MCPC Radar Signal with good Correlation properties

T. VENKATA SIVA NARAYANA[1], DR S.P SINGH[2]
[1, 2]ECE Department, MGIT, Hyderabad

Abstract- Radar systems are becoming significant for range detection, target identification, and resolution augmentation. Traditional radar signals high side lobe levels and limited Doppler tolerance reduce detection accuracy in complex environments. Staggered Multi-Carrier Phase-Coded (MCPC) pulse trains are used for to overcome these challenges and improve radar signal performance. A Multi-Carrier Phase Coded (MCPC) signals in radar systems can be used to improve correlation properties. The staggered MPMC signal can reduce range-Doppler coupling and improves target resolution by ensuring frequency variation. Unpredictability, spectrum dispersion, and correlation are enhanced by adaptive sequence ordering and random permutations. Multi-carrier systems, polyphase coding, and signal staggering will enable present radar systems meet dynamic operating requirements for performance, flexibility, and longevity. Autocorrelation, spectrum analysis, ambiguity function, and periodic ambiguity function are simulated in MATLAB.

Indexed Terms- Staggered MCPC Pulse Trains, Phase codes, Autocorrelation, Spectrum Analysis, Ambiguity Function, Sidelobe Reduction.

I. INTRODUCTION

Multi-Carrier Phase-Coded (MCPC) radar signals use several frequency channels and distinct phase coding methods to improve resolution and robustness. MCPC signal creation involves distributing transmitted energy across several subcarriers, each modulated with a particular polyphase code [1,2] This approach increases temporal and frequency diversity, enhancing the signal's multipath and interference resilience. Multiple carriers are modulated using polyphase codes like P3, P4, Golomb, Zadoff-Chu sequences and Random sequences to form MCPC pulse trains. These phase codes are weighted using Hamming, Chebyshev, Kaiser, Blackman, and Hanning and staggered. This staggered and weighted method gives the radar signal a crisp mainlobe and considerably reduced sidelobes in its autocorrelation and ambiguity functions for greater resolution and less interference. [1,3].

MCPC sequences were chosen for their autocorrelation, which helps create crisp mainlobes and lower sidelobes. Phase coding converts phases into chips or bits inside a pulse. Since every byte in the phase coding modifies the signal's phase, reception's waveform can be reduced. Fixed or random sequence order depends on autocorrelation and Doppler response.

After setting carriers and codes, combining all modulated carriers creates a composite waveform. Wider bandwidth and richer spectral structure allow this composite signal to improve range resolution and Doppler sensitivity.

Thus, the final MCPC waveform combines spectrum efficiency, coding variation, and frequency agility.

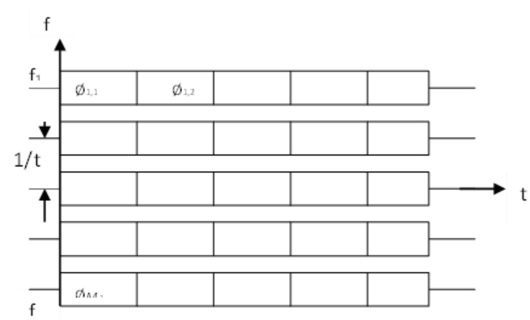

Fig 1: Structure of MCPC signal

II. METHODOLOGY

2.1 Implementation of Overview:

A systematic flowchart shows the staggered MCPC waveform simulation and design phases. This graph shows how modular the system is and simplifies signal production.

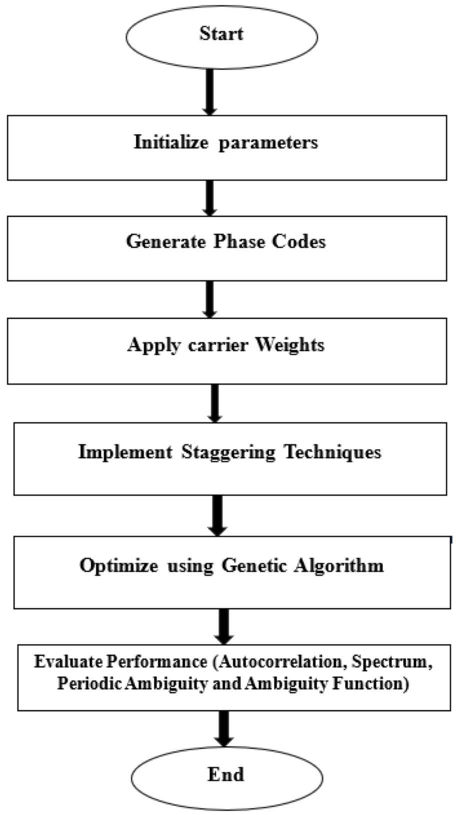

Fig 2: Flow chart indicates the steps for the process to implement the good correlation properties.

The design begins with radar characteristics including polyphase code, pulse length, and subcarrier count. After setting these values, it constructs phase-coded sequences like P3, P4, Golomb, Zadoff-Chu sequences and Random sequences for each subcarrier [4-6]. These sequences encode phase information onto carriers and improve correlation.

Sequence generation modulates each subcarrier with its phase code. This approach produces frequency-domain signals with distinct information values. The staggering phase, where the duty cycle shifts subcarriers in time, is critical to the flow. This purposeful offset between subcarriers reduces mutual interference and boosts waveform Doppler resolution.

Carrier weighting follows modulation and staggering. The sidelobe suppression effects of Hamming, Chebyshev, Kaiser, Blackman, and Hanning windows. These weightings shift the amplitude of each subcarrier to boost the mainlobe and lower the sidelobes in the final signal.

Finally, combining all staggered, weighted subcarriers creates the composite MCPC signal. The autocorrelation, ambiguity, periodic ambiguity, and spectral property analysis of the produced waveform [8,9]. This simulation validates the staggered MCPC technique's improved signal performance and reduces sidelobes.

.

2.2 Initialize the parameter: To initialize the parameter, set up the values are Carriers: Number of frequency channels that will be used in MCPC pulse train. Bits: Length of each pulse, generally measured in bits or chips. Pulses: Generally, represents the overall time duration in radar signal. And remaining parameters like sequence type, sequence order, permutations, staggering techniques and carrier weights are discussed detailed in below. These parameters determine the waveform's time-frequency structure, affecting range resolution, Doppler performance, and signal clarity.

2.2.1 Polyphase codes: The pulse sequence are phase modulated by with different carriers. This stage involves generating the phase codes that will be used in this pulse train.

P3 codes [1]: Phase sequence of P3 polyphase codes are defined as:

$$\emptyset_m = \frac{\pi}{M}\begin{cases}(m-1)^2; & m=1,2,\ldots,M; \text{ for M even}\\ m(m-1); & m=1,2,\ldots,M; \text{ for M odd}\end{cases} \quad ..(1)$$

P4 codes [1]: Phase sequence of P4 polyphase codes are defined as

$$\emptyset_m = \frac{\pi}{M}(m-1)^2 - \pi(m-1); \mathrm{m} = 1,2,\ldots..\mathrm{M} \quad ..(2)$$

Golomb codes: Golomb polyphase codes are used in radar system for lossless data compression method and coding of phase sequence are:

Let n= qm+r, where 0≤r<m. -divide m into n to get the quotient q and remainder r.

Where, q is coded in unary r is coded as a fixed prefix code. Random sequences [9]: These sequences are generated so that each element in the sequence is selected independently of others. Sequence order: It is defined how the phase codes are applied through each pulse in a Multi-Carrier Phase-Coded (MCPC) pulse train. This impact of sequence order is affecting properties like autocorrelation and sidelobe in radar signals. Permutations: A permutation is a rearrangement of the elements of a sequence or order list. It is used in radar signal for the optimization algorithm to find the best arrangement of elements that minimizes interference and maximizes signal clarity.

2.2.2 Carrier Weights: Carrier weights are the factors that will modify the amplitude of each carrier in the MCPC pulse train. Here carrier weights are essentially applying the windowing techniques. The following windowing techniques are applied in this paper

Hamming Window: The Hamming window is defined as

$$W(n) = 0.54 - 0.46\cos\left(\frac{2\pi n}{N-1}\right) \quad ..\ (3)$$

Where, N is the window length, n is the sample index
Chebyshev Window: The Chebyshev window is defined as

$$W(n) = \frac{\cosh\left(\beta.\cos^{-1}\left(\frac{2n}{N-1}-1\right)\right)}{\cosh(\beta)} \quad ..\ (4)$$

Where, $\beta = \cosh^{-1}(10^{0.1R})$
Where, N is the window length, R is the sidelobe window and n is the sample index
Kaiser Window: The Kaiser window is defined as

$$W(n) = I_0(\beta\sqrt{1-\left(\frac{2n}{N-1}-1\right)^2} \quad ..\ (5)$$

Where, N is the window length, n is the sample index
Blackman Window: The Blackman window is defined as

$$w(n) = 0.42 - 0.5\cos\left(\frac{2\pi n}{N-1}\right) + 0.08\cos\left(\frac{4\pi n}{N-1}\right) \quad ..\ (6)$$

for n=0, 1, 2, …, N-1
Hanning Window: The Hanning window is defined as

$$w(n) = 0.5 - 0.5\cos\left(\frac{2\pi n}{N-1}\right) \quad ..\ (7)$$

for n=0, 1, 2, …, N-1

2.2.3 Implementing the Staggering Techniques: The staggering pulse train repetition is a technique that involves modulating the inter-pulse times to expand the unambiguous Doppler domain with little range swath incursion.

2.2.4 Evaluate the Performance:
Autocorrelation Function [9]: This is a type of correlation in which the given signal is correlated with itself, usually the time-shifted version of itself. Mathematical expression for the autocorrelation of continuous time signal x (t) is given by

$$R_{xx}(\tau) = \int_{-\infty}^{\infty} x(t)x^*(t-\tau)dt \quad ...\ (8)$$

where '⋆' denotes the complex conjugate.
Similarly, the autocorrelation of the discrete time signal x[n] is expressed as

$$R_{xx}[m] = \sum_{n=-\infty}^{\infty} x[n]x^*[n-m] \quad ...(9)$$

Spectral Characteristics of staggered MCPC pulse train: Spectral characteristics is the process of obtaining the energy spectrum of a time series and identifying the dominant frequencies present in it.

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt \quad ...(10)$$

Similarly, the spectrum analysis in discrete time signal is expressed as

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j\frac{2\pi}{N}kn} \quad ...(11)$$

Ambiguity Function: The ambiguity function represents the time response of a filter matched to a given finite signal, when that signal is received with a delay τ and a Doppler shift v.

$$|X(\tau, v)| = |\int_{-\infty}^{\infty} u(t)u^*(t+\tau)\exp(j2\pi vt)dt| \quad ..\ (12)$$

Periodic Ambiguity Function: The Periodic Ambiguity Function (PAF) is a measure that uses the analysis of a signal with over all time and frequency.

$$|X_{NT}(\tau, v)| = |\frac{1}{NT_r}\int_0^{NT_r} u(t)u^*(t+\tau)\exp(j2\pi vt)dt| \quad ...(13)$$

where,

$$u(t) = \sum_{n=-\infty}^{\infty} u_n[t-(n-1)T_r] \quad ...(14)$$

III. SIMULATION AND RESULTS ANALYSIS

In this study, performance evaluations were conducted under the following parametric conditions: Number of Carriers = 7; Number of Bits: 7; Number of Pulses : 7; Sequence Type : P3; Sequence Order : Random; Permutation : Random; Carrier Weighting : Hamming Window; Staggering : Equal with a Duty Cycle (Dc) of 33%. The chosen optimization strategies were employed to rigorously investigate autocorrelation behaviour, spectral distribution, periodic ambiguity functions (PAFs), and the comprehensive mitigation of ambiguity-related distortions. The objective was to suppress sidelobe levels while amplifying the mainlobe to bolster detection fidelity

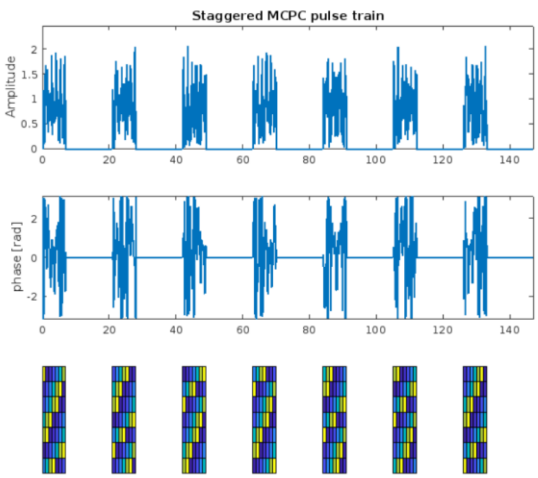

Fig. 3: Signal Structure of P3-Based MCPC Signal Utilizing Hamming Window (7×7)

Figure 3, illustrates the temporal structure of a staggered Multi-Carrier Phase-Coded (MCPC) signal embedded with a Hamming window. The upper graph delineates amplitude modulations across time, representing instantaneous signal power variations, while the lower segment portrays phase transitions, reflecting modulated phase code distributions within the pulse ensemble.

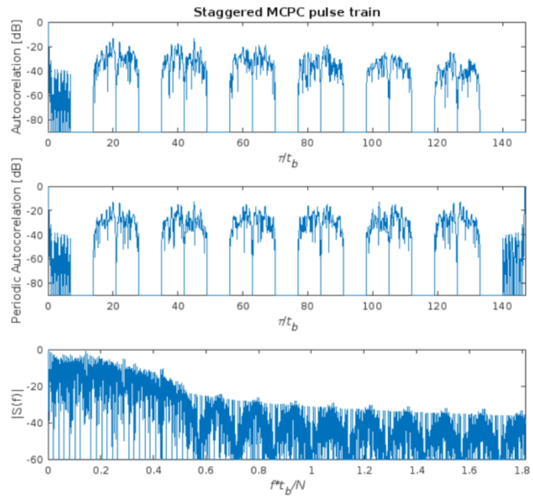

Fig. 4: Autocorrelation, Periodic Autocorrelation, and Spectral Characteristics of P3-Based MCPC Signal with Hamming Window (7×7)

Figure 4, encapsulates the signal's spectral domain attributes alongside its autocorrelation and periodic autocorrelation functions. The configuration retains robust correlation properties and exhibits spectral compactness, rendering it suitable for enhanced radar resolution and target discernment under noisy or cluttered environments.

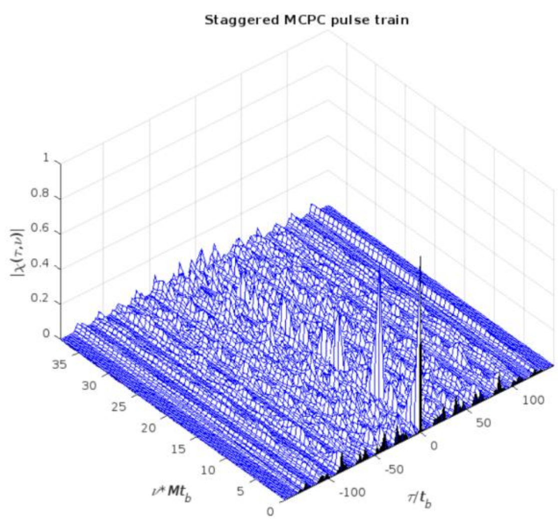

Fig. 5: Ambiguity Function of P3-Based MCPC Signal with Hamming Window (7×7)

As shown in Figure 5, the ambiguity function provides a three-dimensional perspective on the signal's delay-Doppler response. The horizontal axis indicates normalized temporal delay, while the vertical axis portrays Doppler frequency shifts scaled relative to the product of subcarriers and pulse duration. The surface plot's magnitude—represented on the Z-axis—visualizes coherence levels, offering insights into resolution capabilities and ambiguity suppression.

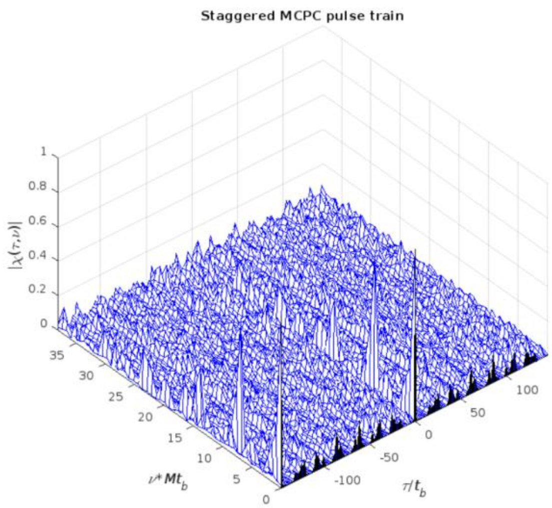

Fig. 6: Periodic Ambiguity Function of P3-Based MCPC Signal with Hamming Window (7×7)

Figure 6, presents the periodic ambiguity function (PAF), revealing spatial periodicities and signal coherence peaks across delay and Doppler shifts. This topological depiction is essential for evaluating phase code robustness in reducing spurious sidelobe intrusions and preserving detection precision across operational bandwidths.

Subsequently, the parameters were adjusted as follows: Sequence Type : P4; Carrier Weighting : Chebyshev Window; Sequence Order : equal; Permutation : equal; Staggering : Equal with a Duty Cycle (Dc) of 25%.—with all other variables maintained—to further assess signal integrity and ambiguity suppression dynamics under altered windowing conditions.

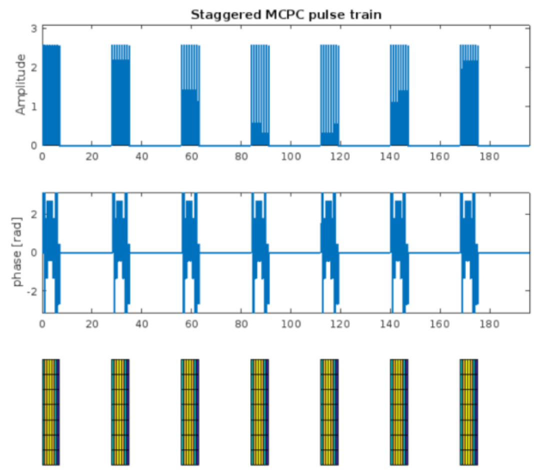

Fig. 7: Signal Structure of P4-Based MCPC Signal with Chebyshev Window (7×7).

Figure 7, portrays the signal morphology of a staggered MCPC waveform with Chebyshev window application. Amplitude dynamics capture the power envelope modulations, while the phase trajectory demonstrates the sequence of encoded phase values dispersed within the pulse continuum, reflecting complex coding strategies.

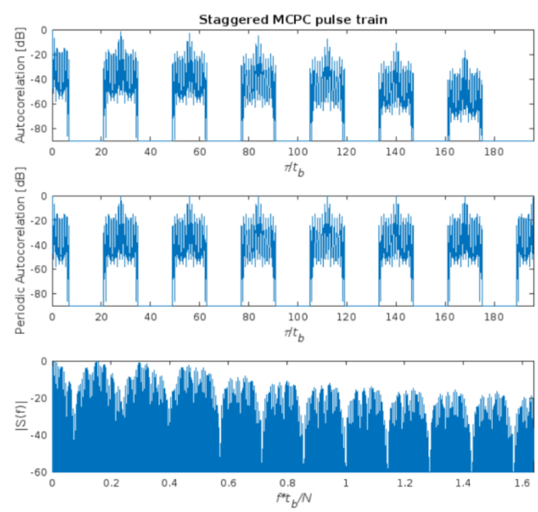

Fig. 8: Autocorrelation, Periodic Autocorrelation, and Spectral Characteristics of P4-Based MCPC Signal with Chebyshev Window (7×7)

In Figure 8, the presented plots underscore the waveform's spectral fidelity and time-domain correlation characteristics. The Chebyshev window facilitates enhanced spectral roll-off, enabling better isolation of mainlobe features and attenuation of side spectral artifacts thus improving radar clutter rejection efficacy.

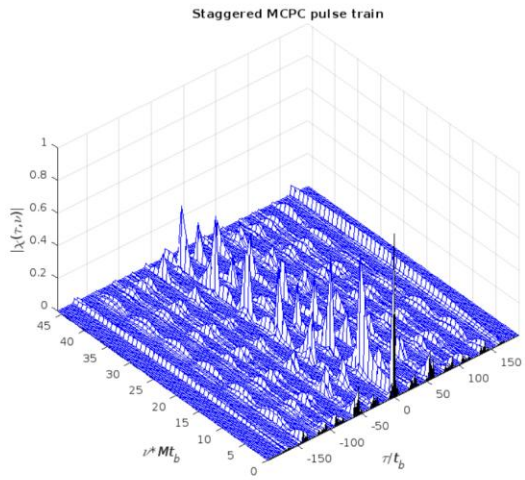

Fig. 9: Ambiguity Function of P4-Based MCPC Signal with Chebyshev Window (7×7).

Figure 9, depicts the ambiguity function of the Chebyshev-windowed waveform, elucidating the signal's resolution profile across time-delay and frequency-shift dimensions. The plot illustrates how phase coding optimizations influence energy concentration, and showcases improved mainlobe sharpness with reduced sidelobe energy spread.

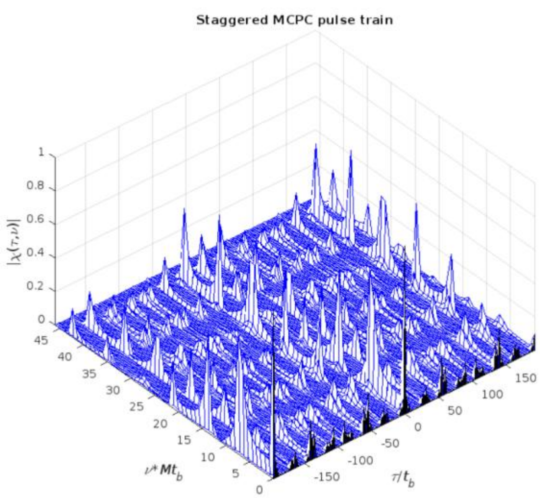

Fig. 10: Periodic Ambiguity Function of P4-Based MCPC Signal with Chebyshev Window (7×7)

As visualized in Figure 10, the periodic ambiguity profile reflects the waveform's periodic time-frequency coherence. Peaks and nulls in this function delineate correlation performance and indicate the degree of ambiguity suppression achievable under periodic excitation conditions.

Subsequently, the parameters were adjusted as follows: Sequence Type: Golomb; Carrier Weighting: Hanning Window; Sequence Order: random; Permutation: equal; Staggering : Golomb-based optimal. with all other variables maintained to further assess signal integrity and ambiguity suppression dynamics under altered windowing conditions.

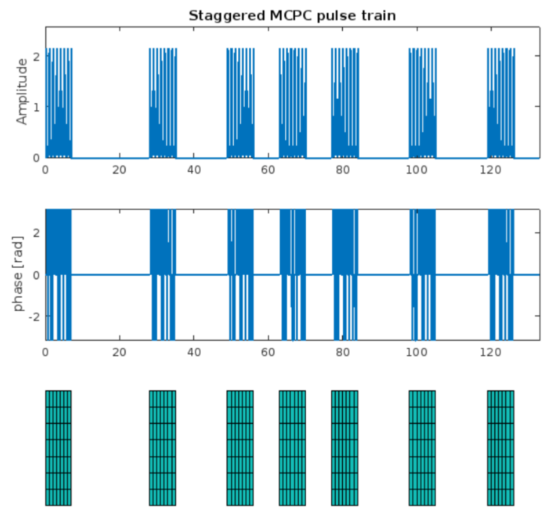

Fig. 11: Signal Structure of Golomb-Based MCPC Signal with Hanning Window (7×7)

Figure 11, illustrates the temporal structure of a staggered Multi-Carrier Phase-Coded (MCPC) signal embedded with a Hanning window. The upper graph delineates amplitude modulations across time, representing instantaneous signal power variations, while the lower segment portrays phase transitions, reflecting modulated phase code distributions within the pulse ensemble.

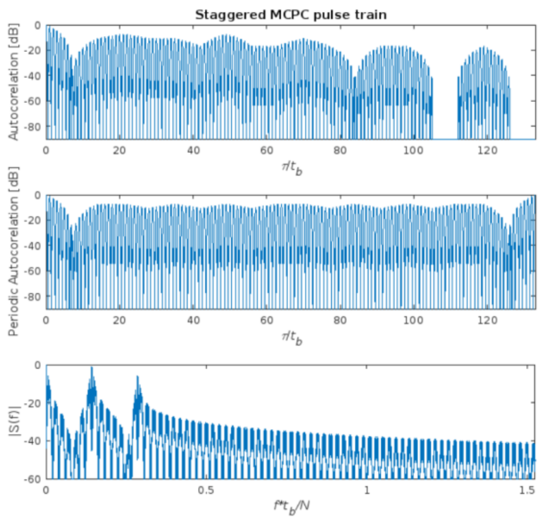

Fig. 12: Autocorrelation, Periodic Autocorrelation, and Spectral Characteristics of Golomb -Based MCPC Signal with Hanning Window (7×7).

Figure 12, encapsulates the signal's spectral domain attributes alongside its autocorrelation and periodic autocorrelation functions. The configuration retains robust correlation properties and exhibits spectral compactness, rendering it suitable for enhanced radar resolution and target discernment under noisy or cluttered environments.

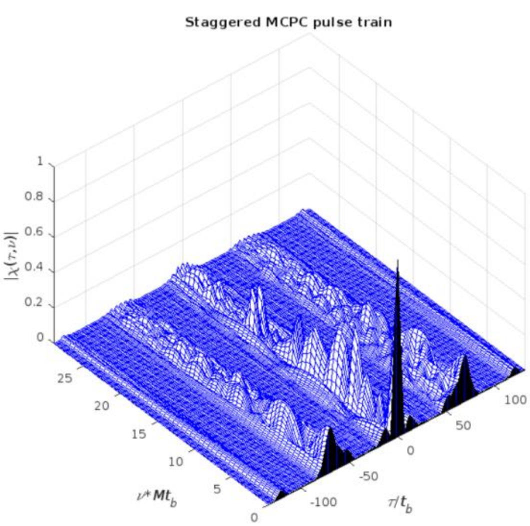

Fig. 13: Ambiguity Function of Golomb -Based MCPC Signal with Hanning Window (7×7)

As shown in Figure 13, the ambiguity function provides a three-dimensional perspective on the signal's delay-Doppler response. The horizontal axis indicates normalized temporal delay, while the vertical axis portrays Doppler frequency shifts scaled relative to the product of subcarriers and pulse duration. The surface plot's magnitude—represented on the Z-axis—visualizes coherence levels, offering insights into resolution capabilities and ambiguity suppression.

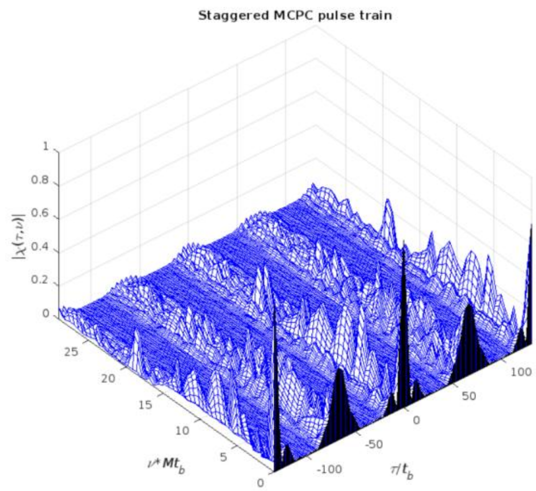

Fig. 14: Periodic Ambiguity Function of Golomb -Based MCPC Signal with Hanning Window (7×7).

Figure 14, presents the periodic ambiguity function (PAF), revealing spatial periodicities and signal coherence peaks across delay and Doppler shifts. This topological depiction is essential for evaluating phase code robustness in reducing spurious sidelobe intrusions and preserving detection precision across operational bandwidths.

Subsequently, the parameters were adjusted as follows: Sequence Type: Random; Carrier Weighting: kaiser 8 Window; Sequence Order: random, Permutation: random, Staggering: Pseudo Random with all other variables maintained to further assess signal integrity and ambiguity suppression dynamics under altered windowing conditions.

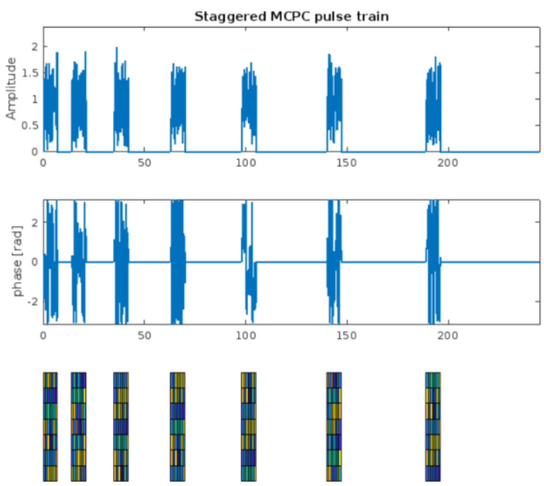

Fig. 15: Signal Structure of Random -Based MCPC Signal with kaiser 8 Window (7×7).

Figure 15, portrays the signal morphology of a staggered MCPC waveform with kaiser 8 window application. Amplitude dynamics capture the power envelope modulations, while the phase trajectory demonstrates the sequence of encoded phase values dispersed within the pulse continuum, reflecting complex coding strategies

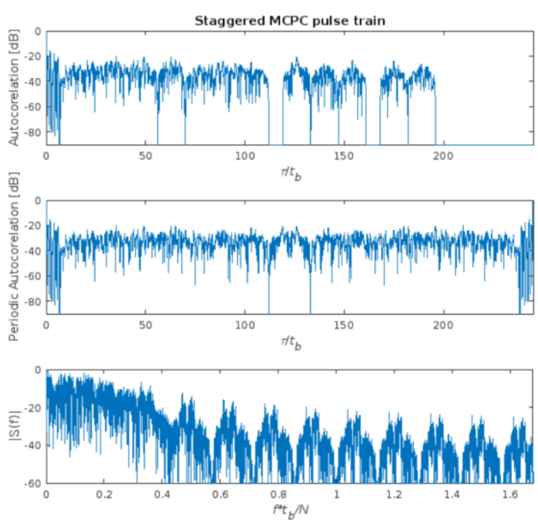

Fig. 16: Autocorrelation, Periodic Autocorrelation, and Spectral Characteristics of Random -Based MCPC Signal with kaiser 8 Window (7×7).

In Figure 16, the presented plots underscore the waveform's spectral fidelity and time-domain correlation characteristics. The kaiser 8 window facilitates enhanced spectral roll-off, enabling better isolation of mainlobe features and attenuation of side spectral artifacts.

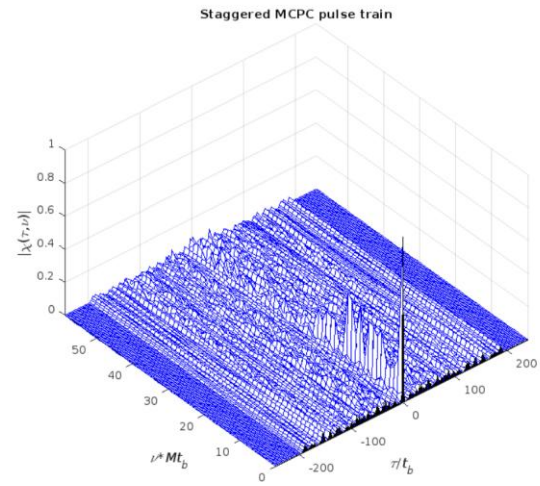

Fig. 17: Ambiguity Function of Random -Based MCPC Signal with kaiser 8 Window (7×7).

Figure 17, depicts the ambiguity function of the kaiser 8 windowed waveform, elucidating the signal's resolution profile across time-delay and frequency-shift dimensions. The plot illustrates how phase coding optimizations influence energy concentration, and showcases improved mainlobe sharpness with reduced sidelobe energy spread.

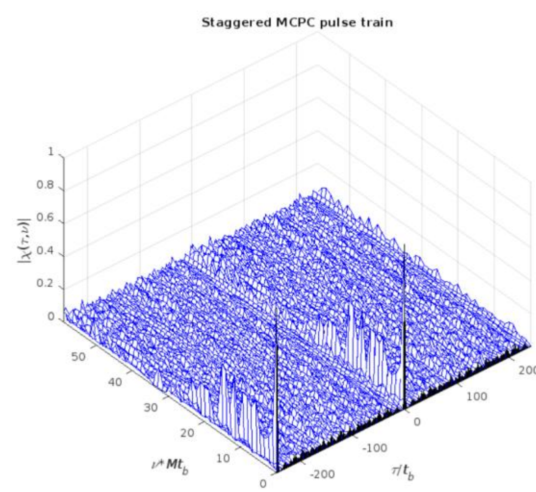

Fig. 18: Periodic Ambiguity Function of Random -Based MCPC Signal with kaiser 8 Window (7×7).

As visualized in Figure 18, the periodic ambiguity profile reflects the waveform's periodic time-frequency coherence. Peaks and nulls in this function delineate correlation performance and indicate the degree of ambiguity suppression achievable under periodic excitation conditions.

A final simulation was conducted under the following advanced parametric scenario: Sequence Type : Zadoff-chu; Carrier Weighting : Kaiser 3 Window, Sequence Order : consequtive; Permutation : consequtive; Staggering : Equal with a Duty Cycle (Dc) of 25%,with all other parameters preserved. This configuration is designed to probe performance under high spectral containment and extreme correlation constraints.

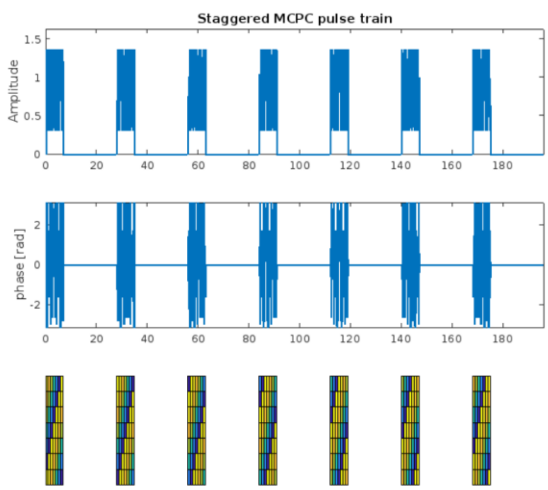

Fig. 19: Signal Structure of Zadoff-chu-Based MCPC Signal with Kaiser 3 Window (7×7).

Figure 19, portrays the signal morphology of a staggered MCPC waveform with Kaiser 3 window application. Amplitude dynamics capture the power envelope modulations, while the phase trajectory demonstrates the sequence of encoded phase values dispersed within the pulse continuum, reflecting complex coding strategies

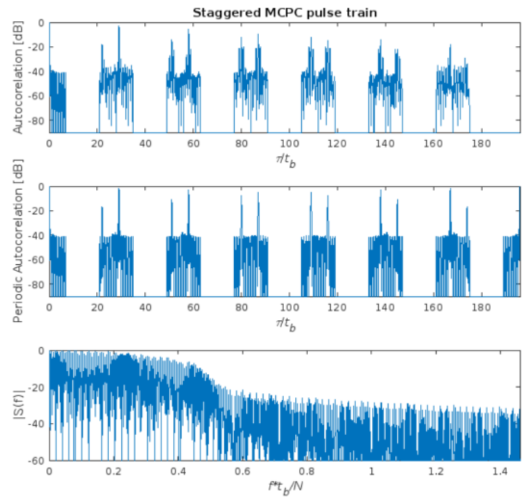

Fig. 20: Autocorrelation, Periodic Autocorrelation, and Spectral Characteristics of Zadoff-chu-Based MCPC Signal with Kaiser 3 Window (7×7).

Fig. 20, shows the spectral characteristics, autocorrelation, and periodic autocorrelation of a staggered MCPC pulse train that maintains good autocorrelation properties and frequency spectrum for enhancing radar resolution and detection capabilities

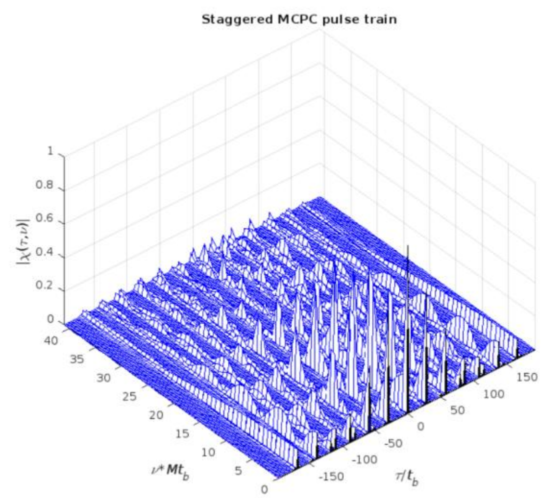

Fig. 21: Ambiguity Function of Zadoff-chu-Based MCPC Signal with Kaiser 3Window (7×7).

Figure 21, depicts the ambiguity function of the Kaiser 3 windowed waveform, elucidating the signal's resolution profile across time-delay and frequency-shift dimensions. The plot illustrates how phase coding optimizations influence energy concentration, and showcases improved mainlobe sharpness with reduced sidelobe energy spread.

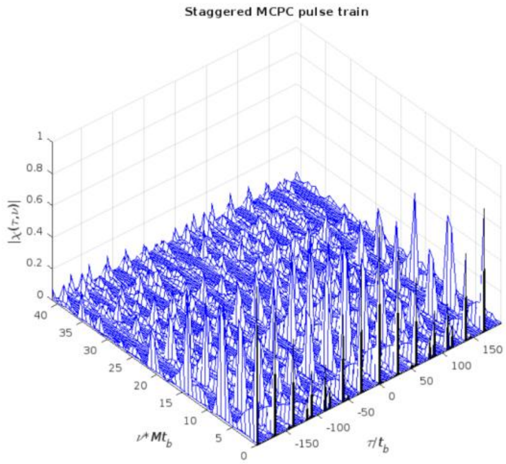

Fig. 22: Periodic Ambiguity Function of Zadoff-chu-Based MCPC Signal with Kaiser 3 Window (7×7).

As visualized in Figure 22, the periodic ambiguity profile reflects the waveform's periodic time-frequency coherence. Peaks and nulls in this function delineate correlation performance and indicate the degree of ambiguity suppression achievable under periodic excitation conditions.

CONCLUSION

This study successfully analysed the generation and optimization of staggered MCPC pulse trains for radar systems by using Matlab. It gives better performance in reducing sidelobe and enhancing mainlobe sharpness, provides clear signal detection, and improves target resolution by combining the genetic algorithm with a staggered MCPC pulse train and carrier weights. This study puts forward further developments in radar technology, increasing both its applicability and dependability.

REFERENCES

[1] N. Levanon: "Multifrequency complementary phase-coded radar signal", *IEE Proc. (London)-Radar, Sonar and Navigation*, 147 (6), 276-284, 2000.

[2] Kretschmer,F,F Lewis, B.L.:"Doppler properties of polyphase coded pulse compression waveforms" Transactions on Aerosp.Electron. Syst., 1983, AES-19,(4),pp.521-531.

[3] R. Frank, "Polyphase codes with good nonperiodic correlation properties," in *IEEE Transactions on ,Information Theory*, vol. 9, no. 1, pp. 43-45, January 1963, doi: 10.1109/TIT.1963.1057798.

[4] Tseng,c.c., and Liu, C.L.(1972), "Complementary sets of Sequences", IEEE Transactions on IT, IT-18,5 (Sep1972), 644-652.

[5] Levanon,N.(2000), "Multifrequency Radar signals" ., In proceeding of the IEEE International Radar conference, Alexandria,VA,May 2000,683-688.

[6] Popovic,B.M.(1990), "Complementary sets based on sequences with Ideal periodic autocorrelation"., Electronic Letters,26,18(Aug 1990) ,1428-14330.

[7] E. Mozeson and N. Levanon: "MATLAB code for plotting ambiguity functions", *IEEE Trans. on Aerospace and Electronic Systems*, AES-38 (3), 1064-1068, 2002.

[8] Bin Deng, Bin Sun, Xizhang We, Xiang Li, "Ambiguity function analysis for MCPC radar signal", 2nd International Conference on Industrial Mechatronics and Automation (ICIMA), Vol. 2, pp.650-653, 2010.

[9] Yunhua Zhang, and Xiao Dong. "Design of low sidelobe random radar signal by frequency-domain modulation method." (2019).

[10] Lewis, B.L., Kretschmer,F,F., and Shelton w.w (1986) Aspects of Radar signal processing, Norwood, MA, Artech House,1986.