Joint Reduction of PMEPR and Sidelobe in Multicarrier Radar Signals using ZC and SC Method

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Abstract: - Employing the multitone waveforms for radar applications has attracted many authors in recent days. Several researchers have investigated the use of multitone waveform and challenges associated while implementation. The serious drawback of using multicarrier waveforms is the high Peak to Mean Envelope Power Ratio (PMEPR) values recorded and large sidelobes. To overcome PMEPR and sidelobe drawbacks a novel method is suggested for reducing sidelobe levels. The projected method applies zad-off chu phase sequence for multicarrier complementary phase coded (MCPC) signals. The comparison of integrated sidelobe ratio and peak sidelobe is obtained. Autocorrelations and complex envelope of the MCPC signal is obtained from the above methods are analyzed with extensive simulations. It is also possible to reduce the PMEPR and sidelobe simultaneously by using secondary user method. The suggested technique results with reduction in sidelobe and PMEPR levels.

Key-Words: - OFDM, MCPC, Zadoff-Chu sequence, Constellation, Primary User, Secondary User.

1 Introduction

In current day scenario there is a huge surge in demand for more information and the rapid growth of multimedia wireless applications, all points towards the need of a novel technology which aide very high speed data transmission rates. Similarly in the field of radar communications also there is a dire need for such new technique which balances the contrarian relationship between range and resolution detection capabilities. The range (or delay) resolution of a radar structure is inversely relative to the bandwidth of the signal transmitted. Therefore, the best evident way to enhance the range and resolution is to curtail the pulse width, because the pulse duration of each bit is inversely proportional to bandwidth [1]. On the other hand, for the better detection capacity of radar, the system must transmit with greater signal energy, and this can be attained by smearing long duration pulses, because the radar transmitting systems are operated close to their peak power limitations. One suggested method is to follow the pulse compression method to counterbalance the differences between the resolution and range of the radar signal.

There may be a huge thirst of bandwidth if single carrier methods are used for radar signal communication. But, taking the advantage of multitone or multicarrier methods, i.e., Orthogonal Frequency Division Multiplexing (OFDM) for the transmission of the radar signal may help to reduce the bandwidth requirements [2]. OFDM is a method of multiplexing the modulated signals. Multiplexing in general represents combing the subcarriers signals, which is formed by various sources. In multicarrier signal the multiplexing is applied to independent (or subcarrier) signals, however, these subcarrier signals are a sub-set of the complex (or main) signal. In OFDM the signal is divided into subcarriers, modulated by data (or phase) and later it is recombined to obtain the final OFDM signal. The concept of OFDM can be applied in radar for detecting the target.

In 2000 Levanon [3] coined a concept called as multicarrier or multitone complementary phase coded (MCPC) radar signal which was developed by the use of digital phase coded method. The Peak to Mean Envelope Power Ratio (PMEPR) in the MCPC signal is supposed to be less. In the conventional method of MCPC signal it was observed, if an attempt is made to lessen the PMEPR value, the sidelobe levels increases and vice versa, this may result into the wastage of energy due to more sidelobes. This will cause the weaker target echoed signal to hide. In addition, saturation of power amplifiers should be avoided along with the sidelobes which may reduce the efficiency.

Number of authors has explored and conducted several experiments to curb the influence of PMEPR on multicarrier schemes and significant emphasis is focused towards applying for data transmission

systems, following are the methods followed such as improved tone reservation scheme with fast convergence [4], adaptive tone reservation scheme [5], SCR-Based tone reservation [6] and Iterative Re-Weighted [7]. Several attempts were made by the authors to weaken PMEPR levels in multitone signals for radar operations. Phase modulation technique is used in [8], PMEPR condensed using ILS technique in [9], GA method has been used [10] and Random Phase Algorithm is used in [11]. In reducing the sidelobes few authors has attempted using constellation adjustment method in [12]. A sidelobe level of 35dB is reduced using genetic algorithm and reported in [13] but computational complexity is high. All the above cited literatures will try to reduce either PMPER or sidelobe separately. However, few authors have focused for jointly addressing the two problems which is reported in the literatures [14-16], but focus is on non-radar signal issues. In the article [17] Zadoff-Chu (ZC) phase method is applied for radar application and in this paper same is extended with SU method for reducing autocorrelation sidelobe level and maintaining low value of PMEPR. This paper is organized as follows. Section 2 summarizes the multitone signal structure. MCPC implementation based on ZC phase sequence is presented in Section 3. MCPC implementation based on SC technique is mentioned in section 4 with extensive simulation results. In section 5 conclusions are drawn which highlights the ability of proposed technique.

2 The Multitone Signal Structure

The multifrequency phase coded radar signal is based on the theory of OFDM scheme. The MCPC signal employs P number of carriers which is composed of P subcarriers transmitted all in parallel, which are parted in frequency by inverse of each duration of t_c bit. This concept of splitting the frequency yields OFDM notion, which is well known in the field of communication. In the OFDM every carrier is phase modulated with P number of bits and each bit will be of t_c duration and these phases are developed with polyphase codes, namely P3 and P4. A schematic block diagram for developing MCPC signal which is based on polyphase P4 codes is shown in Fig. 1.
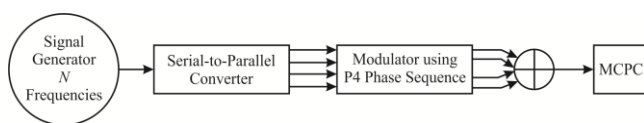

Fig.1. Block diagram of MCPC-OFDM signal generator

2.1 Mathematical Expression for MCPC Signal

The time domain representation of MCPC-OFDM signal is developed with the following equations

$$x(t) = \begin{cases} \sum_{q=1}^{P} W_a \exp\left\{ j\left[2\pi t f_p \left(((p+1)/2) - q \right) + \theta_q \right] \right\} \\ \qquad \sum_{p=1}^{P} u_{q,p}\left[t - (p-1)t_p \right], \qquad 0 \le t \le t_p \\ 0, \qquad\qquad\qquad\qquad\quad elsewhere \end{cases} \quad (1)$$

Where $u_{q,p}(t) = \begin{cases} \exp\left(j\phi_{q,p} \right), & 0 \le t \le t_p \\ 0, & elsewhere \end{cases}$ (2)

where $\phi_{q,p}$ indicates the pth phase of the qth row series. Here θ_q is assumed as random phase shift reckoned to every sub-carrier by the transmitting signal and W_a implies the amplitude scaled for the nth sub-carrier. Equation 3 is polyphase code of type P4 used to develop the phase sequence and mentioned as

$$\phi_p = \frac{\pi (p-1)^2}{P} - \pi (p-1) \quad p = 1, 2, 3 \dots\dots P \quad (3)$$

By assuming P = 5 and by repeatedly differing the values of P from 1, 2,…,5. Then several phase values are attained and it is enumerated in Table 1.

Table 1: Periodically shifted complimentary codes with length of P = 5

Sequence No	P4 Phase elements				
1	0°	-144°	-216°	-216°	-144°
2	-144°	-216°	-216°	-144°	0°
3	-216°	-216°	-144°	0°	-144°
4	-216°	-144°	0°	-144°	-216°
5	-144°	0°	-144°	-216°	-216°

By shifting cyclically, the elements of first row mentioned in Table 1 for P times, results in generation of P different complementary sets of sequences. At the same time applying all the phase values simultaneously to the multiple sub-carriers, the coded signals are attained. The phase modulation follows the frequency ordering of ($-2f_p$, $-f_p$, 0, f_p, $2f_p$) along the subcarriers. The P sub-carriers used with a frequency gap of $f_p = 1/t_p$, where t_p is the interval between the modulated phase elements. By performing the time domain addition of these modulated signal gives P×P MCPC signals. From equations 1, 2 and 3 it is possible to generate the MCPC signal structure with the subcarrier combinations of 7x7, 9x9, 11x11 and so on.

2.2 Simulation Results of P4 based MCPC Signal

The order of the phase combination in MCPC signal represents the phase sequence being employed to modulate a particular subcarrier. To develop the MCPC signal with [3 5 2 1 4] order, the phase sequence of 3rd row mentioned in Table 1 is phase modulated with the first subcarrier, 5th row is phase modulated with second subcarrier, 2nd sequence is phase modulated with the 3rd subcarrier and so on. For the sequence ordering [1 4 3 5 2] MCPC signal is developed as shown in the Fig. 2. Fig. 3 shows the corresponding autocorrelation plot. Similar simulations were also performed for [2 5 3 1 4] ordering and the same has been included below.
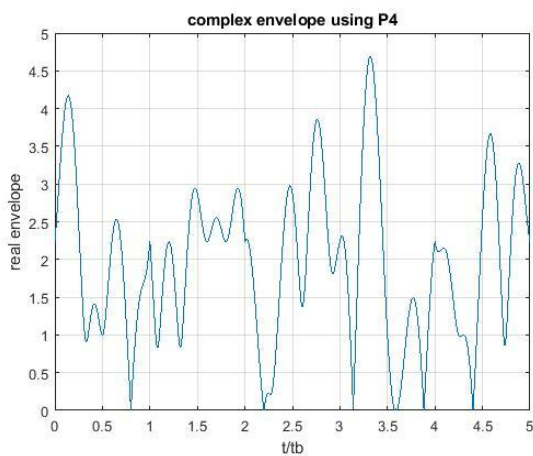
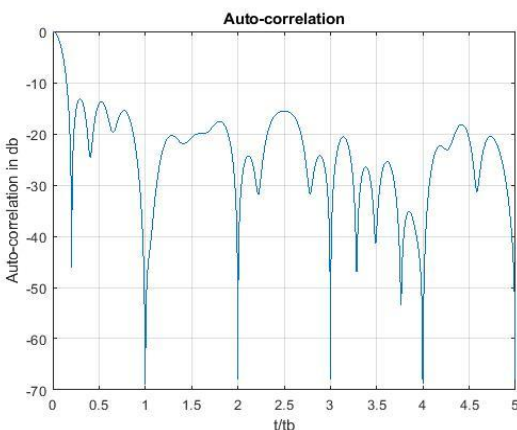Fig. 2. Conventional MCPC signal for 5×5 MCPC [1 4 3 2 5]

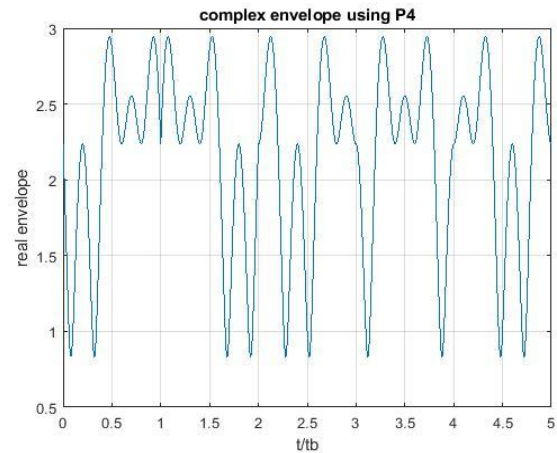Fig. 3. Autocorrelation plot for 5×5 MCPC [1 4 3 2 5]

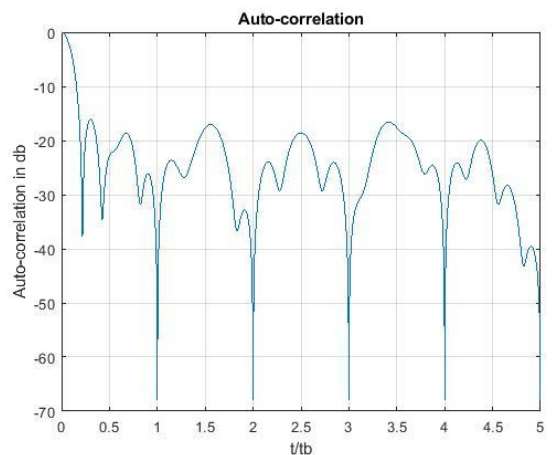Fig. 4. Conventional MCPC for 5×5 MCPC [2 5 3 1 4]

Fig. 5. Autocorrelation plot for 5×5 MCPC [2 5 3 1 4]

Table 2. PMEPR and Sidelobe Levels of 5×5 MCPC Signal

MCPC for various ordering with 5x5	PMEPR	Sidelobe in (dB)
1 4 3 5 2	4.3988	−13.61
2 5 3 1 4	1.7338	−12.4

From Table 2, it is evident that the autocorrelation sidelobe level are -12 dB and -13 dB respectively for the sequential ordering [2 5 3 1 4] and [1 4 3 5 2]. Thus it proves our claim that there is further scope for improvement in dwindling the sidelobe level. To overcome this drawback, in this paper we suggest a new method for developing MCPC signal which is based on ZC phase values.

2.3 Ambiguity Function of MCPC Signal

The output of the matched filter to the signal from the target which is identical to the value of the ambiguity function of MCPC signal at (t, v) = (0, 0). However, this function is used to calculate the

Doppler resolution and range for a particular radar waveform. The ambiguity function can be expressed as shown below

$$|\chi(\tau,v)| = \left| \int_{-\infty}^{\infty} x(t)x^*(t+\tau)\exp(j2\pi vt)dt \right| \qquad (4)$$

where x is the absolute complex envelope of the signal. The positive v represents the target reaching towards the radar system. Positive τ represents the target moving away from the radar. The ambiguity function is a key concept for analyzing or investigating radar signals. Fig. 6 shows the ambiguity function of MCPC signal for the sequence ordering [3 5 2 1 4].
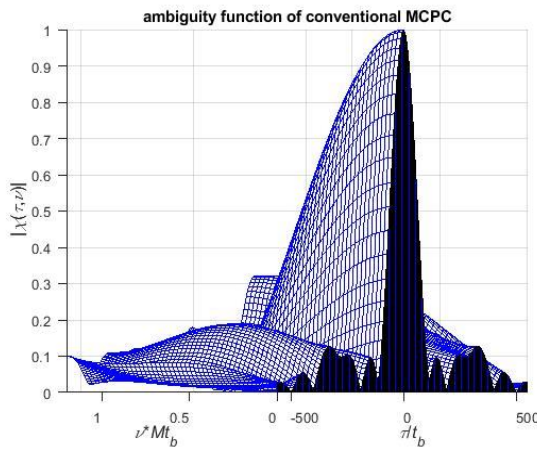

Fig. 6. Ambiguity function of 5×5 MCPC pulse for sequence order [3 5 2 1 4]

3 ZC Phase Sequence MCPC based

The projected ZC method will perform Hadamard product of the signal block with the equivalent ZC phase value of the ZC structure which is attained from the ZC matrix. Every factor in the ZC sequence characterizes complex number. Each ZC complex value will have a phase rotation which alters the corresponding phase of the signal element. This forms the formation of new version of ZC based MCPC signal.

The ZC root sequence of nth complex value is shown in the below equation

$$Z_r = \left[Z_{1r},\, Z_{2r}, \ldots \ldots, Z_{N_{ZC_r}} \right] \qquad (5)$$

can be obtained by the following formula

$$Z_n^r = e^{\left(\frac{-j\pi n(n+1)}{N_{Zc}} \right)} \qquad (6)$$

where NZC is assumed as the length of the ZC sequence. $1 \le n \le NZC$, $1 < g < NZC$, gcd (NZC, g) =1 and $q \in Z$. By exploiting the special property of ZC sequence we obtain the ZC matrix Z, which is given in equation 7.

$$Z = \begin{pmatrix} Z_{11} & \ldots\ldots & Z_{1Nzc} \\ \vdots & \ddots & \vdots \\ Z_{Nzc1} & \ldots\ldots & ZN_{zc}N_{zc} \end{pmatrix} = [Z_1, Z_2, \ldots\ldots Z_{NC}] \qquad (7)$$

$$Z_n = \left[Z_{1n}, Z_{2n}, \ldots\ldots, Z_{NZcn} \right]^T = Z^r$$
$$n = 1,2,\ldots.N_{Zc} \qquad (8)$$

where, Z_r is the ZC root sequence whereas Z_n is the $(n-1)^{th}$ which is a shifted form of the ZC root sequence. The ZC codes phase values are shown in the Table 3.

Table 3. Periodically shifted complimentary codes using ZC

Sequence No	ZC Phase values				
1	0	1.2566	1.2566	0	−2.5133
2	1.2566	1.2566	0	−2.5133	0
3	1.2566	0	−2.5133	0	1.2566
4	0	−2.5133	0	1.2566	0
5	−2.5133	1.2566	1.2566	1.2566	0

Every subcarrier is modulated with ZC phase values which are mentioned in Table 3. These modulated subcarriers are added continuously which leads to generation of MCPC signal based on ZC sequence as shown in Fig. 7.
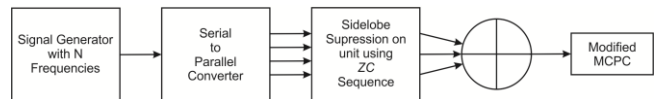

Fig. 7. Block diagram for developing ZC sequence based MCPC signal

In Table 4, comparison of MCPC signal which is based on P4 and ZC sequence is shown. For the various sequence ordering peak sidelobe level and peak of 1st sidelobe level are examined. Fig 8 to Fig 11 shows the corresponding MCPC plots of autocorrelation function and real envelope for the sequence ordering [1 4 3 5 2] and [2 5 3 1 4] respectively.

Table 4. Various Sidelobe of MCPC signal based on P4 with ZC Codes

Sequence	P4 based MCPC			ZC based MCPC	
	PME PR	1st SLL	Peak SLL	1st SLL	Peak SLL
3 2 5 1 4	2.9764	−13.85	−13.85	−16.29	−14.07
5 3 2 1 4	3.4821	−19.16	−14.92	−22.71	−15.30
2 4 3 5 1	2.9764	−12.76	−12.7	−18.96	−14.09
1 3 4 5 2	3.4821	−12.32	−12.32	−16.31	−12.34
2 3 5 1 4	2.9764	−12.27	−12.27	−16.64	−13.57
1 4 3 2 5	3.4821	−16.31	−12.26	−22.67	−15.06
1 4 2 5 3	1.7338	−16.31	−14.42	−19.28	−15.68
2 4 3 1 5	2.9764	−13.72	−12.62	−16.78	−13.71
1 4 3 5 2	4.3988	−13.16	−13.19	−13.19	−13.19
2 5 3 1 4	1.7338	−16.16	−15.16	−19.28	−15.72

A PMEPR of 3.4821 is obtained for the sequence ordering [1 4 3 2 5], both for P4 and ZC based sequences. For the MCPC signal based on ZC, -22.67dB of 1st sidelobe level and peak sidelobe level of -15.06dB is obtained and 1st sidelobe level of -16.31dB and peak sidelobe level of -12.26dB is attained for MCPC based on P4 for the same sequence ordering. Correspondingly a PMEPR of 1.73 is obtained for P4 and ZC based MCPC signal for the sequence ordering [1 4 2 5 3]. The 1st sidelobe level of -19.28dB and peak sidelobe level of -15.68dB is attained for MCPC based on ZC and the 1st sidelobe level of -16.31dB and peak sidelobe level of -14.42dB is obtained for MCPC based on P4. It can be observed from the Table 4 for the sequence ordering [1 4 3 2 5] an augment of nearly 3dB of peak sidelobe and 6dB in 1st sidelobe for MCPC signal based on ZC obtained, when it is correlated to MCPC signal based on P4.
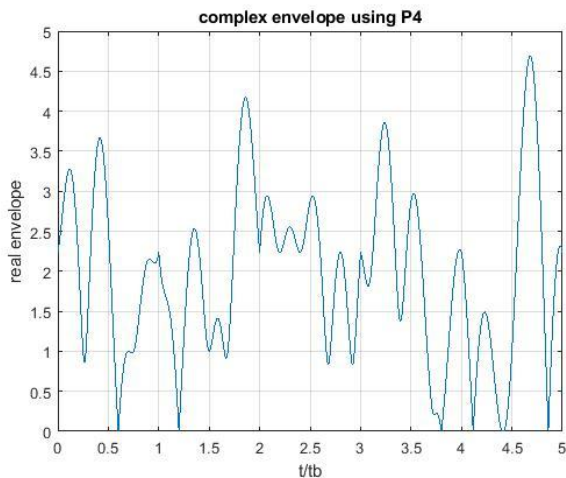

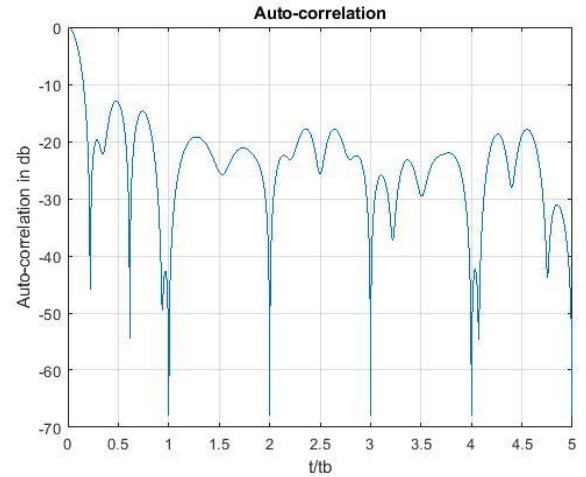Fig. 8. Real envelope of 5x5 MCPC [1 4 3 2 5]

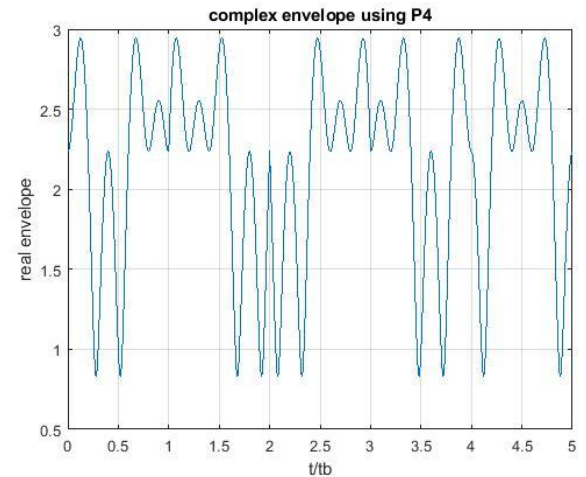Fig. 9. Autocorrelation for 5x5 MCPC [1 4 3 2 5]

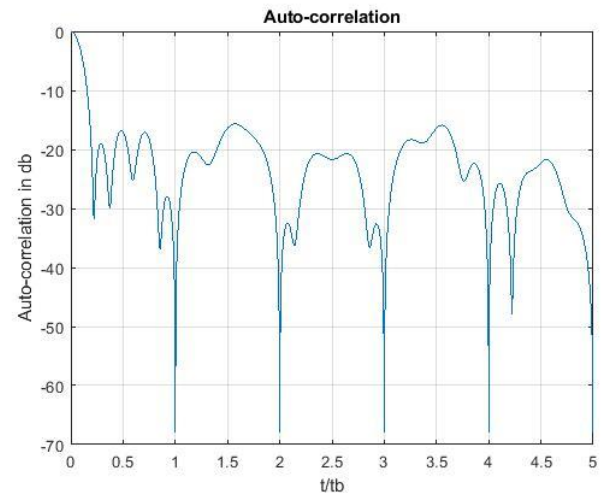Fig. 10. Real envelope of 5x5 MCPC for the sequence order [2 5 3 1 4]

Fig. 11. Autocorrelation of 5x5 MCPC for the sequence order [2 5 3 1 4]
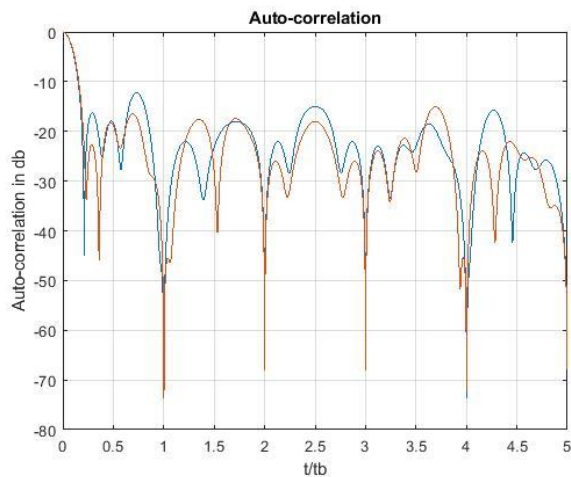
Fig. 12. Autocorrelation plots of MCPC using both P4 and ZC sequences

The Fig.12 shows the comparison of sidelobe levels in MCPC using P4 and ZC sequences. The blue color waveform is obtained by using P4 sequence and red color waveform is obtained by using the ZC sequences. It can be observed from the autocorrelation function plot, an improvement in sidelobe level using ZC based MCPC signal when compared with P4 polyphase sequence based MCPC. In the Table 5, a comparison of integrated sidelobe level ratio (ISLR) for MCPC signal based on P4 and ZC is attained for various ordering. For [4 1 5 3 2] ordering an improvement of 1.36 dB is obtained for MCPC based on ZC sequence method. Similarly Table 6 shows the comparison of peak sidelobe level ratio (PSLR) for MCPC based on P4 and ZC. For [4 1 5 3 2] ordering an improvement of 2.38 dB is obtained for MCPC based on ZC sequence method.

Table 5. ISLR comparison of P4 and ZC sequences

Sequence	Integrated sidelobe level ratio (ISLR) of MCPC	
	Based on P4	Based on ZC
4 1 3 2 5	1.4523	1.3054
4 2 3 1 5	2.0750	1.2935
1 3 4 2 5	1.6484	1.4515
4 1 3 5 2	1.8043	1.3626
1 3 5 2 4	1.5031	1.2081
3 1 5 4 2	1.5988	1.4816
5 2 3 4 1	1.3869	1.2408
4 1 5 3 2	1.6996	1.3935
1 3 2 5 4	1.6465	1.6038
4 2 3 5 1	1.2576	1.1306

Table 6. PSLR comparison of P4 and ZC sequences

Sequence	Peak sidelobe level ratio (PSLR) of MCPC	
	Based on P4	Based on ZC
5 2 3 4 1	0.2782	0.1811
4 1 3 5 2	0.2085	0.1891
5 1 4 3 2	0.2725	0.2527
1 3 2 5 4	0.2219	0.1823
4 2 3 5 1	0.2435	0.1823
4 2 3 1 5	0.2031	0.1933
5 2 3 4 1	0.2076	0.1711
4 1 3 2 5	0.1713	0.1462
4 1 5 3 2	0.2851	0.2810
1 3 5 2 4	0.2087	0.2041

4 MCPC Based on Signal Cancellation Method

The fundamental concept in signal cancellation technique is to prolong the part of the constellation points on the Secondary User (SU) sub-carriers and inert the suitable cancellation symbols on Primary User (PU) subcarrier to produce the cancellation signal to decrease both PMEPR and sidelobe levels [13]. Here adding the cancellation symbols which cancels the part of the signal is considered at the transmitter. The signal cancellation (SC) method frames this problem as a quadratically constrained quadratic program to obtain optimal cancellation signal.

In the suggested SC approach, the constellation modification of the symbol Cs = [Cs(0), Cs(1),… Cs(N-1)] is combined with the primary data symbol X, where Cs (k) =0 for $k \notin R$ on the SU subcarriers. Since we are not considering the SU subcarriers we concentrate only on the PU subcarriers. So, on the PU sub-carriers we add the signal cancellation (SC) symbol Cp = [Cp(0), Cp(1),…,Cp(N-1)] to the primary data symbol X. Where Cp(k) = 0 for $k \in R$. If we consider C = Cs + Cp as the total SC symbol of the SC technique, the following conditions must be satisfied

$$C(k) = \begin{cases} C_s(k), & k \in R \\ C_P(k), & k \notin R, \end{cases} \quad (9)$$

Here Cs is not considered, then the total SC symbol will be C = Cp and the transmitted symbol $\hat{x}$ of the SC technique can be shown as

$$\hat{X} = X + C_p = X + C \quad (10)$$

The transmitted time domain signal $\hat{x}$ of the SC technique can be attained by the following equation

$$\hat{X} = KX + KC_s + KC_p = KX + KC \qquad (11)$$

Hence the joint PMEPR reduction and sidelobe reduction issues can be framed as an optimization problem, i.e,

$$\min_{C} \quad \|KX + KC\|_{\infty}$$
$$subject\ to \quad \|X + C\|_2 \le \beta\|X\|_2$$
$$\|X + C\|_2^2 \le \varepsilon \qquad (12)$$
$$C(k) \in M, \ for\ k \in R$$

where in the above constraints represents different objective functions in which β represents the factor to control the maximum sidelobe power. By solving the above constraints which are the convex sets through the convex optimization tool, we obtain the optimal cancellation signal. But this involves computational complexity in solving the constraints. To address the quadratically constrained quadratic program (QCQP) problem, the solution is to generate the SC symbol which is based on the required constraints by considering one of the data symbol with opposite magnitude as the SC symbol (i.e., cancelling one of the subcarriers or one of the permutation of frequencies at the transmitter).
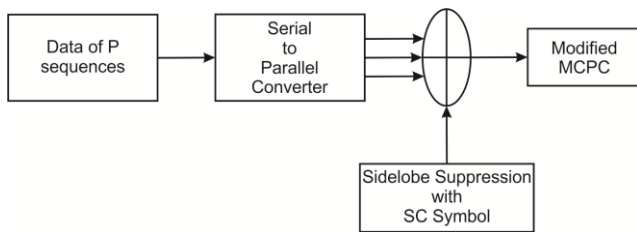

Fig. 13. Block diagram of MCPC using SC method

The above Fig. 13 shows the block diagram of developing MCPC signal based on SC symbol which suppress the sidelobe. This SC symbol is added with the modulated subcarriers to generate the modified MCPC signal with different phase showing better sidelobe levels when compared with conventional MCPC method which uses P4 sequence. The following section shows the simulation results of MCPC based on SC method. Fig. 14 and 15 shows the real and autocorrelation plot of MCPC signal developed based on SC symbol for [1 4 2 3 5] ordering. Similarly Fig. 16 and 17 shows the real and autocorrelation plot of MCPC signal based on SC symbol for [4 5 2 1 3] ordering.
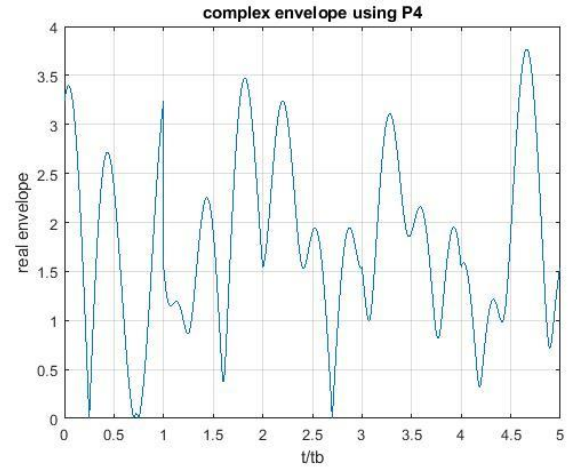

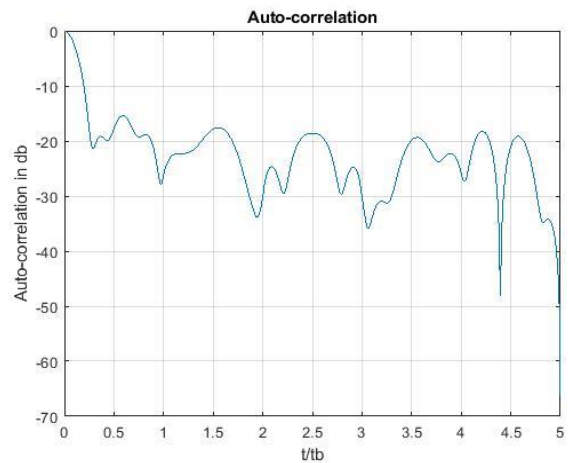Fig. 14. Real plot of MCPC using SC for the sequence order [1 4 2 3 5]

Fig. 15. Autocorrelation plot of MCPC using SC for the sequential order [1 4 2 3 5]
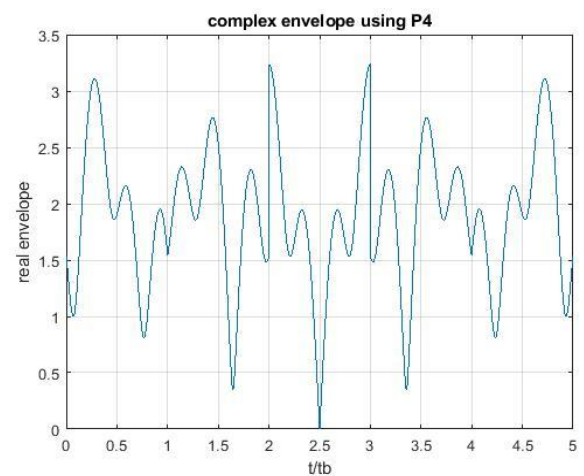

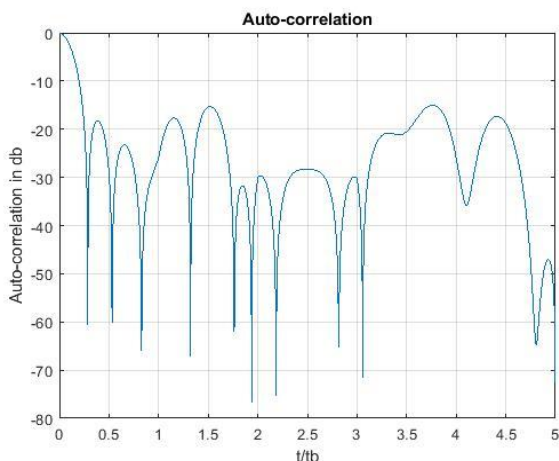Fig. 16. Real plot of the MCPC using SC for the sequence order [4 5 2 1 3]

Fig. 17. Autocorrelation plot of MCPC using SC for the sequence order [4 5 2 1 3]

In the Table 7, a comparison of PMEPR and 1st sidelobe level for MCPC signal based on P4 and SC is obtained for various ordering. For [1 2 5 4 3] ordering an improvement of 0.7075 in PMEPR and 3.28dB in 1st sidelobe level is obtained for MCPC signal based on SC sequence method. Correspondingly for [4 3 1 2 5] ordering an improvement of 0.3579 in PMEPR and 8.88dB in 1st sidelobe level is obtained for MCPC based on SC sequence method.

Table 7. Comparison of PMEPR and Sidelobe Levels of MCPC using P4 with SC technique

Sequence	MCPC with P4		MCPC with SC	
	PMEPR	1st SLL	PMEPR	1st SLL
1 3 4 2 5	3.4821	−13.82	3.6913	−15.4
3 5 2 1 4	2.9764	−13.85	2.6185	−21.5
4 5 3 2 1	4.3988	−13.57	3.6943	−17.58
3 2 4 5 1	4.3988	−11.68	3.6943	−14.16
4 5 2 1 3	2.9764	−14.78	2.6185	−18.26
3 4 5 2 1	4.3988	−13.77	3.5478	−15.73
4 3 5 1 2	4.3988	−11.97	3.6943	−16.24
4 3 1 2 5	2.9764	−14.97	2.6185	−23.85
1 2 5 4 3	4.3988	−12.13	3.6913	−15.41
3 4 5 2 1	4.3988	−13.77	3.5478	−15.81

Fig.18 shows comparison of autocorrelation plot of MCPC signals based on P4 and SC methods for [4 3 1 2 5] ordering, it can be observed from the plot an improvement of 3.48dB in 1st sidelobe level of MCPC signal based on SC method.
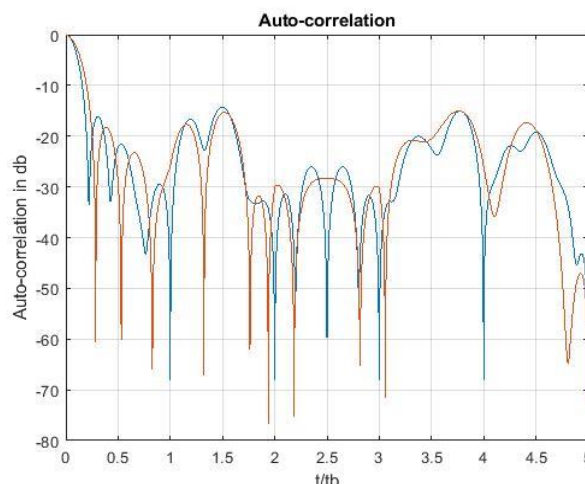

Fig. 18. Autocorrelation plots of MCPC using both P4 and SC technique

5 Conclusion

In this literature an endeavor is made to optimize the MCPC radar signal performance based on ZC and SU method. Two methods, namely ZC sequence and SU methods has been considered for reducing the PMEPR and sidelobe level simultaneously. An augment of 6dB in 1st sidelobe and 3dB of peak sidelobe for MCPC based on ZC is attained when correlated with conventional P4 method, also an improvement of 1.36dB in ISLR and 2.38dB in PSLR is obtained respectively. MCPC signal based on SC approach were also developed. Numerical results in the simulation shows, for [1 2 5 4 3] ordering an improvement of 0.7075 in PMEPR and 3.28dB in 1st sidelobe level is obtained for MCPC signal based on ZC sequence method. Similarly for another sequence ordering [4 3 1 2 5] an improvement of 0.3579 in PMEPR and 8.88dB in 1st sidelobe level is obtained.

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