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An Overview of Coherent and Non-coherent Pulse Compression Waveforms

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ABSTRACT: One central issue in the design of radar waveform is its capability to resolve two closely spaced small targets, which are located at long range. In this context the most promising technique that is used by modern radar systems is pulse compression. This technique combines the advantages of energy associated with long pulse-width and range-resolution corresponding to a short duration pulse. The matched filter used in receiver accumulates the received energy in to a short pulse. This paper presents an overview of the aperiodic and periodic phase coded waveforms for Coherent and Non- Coherent Pulse Compression radar systems.

Keywords: Autocorrelation, Cross-correlation, matched filter, pulse compression, range-resolution.

I. INTRODUCTION

Woodward's [1] studies play significant role in the context of radar signal design. The basic concept of his presentations is to achieve energy requirement for detection of a target at long ranges, a wide pulse can be transmitted. after meeting the detection requirements, the high range-resolution conditions are simply achieved by modulating or coding the transmitted pulse. This new technological development in the field of radar waveform design is known as pulse compression technique [2-5]. Two widely used modulation or coding techniques are either frequency modulation or phase modulation. Under the frequency modulation technique, Linear Frequency Modulation (LFM), stepped LFM, Non-linear FM (NLFM), discrete frequency shift (time-frequency coding) waveforms are considered whereas phase coding includes biphase (Barker codes, compound Barker codes etc.) and polyphase codes (Frank codes, P1, P2, P3, P4 codes etc.) [3, 6, 7]. Generally, biphase code modulation is more preferable in pulse compression radars because of its simplicity in generation and needs less signal processing in the receiver. Two basic pulse compression techniques are Coherent Pulse Compression (CPC) and Non-coherent Pulse Compression (NCPC). This paper presents the waveforms that can be used in coherent and non-coherent radar systems for enhancing the detection and resolution capabilities.

II. PHASE CODED PULSE COMPRESSION WAVEFORMS

In phase-coding technique, the duration of the pulse 'τ' is considered as a connecting set of N subpulses or chips of duration $T = \tau/N$, and the phase of each subpulse is chosen either 0^0 or 180°. The transmitted frequency of each chip remains constant but the phase of each subpulse is switched between 0° or 180° based on some predetermined values. That is, each pulse of such waveform has a 100% duty cycle. The correlated compressed pulse is achieved at the output of matched filter used in radar receivers. In phase coded signals, the pulse compression ratio is N, where N is the number of subpulses ($N = \tau/T$), which is approximately equal to $B\tau$, where $B \approx 1/T$. The output of the matched filter will have a narrow peak (mainlobe), whose magnitude is N times that of the magnitude of long received pulse, and mainlobe width will be equal to time duration of single chip 'T'. The remaining portions of the matched filter output that extend over $-\tau$ to τ, are referred as "*sidelobes*". When such waveforms are used in radar applications for the detection of small targets, the sidelobes must be low. In other words, the main parameter for the aptness of sequences is low peak sidelobes (PSL) at the output of matched filter. Fig. 1 shows the correlated output of Barker code of length 13. This is an example of coherent pulse compression. In case of CPC, the received signal is time delayed version of transmitted signal and matched filter output is referred as autocorrelation function.

III. NON-COHERENT PULSE COMPRESSION

Non-coherent pulse compression (NCPC) is a new variant of pulse compression and was suggested by N. Levanon [8-10] and some of the advantages of non-coherent pulse compression technique are discussed in [11]. The basic idea of NCPC is to apply the pulse compression technique to non-coherent radars and radar like systems such as lidar, where transmitted signal is in the form of on-off {1, 0} and referred as on-off keying (OOK) signal. Fig. 2 shows the receiver block diagram of non-coherent pulse compression technique. The reference signal is the two-valued sequence $\{1, -\beta\}$ which is derived from the transmitted signal.

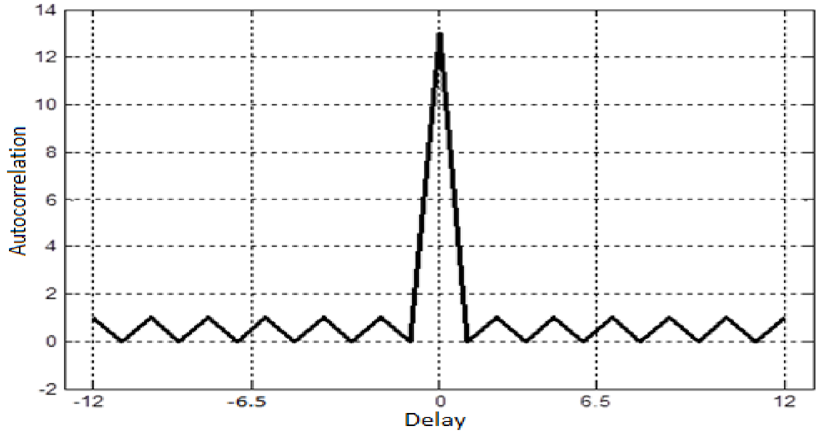

Fig. 1. Autocorrelation function of Barker code N =13.

N **= [1 1 1 1 1 -1 -1 1 1 -1 1 -1 1]**

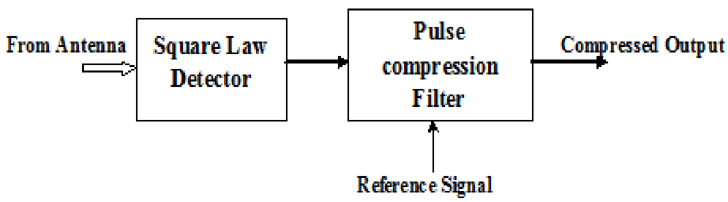

Fig. 2. Block Diagram of Non-Coherent Pulse Compression Receiver.

The simplest way of generating the on-off keying (OOK) signals are based on Manchester-coded binary sequences (e.g., Barker, MPSL etc.). The procedure of generating a Manchester-coded waveform from Barker code is (1 → 10, 0 → 01) and Barker sequence of length 13 becomes 26. Therefore, the transmitted signal is sequence ***a,*** of length N=26, which is given in (1) is a Manchester-coded Barker sequence. Sequence ***b*** is the reference sequence given in (2), which is derived from the sequence ***a***, by replacing '0' with '-1' that is β value in this case is 1. The output of the mismatch filter is cross-correlated and shown in Fig. 3. The mismatch filter output is given by (3).

a = [1 0 1 0 1 0 1 0 1 0 0 1 0 1 1 0 1 0 0 1 1 0 0 1 1 0] (1)

b = [1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1]. (2)

$$\sum_{k=1}^{N} |a_k|^2 \, b_k \tag{3}$$

Where $\boldsymbol{a}_k$ and $\boldsymbol{b}_k$ are the elements of ***a*** and ***b*** respectively given in equations (1) & (2).

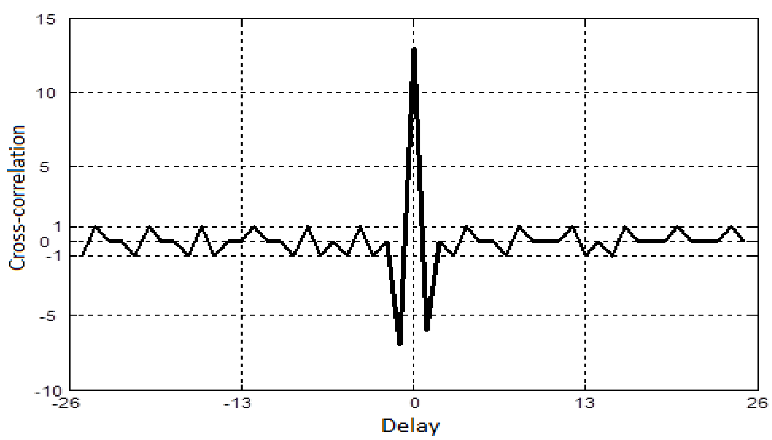

Fig. 3. Cross-correlation of the transmitted and reference signals, Barker Manchester code **N=26**

a= [1 0 1 0 1 0 1 0 1 0 0 1 0 1 1 0 1 0 0 1 1 0 0 1 1 0]

b= [1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1]

IV. PRN CODED WAVEFORMS

It is well known that Barker codes exhibit lowest aperiodic autocorrelation peak sidelobe equal to 1, but do not exist for the lengths greater than 13. Another type of biphase sequences that can be generated for large lengths are pseudo-random-noise (PRN) or M-sequences. The name derived from the fact that the algorithm used to generate the 0° and 180° phase shifts is also used to generate pseudo random numbers. PRN waveforms widely used in spread spectrum and other digital transmission systems. PRN waveforms or M-sequences can be generated for lengths of $N = 2^M - 1$ where M is the number of feedback shift registers. Fig. 4. Shows the m-stage feedback shift register where each shift register element is flip-flop and the adder gives modulo-2 addition. These M-sequences are having well controlled sidelobes and when the length of the sequence increases, better sidelobe suppression is achieved.

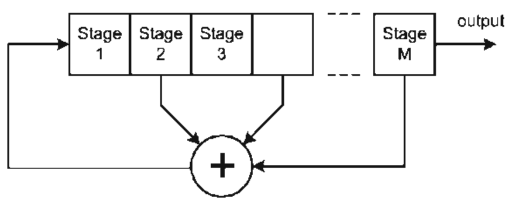

Fig. 4. M-stage Feedback Shift Register.

V. PERIODIC WAVEFORMS

A. Periodic Binary Waveforms

This section presents another type of processing of M-sequences to take the advantage of an interesting property of M-sequences. The property is referred as periodic autocorrelation property.

Let $s_i(n)$ be a sequences of length N and its periodic repetition with period τ is represented by $\hat{s}_i(n) = s_i(n + \tau)$. Equations (4) and (5) are showing the periodic autocorrelation and cross-correlation functions respectively, and can be represented as:

$$R_{ii}(\tau) = \sum_{n=0}^{N-1} s_i(n)\, \hat{s}_i^*(n+\tau) \quad (4)$$

$$R_{ij}(\tau) = \sum_{n=0}^{N-1} s_i(n)\, \hat{s}_j^*(n+\tau) \quad (5)$$

$$R_{ii}(\tau) = \begin{cases} E, & \text{for } \tau = 0 \\ 0, & \text{for } \tau \neq 0 \end{cases} \quad (6)$$

M-sequences exhibit lowest periodic autocorrelation function (PACF) equal to $|R_{ii}(\tau \neq 0) = 1|$. M-sequences which are represented as two valued binary codes {±1}, having code length N, produces *periodic auto-correlation* of peak value equal to N and uniform sidelobes of value -1. Fig. 5 shows the periodic autocorrelation function of M-sequence of code length 7. The motivating property of M-sequences is that in PACF, the magnitude of sidelobes is constant and level is '-1' and can be given as:

$$R_{ii}(\tau) = \begin{cases} N & \tau = 0, N, 2N, \cdots \\ -1 & \text{otherwise} \end{cases} \quad (7)$$

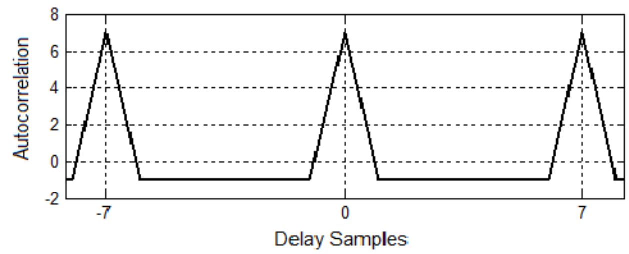

Fig. 5. Periodic Autocorrelation Function of M-sequence N=7.

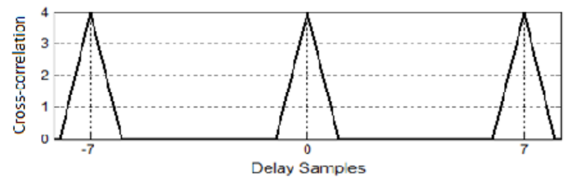

Fig. 6. Periodic Cross-correlation of M-sequence N=7.

This property was also exploited in [12, 13] for the construction of perfect periodic binary sequences with good autocorrelation properties that can be used in communications and continuous wave (CW) pulse compression radar systems. These sequences are suitable for coherence processing of radar signals. However, for non-coherent applications, such as non-coherent radar (using magnetrons), lidar, ultrasound, ground penetrating radar, optical masks and optical time domain reflectometer (OTDR) etc. need on-off {1, 0} sequences in transmitted signal. In this context Levanon [10] and Jahangir [14] demonstrated the *ideal periodic correlation properties* of M-sequences by taking the unipolar version {1, 0} for transmission and cross-correlating with the reference signal {+1, −1} of the same sequence. Fig. 6 shows the cross-correlation property of such M-sequence signal of length 7, where all off-peak sidelobes are zero. This can be achieved only when the number of 1's must be larger than the number of 0's by one element in transmitted signal. By observing Fig. 6, one can understood that the value of the mainlobe is 4 because the number of 1's are 4, and number of 0's are 3 in the transmitted sequence. It is evident that this ideal periodic cross-correlation property is achieved at the cost of energy loss.

It specifies that when M-sequences are used in coherent pulse compression systems, the energy efficiency is 100% whereas when these sequences are modified for the applications of non-coherent pulse compression systems, the energy efficiency is slightly greater than 50% and approaches 50% when sequence length is large. This is due to the reduction in duty cycle. The equation for calculating efficiency (η) is given as:

$$\eta = \sum_{n=0}^{N-1} \frac{s^2(n)}{|s^2(n)|_{max}} \quad (8)$$

If the duty cycle of the transmitted signal is reduced, it decreases the amount of energy in the transmitted pulse that decides the maximum detection range of target. Therefore, there is a need to identify the sequences of large length with less number of zeros and having ideal cross-correlation property.

B. Perfect Periodic Ternary Waveform

This section deals with the search of sequences, which satisfy two conditions: (i) to achieve high range resolution needs longer sequence length. (ii) more number of 1's than '0's in a sequence to achieve higher duty cycle. The additional advantage of using higher average duty cycle is that the pulse–train conflict between average power and unambiguous range also avoided [10]. Therefore, this paper presents the ternary sequences which have good energy efficiency and having perfect periodic autocorrelation property that are useful for both coherent and non-coherent radar applications. In this background, work of Hoholdt and Justesen [15] is significant. Two sequences of lengths 21 and 73, which are optimized in [15] are considered here in this paper. Fig. 7, exhibits the autocorrelation function of perfect periodic ternary sequence N = [1 1 1 1 -1 1 0 1 0 -1 1 1 -1 0 0 1 -1 0 -1 -1], which consists 5 0's and 16 +1's and -1's. This gives that the peak value of autocorrelation function is 16 and all sidelobes are zero. The efficiency of the sequence is 76%. The sequences of this type are widely preferred in radars where coherent processing is used. On the other hand, when this sequence is used for non-coherent radar application, on-off periodic waveforms are required. Therefore, all -1's becomes +1's and zeros remain same. This will not degrade the energy efficiency of the transmitted signal. The only problem here is to derive the reference signal so that the cross-correlation between transmitted signal and reference signal produces zero sidelobes. Fig. 8 shows the cross-correlation function after non-coherent processing. It is evident from the fig. 7 and 8 that this sequence can be used for both ***coherent and non-coherent pulse compression radar systems simultaneously***.

In table 1, another sequence of length N = 73 is also considered. When signal is processed coherently, the transmitted and reference signals are same whereas for non-coherent processing reference signal is different from the transmitted signal. Here it is calculated the value of β for reference signal when used for non-coherent processing. In both the cases only 9 zeros are in transmitted signals and energy efficiency is 87.7%.

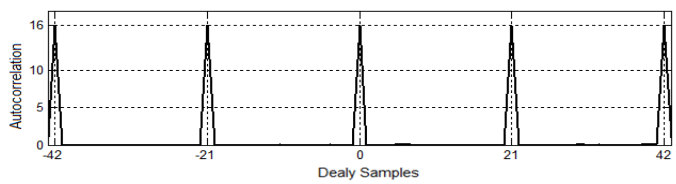

Fig. 7. Coherent processing of Ternary Signal N = 21.

Signal & Reference = [1 1 1 1 1 -1 1 0 1 0 -1 1 1 -1 0 0 1 -1 0 **-1 -1].**

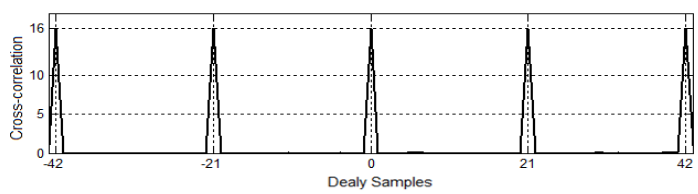

Fig. 8. Non-coherent processing of Ternary Signal N = 21.

Signal = [1 1 1 1 1 1 1 0 1 0 1 1 1 1 0 0 1 1 0 1 1]
Reference = [1 1 1 1 1 1 1 -3 1 -3 1 1 1 1 -3 -3 1 1 -3 1 1]

Table 1.

N	(η in %)	Coherent Processing	On-Off signal for Non-coherent Processing
73	**87.7**	**Transmitted Sig:** [-1 0 0 1 0 1 1 1 0 1 1 -1 1 -1 1 -1 0 1 1 1 1 -1 -1 1 1 -1 -1 -1 1 -1 -1 -1 0 1 1 -1 1 0 1 1 1 1 -1 -1 -1 1 1 1 -1 1 -1 -1 -1 -1 1 -1 0 1 1 -1 1 -1 -1 -1 1 1 0 1 1 -1 1 1 -1 1 1] **Reference Sig:** [-1 0 0 1 0 1 1 1 0 1 1 -1 1 -1 1 -1 0 1 1 1 1 -1 -1 1 1 -1 -1 -1 1 -1 -1 -1 0 1 1 -1 1 0 1 1 1 1 -1 -1 -1 1 1 -1 1 -1 -1 -1 -1 1 -1 0 1 1 -1 1 -1 -1 -1 1 0 1 1 -1 1 1 -1 1 1]	**Transmitted Sig:** [1 0 0 1 0 1 1 1 0 1 1 -1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1] **Reference Sig:** [1 β β 1 β 1 1 1 β 1 1 1 1 1 1 1 β 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 β 1 1 1 1 β 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 β 1 1 1 1 1 1 1 1 β 1 1 1 1 1 1 1 1: β = -7]

VI. CONCLUSION

Non-Coherent Pulse Compression (NCPC) radars or radar like systems use coded on-off keying (OOK) modulation. NCPC is envelope detector that depends on intensity of signal reflected from target. Aperiodic on–off pulse sequences for such systems are discussed using Manchester coded waveform of Barker code of length 13. The major drawback of the Manchester coding is that two negative peaks appear near the mainlobe and the signal may go undetected if it falls in this range. Coherent and Non-coherent pulse compression waveforms are discussed by taking the examples of M-sequences and perfect periodic ternary sequences. It is also demonstrated that the perfect periodic ternary sequences can be used simultaneously without degrading the energy efficiency for both coherent and non-coherent applications.

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