also, $$F_\eta = 1 - \frac{\max\limits_{k \neq 0} \overline{C_\eta(k)}}{\overline{C_\eta(0)}} \quad \text{Or} \quad F_\eta = 1 - \frac{1}{D_\eta} \quad (6)$$

Where, $$D_\eta = \frac{\overline{C_\eta(0)}}{\max\limits_{k \neq 0} \overline{C_\eta(k)}} \quad (7)$$

is the discrimination at η.

The over head bars in Eq. 4 & 6 denote the averaging over the ensemble of R. We have considered the ensemble of R has 100 runs of additive noise signals with transmitted sequence in order to obtain more accurate performance. Here, F is a monotone function of D as in Eq. 6. When D goes to infinity, F becomes unity. The range of F is from 0 to 1, making the F a non-euphuistic measure.

In the detection process by employing coincidence detection, 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.

A. Hamming Backtrack (HBT) Algorithm for PSS

To obtain high goodness of performance measure, the poly-semantic sequences should undergo Hamming scan [4] by considering figure of merit as desideratum. The Hamming scan algorithm may not perform recursive search among all these Hamming neighbors and results in suboptimal solution to the signal design problem. When poly-semantic Hamming scan yields no sequence with a figure of merit better than the previous sequence, the backtracking Hamming scan algorithm can be employed to improve further the objective function of the resulting sequence. It considers a prescribed number n called span of the best Hamming neighbors (though they are all inferior to starting sequence) and improves them separately by repeated recursive Hamming scan, say c times (called climb). If some sequences superior to the starting poly-semantic sequence results the best among them is selected. A span of n=6 and a climb of 2 is used in the proposed algorithm. If the Hamming backtracking succeeds in improving the figure of merit, the search can resume by further application of poly-semantic Hamming scan.

B. Phase reversal effect due to Doppler shift:

Another advantage of poly-semantic sequences is due to its bi-phase mono-alphabetic nature. The bit error due to Doppler frequency occurs when the phase shift of the pulse exceeds $\pm\pi/2$ unlike the poly phase sequences which results into a bit error for phase shift exceeds $\pm\pi/M$, where M indicates the number of phase levels in the sequence. Fig. 1(a) shows the range of phase shift without bit errors for bi-phase sequences (M=2) and Fig. 1(b) for poly-phase sequences with M = 4.

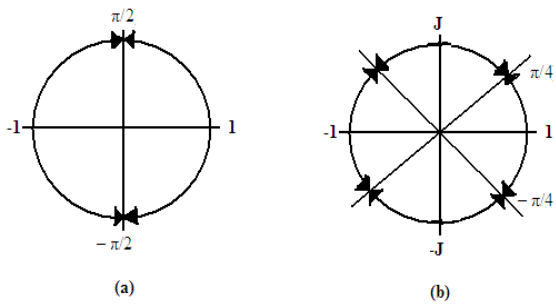


Fig.1 Range of phase shift without bit errors (a) for bi-phase sequences (M=2) (b) poly-phase sequences with M = 4.

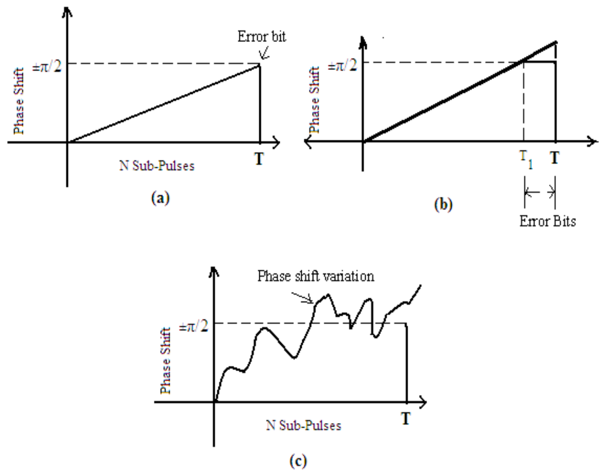


Fig.2 Doppler phase shift on received bi-phase sequences (a) when phase shift is equal to $\pm\pi/2$ (b) when phase shift is greater than $\pm\pi/2$ (c) when additive noise is added along with Doppler phase shift.

In noise free environments, the phase shift due to Doppler added to the sub-pulses is monotonic function as required for goodness of measure. In poly-semantic sequences of length N, the maximum phase shift allowed on each sub-pulse without bit errors is less than $\pm\pi/2N$ in a duration of ($\tau = T/N$ sec). Where as in poly-phase sequences the maximum allowable phase shift is less than $\pm\pi/MN$ without bit errors. Therefore the poly-semantic sequences have M/2 times more Doppler tolerance when compared to poly phase sequences.

In poly-semantic sequences, when the phase shift is equal to $\pm\pi/2$, the last sub-pulse in the sequence takes phase reversal. So the last bit becomes error as shown in Fig.2 (a). If the phase shift exceeds $\pm\pi/2$, as shown in Fig.2 (b) for the corresponding bits from time T_1 to T (where $T_1 < T$), the bits become errors.

III. IMPROVED FIGURES OF MERIT OF PSS AT LARGER LENGTHS

Generally the figure of merit of any sequence deteriorates as the noise strength increases and has individual performance deterioration pattern. That is the rate of deterioration can also vary from sequence to sequence. Thus, a sequence with superior performance at low noise levels could have a faster rate of deterioration than another sequence which has inferior performance at low noise levels coupled with slower rate of deterioration. Under such situations, the ranking of sequences may be different at different noise levels [7], [8]. This situation becomes worse when the Doppler shift is also added to the return signal in addition to noise. But, for poly-semantic sequences the rate of deterioration in figure of merit remains uniform with respect to increase in noise and Doppler shift. The Figure of merit of the poly-semantic sequence depends on the Hamming neighborhood of the transmitted signal so that the received signal is allowed to be anywhere in that neighborhood. Since the poly-semantic sequences are optimized with HBT algorithm, at higher sequence lengths as the size of the neighborhood increases, we can achieve better noise and Doppler performance in terms of figures of merit. Table (1) gives the figures of merit of poly-semantic sequences of length, N = 585 to 5100. These results provide evidence that the figure of merit is high at lager lengths and become stable as length increases further.

IV. SIMULATION RESULTS AND PERFORMANCE EVALUATION

A. Noise Robustness

When the PSS is perturbed by additive noise of different strengths, the noise effect on figures of merit at different sequence lengths is shown in Fig. 3. The noise performance is examined for different values of η ranging between 0 dB to -20 dB. The noise performance results clearly show that the PSS exhibits high noise robustness at the higher sequence lengths.

TABLE.1

Figures 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

B. Doppler Tolerance

As explained in Sec. II, when the target is in constant motion, a linear phase shift given by $d\phi = \sigma\pi / N$, where $0 < \sigma \leq 1$ proportional to velocity will be added on to the received decoded sequences. The performance of poly-semantic sequences in terms of figure of merit without additive noise is shown in the Fig. 4 at different Doppler phase shifts (DS) in the interval of [0.4π/N, 0.8π/N] per sub-pulse. It is observed from the figure that as Doppler shift is increasing above 0.5π/N, the performance of figure of merit deteriorates.

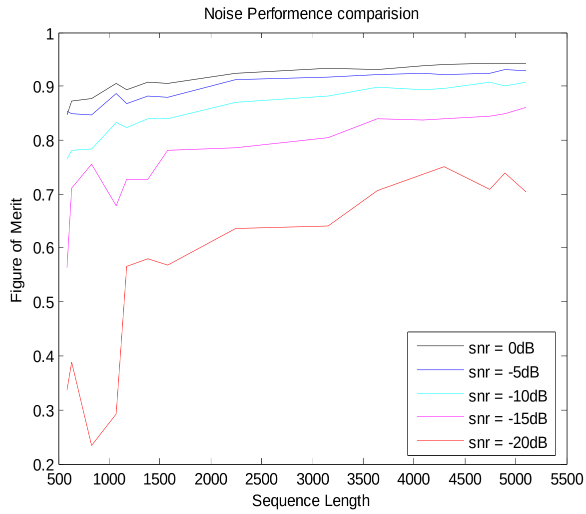


Fig. 3 Noise performance of poly semantic sequences

If the Doppler phase shift increases to 0.8π/N, figure of merit falls below 0.3, the information due to target will be masked and it is not possible to identify the target. Thus the sequences have Doppler tolerance up to 0.7π/N with corresponding figure of merit of 0.3.

C. Combined effect of noise and Doppler shift

When the signal encounters the effect of both additive noise and Doppler shift due to moving target, the phase shift variation in the received signal becomes non-monotonic function as shown in Fig 2(c). In such a case due to joint effect, some of the sub-pulses (randomly) in the sequences may have phase shift more than 0.5π/N. At threshold detection these sub-pulses undergo phase reversal. The number of such erroneous sub-pulses in the received signal increase, the performance of figure of merit decreases. This results into deterioration in the performance of detection. For example, consider the poly-semantic sequences with length N=500 to 5000 at SNR= 0 dB and varying Doppler shift in the interval of [0.4π/N, 0.8π/N]. Fig. 5 gives the figure of merit of PSS sequences at different lengths.

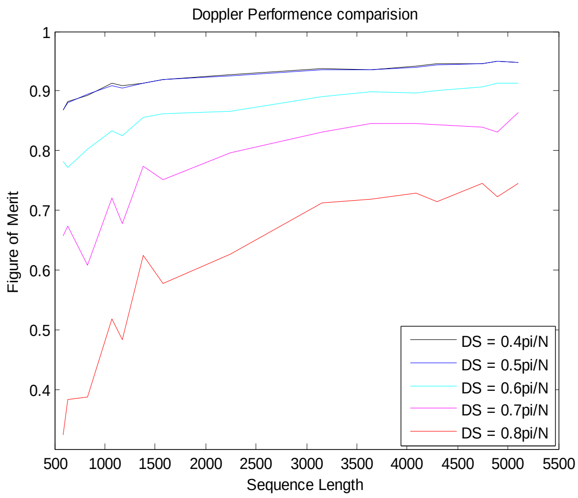


Fig.4 Doppler performance of poly-semantic sequences

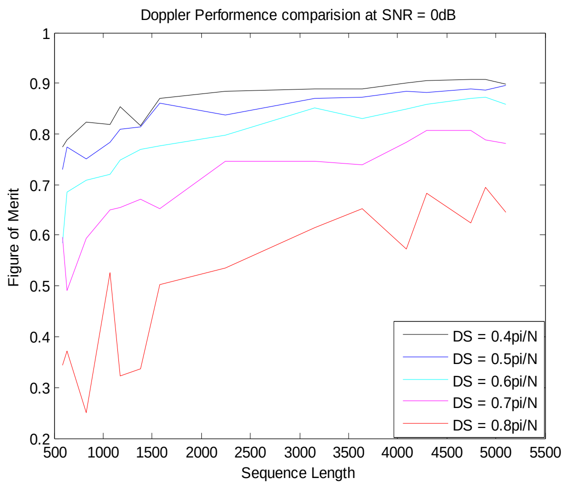


Fig. 5 Noise and Doppler performance of poly semantic sequences at different Doppler phase shifts (DS) and fixed SNR of 0 DB.

Also, Fig. 6 shows at fixed Doppler shift of 0.45π/N and varying SNR. It is observed that the sequences exhibits more Doppler tolerance at higher length when compared to lower length since the phase variation per bit is small at higher lengths.

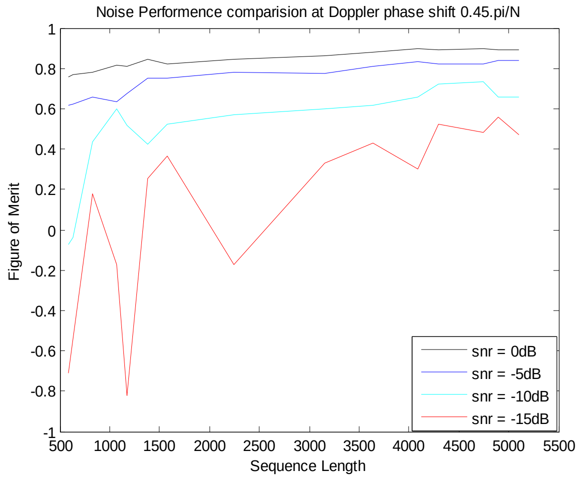
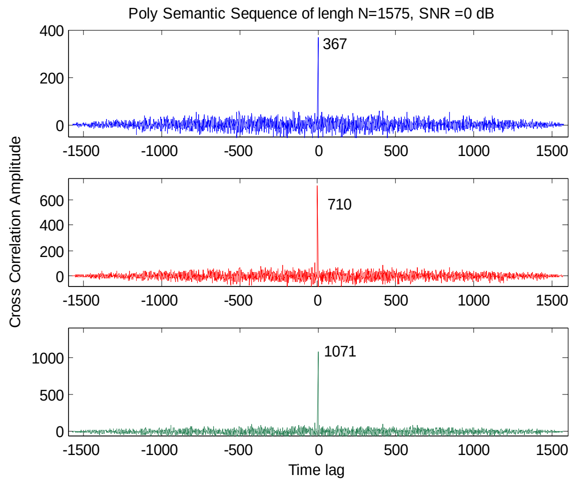


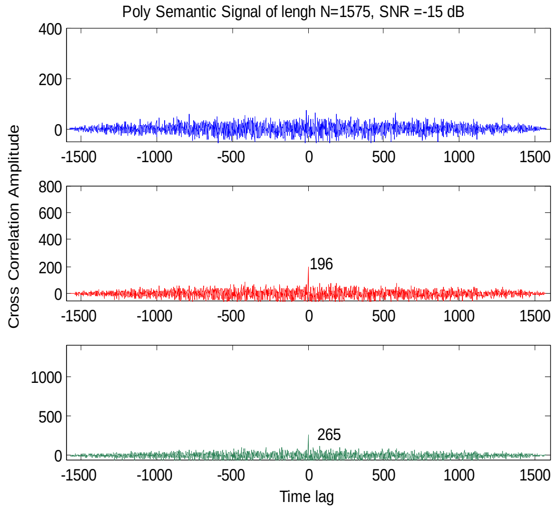
Fig. 6 Noise and Doppler performance of poly-semantic sequences at different noise levels of SNR and fixed Doppler phase shift of 0.45π/N.

D.Detection performance

To estimate the target detection performance, we consider a poly-semantic sequence of length N=1575 with η = 0 dB. The return signal R in noise environment is triply processed at three different stages of its construction. The resulting coincidence detection is shown in Fig. 7(a). When η decreases below 0 dB, the rate at which figure of merit deteriorates increases. It is observed from Fig.7 (b), when η = -15dB, the main lobe peak at zero lag in the first display is completely masked due to high dense noise.



(a)



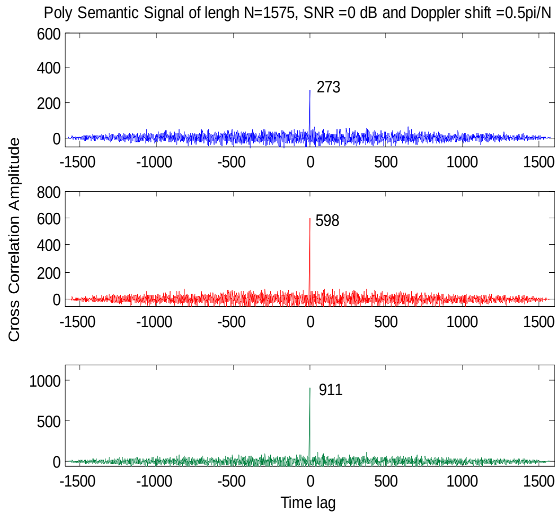
(b)

Fig.7 coincidence detection of the poly-semantic sequence at length N=1575 (a) when SNR = 0 dB and (b) SNR = -15 dB

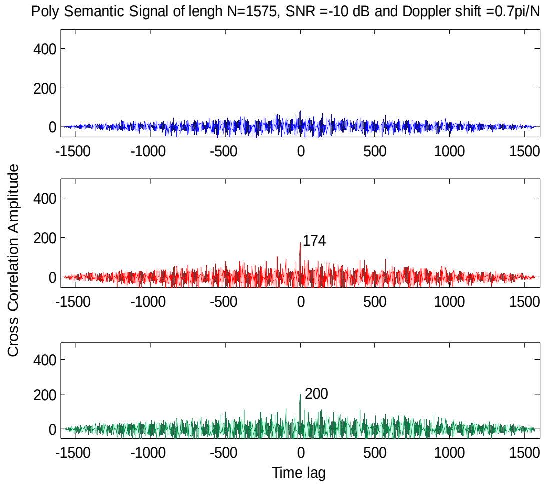
It is still possible to detect the target from the coincidence peaks of second and third display channels. The joint coincidence of autocorrelation peaks simultaneously in different channels indicates the presence of target. It is also interesting to observe that the surrounding side lobes will not align or synchronize in three channels. This eliminates the possibility of false target detection due to time side lobes. The figures of merits values corresponding to three detection stages in Fig. 7(b) are 0.0685, 0.2973 and 0.5314 respectively. When η exceeds -15dB, the target detection becomes very critical.

Again consider the sequences of N=1575. When both noise and Doppler effects are present, the coincidence detection is shown in Fig. 8(a) when SNR = 0 dB, Doppler shift 0.45pi/N and 8(b) SNR = -15 dB, Doppler shift $0.7\pi/N$.

It is observed that when the Doppler shift is greater than SNR = -15 dB, Doppler shift $0.7\pi/N$ the target detection becomes difficult. The figures of merit for three stages of coincidence detection are 0.1013, 0.3908, and 0.3166 respectively.



(a)



(b)

Fig.8 coincidence detection of the poly-semantic sequence at length N=1575 (a) when SNR = 0 dB , Doppler shift 0.45π/N and (b) SNR = -10 dB, Doppler shift 0.7π/N

V. CONCLUSIONS

In this paper poly-semantic sequences (PSS) are analyzed for the detection of point target in high density additive noise and Doppler environment for the application of high resolution Doppler radar system. 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 30 dB. The noise performance comparison result of the proposed HBT algorithm with η ranges between 0 dB and -20dB for PSS of various lengths is shown in Fig. 3, and the performance comparisons on figure of merit with the noise and Doppler shift are shown in Fig. (4)&(6). These results clearly indicate that the PSS have superior noise rejection and Doppler tolerance when η is below -20 dB at larger lengths above 3700. 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. Another important advantage of PSS is that their detection ability is further improved in noise free or noisy environment through coincidence detection scheme. The poly-semantic sequences at higher lengths with coincidence detection has noise tolerance of SNR= -15dB. While compared with poly phase sequences, poly semantic sequences has achieved better noise rejection ability, higher range resolution and superior Doppler tolerance. These examining results lead PSS to be very suitable for the high resolution Doppler radar systems. However, these advantages will be achieved with an additional affordable signal processing at the receiver.

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