Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 56 Issue: 10:2023
DOI: 10.5281/zenodo.8433576

SIDE LOBE SUPPRESSION AND LOW PAPR IN PULSE COMPRESSION RADAR USING GAUSSIAN FILTER BASED COSTAS CODING

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Abstract

The abstract presents a novel approach for achieving side lobe suppression and low peak-to-average power ratio (PAPR) in pulse compression-based radar systems using Gaussian filter-based Costas coding. Pulse compression radar relies on coded waveforms to achieve high range resolution and accurate target detection. However, conventional Costas coding techniques may exhibit undesired range side lobes and high PAPR, which can degrade radar performance. To address these issues, we propose the integration of a Gaussian filter into the pulse compression process. The Gaussian filters act as a windowing function, shaping the transmitted pulse waveform to achieve improved side lobe suppression and reduced PAPR. By convolving the modulated pulse with a Gaussian filter, the transmitted waveform exhibits enhanced autocorrelation properties and minimized side lobes. This leads to accurate target range estimation while maintaining a lower PAPR, enhancing power efficiency and mitigating interference effects. Simulation and optimization techniques can be employed to determine the optimal design parameters of the Gaussian filter for specific radar system requirements. The proposed approach offers a promising solution for achieving superior radar performance with minimized side lobes and reduced PAPR in pulse compression-based radar systems.

Keywords: Gaussian Filter, Costas Coding, Pulse Compression Radar, Side Lobe Suppression, Peak-To-Average Power Ratio (PAPR), Range Resolution, Windowing Function

I. INTRODUCTION

Pulse Compression Radar (PCR) plays a vital role in modern radar systems by enhancing range resolution and target detection capabilities. However, it is susceptible to unwanted side lobes and high Peak-to-Average Power Ratio (PAPR), which can compromise the accuracy and efficiency of radar signal processing [18]. To overcome these challenges, Gaussian filter-based Costas Coding has emerged as an effective technique, providing a solution for reducing side lobes and minimizing PAPR in PCR systems.

In pulse compression, a long-duration pulse is transmitted and then compressed to achieve high-range resolution [1]. This compression is typically achieved by convolving the received echo with a matched filter, which enhances the return signal, making it easier to detect and accurately locate targets. However, the matched filter's response often results in unwanted side lobes, i.e., secondary peaks appearing in the compressed signal's range profile. These side lobes can cause clutter, reduce target detection performance, and potentially introduce false alarms.

Furthermore, the transmitted signal in PCR is subject to high PAPR, which refers to the ratio between the peak power and the average power of the signal. High PAPR can exceed the dynamic range of the radar system, leading to non-linear distortions and inter-

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modulation effects. These distortions not only degrade target detection but also increase the complexity and cost of the radar system design.

To address these challenges, Gaussian filter-based Costas Coding has been introduced as an effective solution. The Costas Coding technique involves modulating the transmitted pulse with a binary phase sequence to suppress side lobes and improve the signal-to-noise ratio (SNR). The Gaussian filter is then applied to the modulated pulse, further shaping its spectrum, and reducing side lobes. This coding scheme ensures that the transmitted signal has a low PAPR, making it compatible with power-limited radar systems and reducing the potential for non-linear distortions.

The Gaussian filter's ability to shape the pulse spectrum effectively reduces side lobes, thereby enhancing the accuracy of target detection and clutter rejection [2]. By carefully selecting the filter parameters, such as the filter width and roll-off rate, the side lobe levels can be minimized, resulting in a sharper main-lobe and improved range resolution.

Moreover, the low PAPR characteristics of Gaussian filter-based Costas Coding enables the use of more efficient power amplifiers with lower cost and complexity. The reduction in PAPR also alleviates non-linear distortions, improving the linearity of the amplification process and maintaining the fidelity of the received signal [20].

Gaussian filter-based Costas Coding offers a promising solution for mitigating side lobes and reducing PAPR in pulse compression radar systems [3]. By employing this technique, radar systems can achieve enhanced target detection capabilities, improved range resolution, and more efficient utilization of power amplifiers. These advancements contribute to the overall performance and reliability of modern radar systems, enabling them to excel in various applications, including surveillance, tracking, and remote sensing.

II. SYSTEM DESCRIPTION

Side lobe suppression and low peak-to-average power ratio (PAPR) are two important considerations in pulse compression radar systems [22]. To achieve these objectives, a combination of techniques can be employed, including the use of a Gaussian filter and Costas coding.

Pulse compression radar is a technique used to improve the range resolution of radar systems [4] [17]. It works by transmitting a long pulse with a wide bandwidth and then compressing the received echoes using a matched filter. The compressed pulse allows for better target resolution and increased detection performance.

A Gaussian filter is a type of low-pass filter that attenuates higher frequency components while preserving lower frequency components [5]. In pulse compression radar, a Gaussian filter is used to shape the transmitted pulse and reduce the side lobes in the frequency domain [22]. The filter helps in minimizing interference from other signals and clutter, improving the radar's ability to detect and identify targets accurately.

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By applying the Gaussian filter; the transmitted pulse is modulated to have a Gaussian-shaped envelope, which results in a lower side lobe level compared to a rectangular or other types of pulse shapes. This reduces the interference caused by the side lobes and improves the radar's target detection capabilities.

Costas coding is a form of phase coding used in pulse compression radar systems [7]. It introduces specific phase modulations to the transmitted pulse, which helps in reducing the peak-to-average power ratio (PAPR) of the radar signal. PAPR is a measure of the difference between the peak power and the average power of the radar signal.

Matched filtering with a Gaussian filter is a technique used in signal processing and communications to enhance the detection of signals and improve signal-to-noise ratio [8] (SNR). The process involves correlating a received signal with a Gaussian-shaped filter to maximize the SNR and detect the presence of signals with similar characteristic.

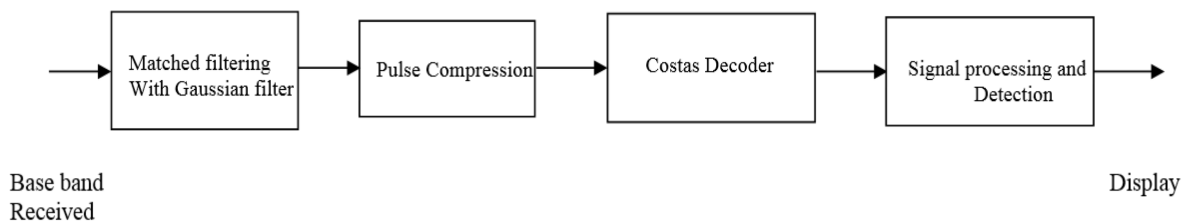

Fig 1: Block diagram of Pulse Compression with Gaussian filter.

In Costas coding, a sequence of binary codes is used to modulate the phase of the transmitted pulse. The codes are carefully designed to ensure that the resulting radar signal has a low PAPR. By reducing the PAPR, the radar system can operate at a higher average power without exceeding the peak power limits. This leads to improved radar performance, increased signal-to-noise ratio (SNR), and enhanced detection capabilities.

The combination of Gaussian filtering and Costas coding in pulse compression radar systems provides several benefits. The Gaussian filter reduces the side lobes of the transmitted pulse, minimizing interference from unwanted signals and clutter. This results in better target discrimination and improved radar performance.

Further, Costas coding reduces the peak-to-average power ratio of the radar signal [6]. This allows the radar system to operate at higher average power levels without exceeding the peak power limits, which enhances detection capabilities and increases the radar's signal-to-noise ratio. The combination of side lobe suppression and low PAPR improves the radar's ability to detect and identify targets accurately, especially in the presence of interference and clutter.

By employing Gaussian filtering and Costas coding techniques, pulse compression radar systems can achieve better side lobe suppression, lower PAPR, and improved target detection capabilities. These techniques play a crucial role in enhancing the performance and reliability of radar systems in various applications, including military, surveillance, and weather monitoring.

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The function of encoder is used to convert a binary data sequence into its equivalent Costas code of length N. The purpose of this encoding process is to enable the receiver to mitigate the impact of noise and interference encountered during transmission.

Costas codes are a type of synchronization code commonly used in communication systems to recover the carrier frequency and phase from a modulated signal [6]. They are designed to have desirable correlation properties, allowing the receiver to accurately estimate and synchronize with the transmitted signal.

By encoding the binary data sequence into a Costas code of length N, the receiver can benefit from the correlation properties of the code, which aids in mitigating the effects of noise and interference. This encoding process helps to improve the robustness and reliability of the communication system by enhancing the receiver's ability to accurately recover the transmitted signal despite the presence of disturbances. The BT ratio, BER (Bit Error Rate) and PAPR (Peak-to-Average Power Ratio) are all important metrics in radar and communication systems.

The BT ratio, also known as the time-bandwidth product or pulse compression ratio, is a parameter used in signal processing and radar systems to characterize the trade-off between time resolution and frequency resolution. It is commonly expressed as the product of the pulse duration (T) and the signal bandwidth (B). The equation for the BT ratio is:

$BT = T * B$ where,

BT is the BT ratio or time-bandwidth product,

T is the pulse duration (also known as pulse width or pulse length), and B is the signal bandwidth.

The BT ratio is an important factor in pulse compression techniques, where longer duration pulses are used to achieve better range resolution, while maintaining good frequency resolution [9]. By using a longer pulse and a matched filter, the compressed pulse can provide high-resolution range information. Different applications may have different optimal BT ratios based on factors such as target distance, desired range resolution, available bandwidth, and system limitations.

The BER measures the quality of the received signal by quantifying the number of erroneous bits compared to the total number of transmitted bits [10]. A lower BER indicates a higher quality and reliability of the received signal, while a higher BER suggests a higher level of noise or interference affecting the system's performance.

PAPR measures the maximum instantaneous power of a signal compared to its average power. It quantifies the fluctuations and peaks in the signal's power. Higher PAPR values require the transmitter and power amplifiers to handle larger power peaks, which can be challenging and costly.

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A Gaussian filter can be used in radar and communication systems in different ways:

Pulse Shaping: A Gaussian filter can shape the transmitted pulse to achieve desirable characteristics, such as good spectral properties and low side lobes [5]. By using a Gaussian filter for pulse shaping, the transmitted pulse can have a well-defined spectrum, which can help improve the range resolution and reduce interference.

Matched Filtering: On the receiver side, a Gaussian filter can be used as a matched filter to maximize the SNR and improve the detection performance [11]. The received signal is correlated with a replica of the Gaussian filter, which is designed to match the transmitted pulse's shape. This matched filtering operation helps amplify the desired signal and suppress noise and interference.

By using a Gaussian filter for pulse shaping and matched filtering, radar and communication systems can achieve improved range resolution, enhanced SNR, and better target detection [5]. These benefits ultimately contribute to lower BER and improved system performance.

Regarding the PAPR, it is a measure of the signal's power characteristics and are typically addressed using techniques like signal clipping, coding, or filtering. While a Gaussian filter may not directly affect the PAPR, it can indirectly impact the power characteristics by shaping the pulse and controlling the spectral properties, which might influence the PAPR in the overall system. However, specific PAPR reduction techniques are typically employed separately to address PAPR-related challenges.

In communication systems, pre-modulation Gaussian filtering is a technique used to shape the spectrum of the transmitted signal. It involves passing the baseband signal through a Gaussian filter before modulating it onto a carrier wave for transmission. This filtering process can introduce a phenomenon called Inter-symbol Interference (ISI) in the transmitted signal [11].

ISI occurs when the transmitted symbols (bits) spread out and overlap in time, causing interference between adjacent symbols. This interference can lead to errors in the received signal, making it more difficult to accurately decode the transmitted information.

However, the above statement suggests that the degradation caused by ISI is small if the 3dB bandwidth bit duration product (BT) is greater than 0.5. Let's break down this statement and understand its implications.

The 3dB bandwidth (B) of a system refers to the frequency range over which the power of the signal is at least half of its maximum power. It is a measure of how quickly the signal's power drops off as you move away from its central frequency.

The bit duration (BT) is the time taken to transmit a single bit of information [9]. It represents the time allocated to each symbol in the transmitted signal.

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The product of the 3dB bandwidth and bit duration (BT) represents the overlap between adjacent symbols in the time domain. It indicates how much the symbols spread out in time due to the Gaussian filtering process.

Now, if the BT value is greater than 0.5, it means that the symbols have a relatively narrow spread in time compared to their duration. This implies that the symbols are not heavily overlapped, and the interference between adjacent symbols is minimal.

This could be due to various factors such as the receiver's equalization techniques, signal-to-noise ratio, or error correction coding used in the system.

However, it's important to note that the specific value of 0.5 is arbitrary and context dependent. Different communication systems may have different tolerance levels for ISI, and the acceptable BT value may vary accordingly. Additionally, other factors like the modulation scheme, channel characteristics, and noise levels can also influence the overall system performance.

In summary, the statement suggests that if the product of the 3dB bandwidth and bit duration (BT) is greater than 0.5, the degradation caused by ISI in a pre-modulation Gaussian filtering system is small. This indicates that the transmitted signal can be effectively received and decoded with minimal errors, even though some interference may be present.

When the input data is in the form of Non-Return-to-Zero (NRZ) data and is passed through a pulse shaping filter, it means that the original binary data is transformed into a waveform that is suitable for transmission through a communication channel.

NRZ data is a binary representation where each bit is represented by a constant amplitude level. A '0' bit is typically represented by a low voltage level, while a '1' bit is represented by a high voltage level. This format is simple and easy to implement, but it can have drawbacks in terms of spectral efficiency and susceptibility to noise.

To improve the transmission characteristics, a pulse shaping filter is used. The purpose of the pulse shaping filter is to modify the shape of the NRZ waveform, often by applying a specific pulse shape, before transmitting it [15]. The filtering process is designed to reduce Inter symbol Interference (ISI) and improve the spectral efficiency of the signal [12].

By applying a pulse shaping filter, the NRZ waveform is convolved with the desired pulse shape. The resulting waveform has a modified shape, typically with smoother transitions between symbols and a reduced bandwidth. The specific pulse shape used can vary, but common choices include raised cosine, Gaussian, or square root raised cosine filters.

The pulse shaping filter helps in achieving a more efficient utilization of the available bandwidth by reducing the energy spread and reducing the interference between adjacent symbols. This leads to improved signal quality and reduced probability of errors during transmission.

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It's important to note that the choice of pulse shaping filter depends on various factors such as the specific communication. system, channel characteristics, desired bandwidth efficiency, and the tolerance for ISI. Different pulse shapes have different trade-offs between bandwidth efficiency and ISI suppression.

In summary, when the input data is in the form of NRZ data and is given to a pulse shaping filter, the filter modifies the shape of the waveform to improve transmission characteristics. The filtering process helps in reducing ISI and increasing the spectral efficiency of the signal, leading to improved signal quality and lower error rates during transmission as shown in fig 2.

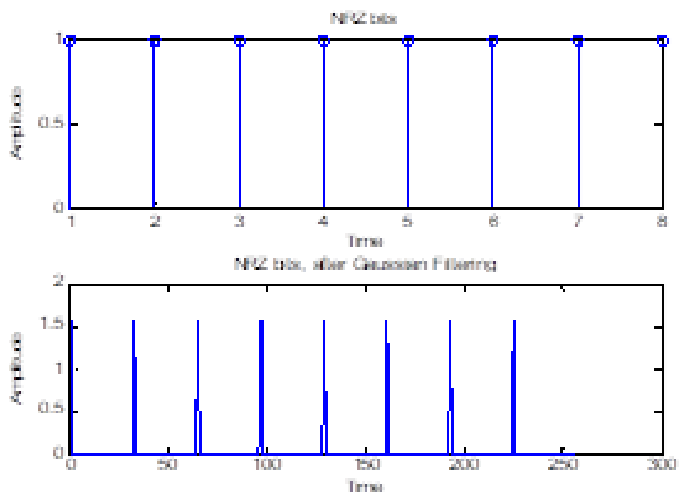

Fig 2: Comparison of NRZ Input Data and Output after Gaussian Filtering

III. USING GAUSSIAN FILTER

The Gaussian filter is a type of filter that uses a Gaussian function as its impulse response. It operates by convolving the input signal with the Gaussian function. The Gaussian function is a bell-shaped curve that smoothly attenuates the signal's frequency components as they move away from the centre frequency.

The Gaussian filter is a type of filter that uses a Gaussian function as its impulse response. It operates by convolving the input signal with the Gaussian function. The Gaussian function is a bell-shaped curve that smoothly attenuates the signal's frequency components as they move away from the centre frequency.

Costas coding is a type of coding scheme used in pulse compression radar systems. It involves modulating the transmitted waveform with a specific code sequence that possesses good auto-correlation properties.

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Costas coding, also known as Costas arrays or Costas permutations, is a special type of permutation used in coding theory and radar applications. It is used to minimize the ambiguity in radar pulse compression and symbol synchronization. The equation for Costas coding is not a single formula but rather a set of conditions that the permutation must satisfy.

The primary condition for a permutation to be a Costas array is that the distance between any two points in the permutation, measured in both the horizontal and vertical directions, must be unique [13]. Mathematically, this can be represented as follows:

For a permutation of length N, denoted as C = {c1, c2...cN}, where ci represents the position of the ith point, the following conditions must hold:

For any pair (i, j) where 1 ≤ i< j ≤ N:

|ci - cj| ≠ |i - j|

For any pair (i, j, k) where 1 ≤ i< j < k ≤ N:

|ci - ck| ≠ |i - k|

These conditions ensure that no two points in the permutation align horizontally, vertically, or diagonally, which reduces the ambiguity in radar pulse compression and symbol synchronization.

It's worth noting that finding Costas arrays becomes increasingly difficult as the length N increases. In fact, the search for large Costas arrays is an active area of research in combinatorial mathematics.

The Costas coding process begins by generating a unique code sequence with desired properties. This code sequence is typically a periodic sequence with specific mathematical characteristics. The code sequence is then modulated with the radar's baseband waveform or pulse, typically using techniques such as amplitude modulation or frequency modulation. The modulated waveform is transmitted through the radar system. At the receiver, the received signal is correlated with the same code sequence used for modulation.

The autocorrelation of a Linear Frequency Modulation (LFM) waveform with a Gaussian envelope refers to the calculation of the correlation between the LFM waveform and a delayed version of itself after both have been multiplied by a Gaussian function.

The autocorrelation is computed by multiplying the delayed and shifted waveform with the original Gaussian-envelope-modulated LFM waveform. This process involves multiplying the corresponding samples of the two waveforms at each time instant and summing up the results.

The auto-correlation function of LFM with Gaussian envelope is given by [10]

$$A_{GLFM}(\tau) = exp[\frac{-\pi\tau^2}{2\tau_{pt}^2}[1 + r_0\tau_{pt}^4]] \quad \text{…………} \ (2)$$

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τ_{pt} represents the effective pulse duration, $r_o$is the rate of frequency at time t=0 and τ is the pulse width.

The effective pulse duration is.

$$\tau_{pt} \equiv \frac{\left[\int_{-\infty}^{+\infty} |\mu(t)|^2 dt\right]^2}{\int_{-\infty}^{+\infty} |\mu(t)|^4 dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

By considering equation (2) & (3) states that autocorrelation function depends on pulse duration, pulse width and here in LFM at the demodulator side the pulse width is compressed.

The correlation process measures the similarity between the received signal and the code sequence. By correlating the received signal with the code sequence, the radar system can achieve pulse compression, reducing the pulse width in the range domain and improving range resolution.

The correlation process also helps in suppressing side lobes, enhancing target detection capabilities, and improving the system's ability to distinguish targets in the presence of clutter or noise.

An LPF (Low-Pass Filter) is a filter that allows low-frequency components of a signal to pass through while attenuating higher-frequency components. The LPF receives an input signal, which can be in the time domain or the frequency domain. The LPF operates by selectively attenuating or reducing the amplitude of the higher-frequency components of the input signal. This attenuation is achieved by utilizing electronic components or digital algorithms that implement mathematical operations. The cut-off frequency of the LPF determines the frequency beyond which the signal's components are significantly attenuated. The output of the LPF is the filtered signal, which contains the low-frequency components of the input signal. LPFs are commonly used in radar systems to filter out noise, unwanted high-frequency interference, or harmonics introduced during signal processing or transmission. The LPF helps in improving the overall signal quality, reducing the probability of false detections, and enhancing the radar system's performance in target detection and tracking.

In summary, the Gaussian filter shapes the spectral characteristics of the signal, Costas coding improves pulse compression and side lobe suppression, LFM modulation provides desirable waveform properties, BER measures the error rate in the received signal, and LPF filters out high-frequency noise and interference. These blocks work together to enhance the performance and capabilities of radar systems.

To differentiate the Range-Doppler Coupling plots for IF bandwidths of 1 MHz and 4 MHz, we need to understand how the choice of IF bandwidth affects the range resolution and Doppler resolution in radar systems.

IF Bandwidth = 1 MHz:

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A smaller IF bandwidth, such as 1 MHz, means that the radar system uses a narrower frequency range for intermediate frequency processing. This narrower bandwidth results in better range resolution but poorer Doppler resolution.

Range Resolution: With a narrower IF bandwidth, the range resolution improves. This is because the narrower frequency range allows the radar system to distinguish between closely spaced targets, resulting in sharper peaks in the Range-Doppler Coupling plot in the range dimension.

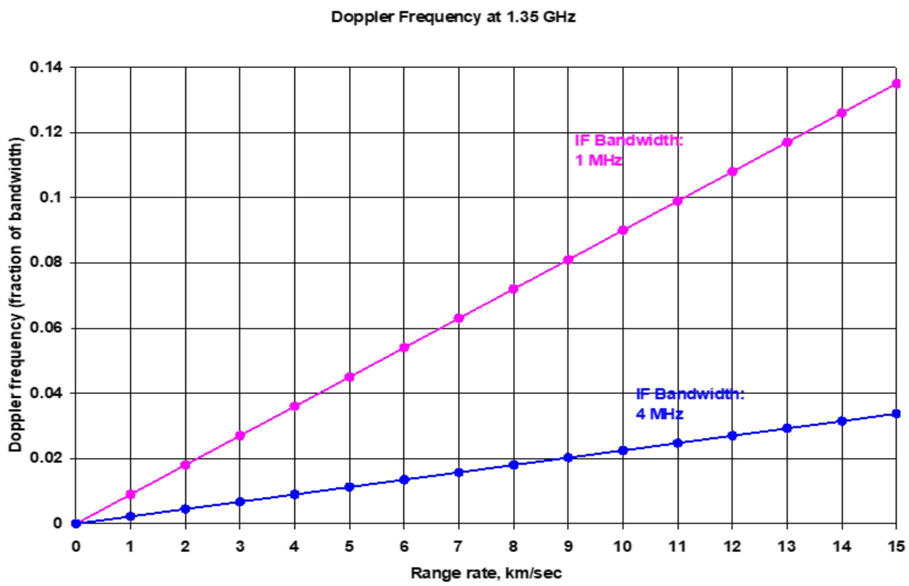

Fig 3: Range-Doppler Coupling plot to optimize the performance of radar systems.

Doppler Resolution: However, the Doppler resolution degrades with a smaller IF bandwidth. The narrower frequency range limits the system's ability to differentiate between targets with different radial velocities, leading to broader spread of energy in the Doppler dimension of the Range-Doppler Coupling plot.

IF Bandwidth = 4 MHz:

A larger IF bandwidth, such as 4 MHz, means that the radar system uses a wider frequency range for intermediate frequency processing. This wider bandwidth results in better Doppler resolution but poorer range resolution.

Range Resolution: With a wider IF bandwidth, the range resolution degrades. This is because the wider frequency range reduces the system's ability to distinguish between closely spaced targets, resulting in broader peaks in the Range-Doppler Coupling plot in the range dimension.

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Doppler Resolution: On the other hand, the Doppler resolution improves with a larger IF bandwidth. The wider frequency range allows the radar system to differentiate between targets with different radial velocities more accurately, leading to narrower spread of energy in the Doppler dimension of the Range-Doppler Coupling plot.

In summary, the choice of IF bandwidth in a radar system involves a trade-off between range resolution and Doppler resolution. A smaller IF bandwidth provides better range resolution but poorer Doppler resolution, while a larger IF bandwidth provides better Doppler resolution but poorer range resolution. The Range-Doppler Coupling plot visually represents this trade-off and helps in understanding the performance characteristics of the radar system for different IF bandwidth settings. In fig 3, shows range-Doppler coupling plot to optimize the performance of radar systems

The resulting autocorrelation function provides information about the pulse compression properties of the LFM waveform with the Gaussian envelope. It reveals the presence of side lobes and the main lobe width, which are important characteristics for radar systems. A sharp, narrow main lobe with reduced side lobes indicates good pulse compression and range resolution.

Thus, by compressing the pulse width, the autocorrelation function $A_{GLFM}(\tau)$ reaches close to unity.

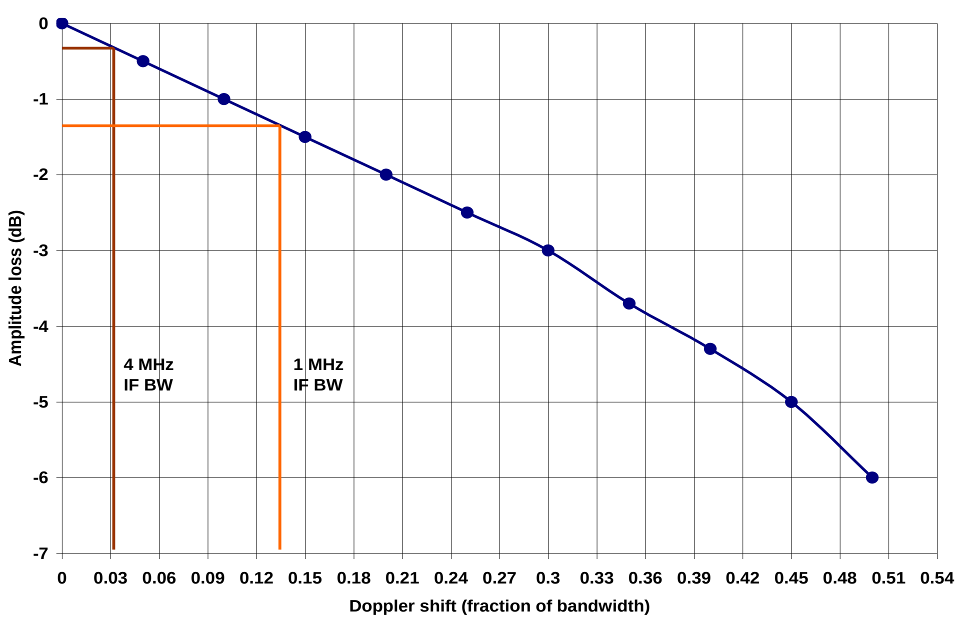

Fig 4: Graph of Amplitude Losses versus frequency shift

In this graph, we are interested in observing how the amplitude of a signal changes with respect to the frequency shift caused by the Doppler effect. The Doppler effect introduces a frequency shift in the received signal when the target (reflecting object) is moving relative to the radar system.

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Here's a general description of what the graph might look like:

X-axis: Frequency Shift (Δf)

This axis represents the frequency shift caused by the Doppler effect. It can be positive (indicating an increase in frequency, moving toward the radar) or negative (indicating a decrease in frequency, moving away from the radar). The unit is typically in Hertz (Hz) or kilohertz (kHz).

Y-axis: Amplitude Losses (Attenuation) in dB

This axis represents the amplitude losses experienced by the radar signal as it propagates through the medium and encounters attenuation. The unit is typically in decibels (dB).

The graph might have the following characteristics:

Frequency Shift (Δf) is centred around zero on the x-axis, indicating no frequency shift when the target is stationary relative to the radar (no relative motion).

As the target starts moving away from the radar (negative Δf), the amplitude losses may increase gradually as the signal propagates through the medium.

Similarly, as the target starts moving toward the radar (positive Δf), the amplitude losses may also increase gradually with distance.

The graph may show an increasing trend of amplitude losses as the frequency shift increases in either direction from zero.

Fig (5) shows the autocorrelation for an LFM pulse with a pre-modulation Gaussian filter. The characteristics of the autocorrelation plot will depend on the specific parameters of the LFM pulse, the Gaussian filter, and the delay between the original and delayed pulse. Fig 4 shows the graph of amplitude losses versus frequency shift.

To visualize the autocorrelation in a figure, generate a plot with time on the x-axis and the amplitude of the autocorrelation on the y-axis. The main lobe will be the central peak, and the side lobes will appear as smaller peaks or fluctuations on both sides of the main lobe. The plot can provide a visual representation of the pulse compression properties and the level of side lobe suppression achieved by the pre-modulation Gaussian filter.

Autocorrelation function serves radar to detect two closely similar, near and far target signals delayed by it.

By applying the autocorrelation function to the received radar signal, the radar system can analyse the similarities between the signal and its delayed version. The autocorrelation function (ACF) measures the correlation between the signal and the delayed signal as a function of the delay or time shift. This correlation information can help identify the presence of multiple closely spaced targets.

In this paper, the autocorrelation function shown in Fig 3 specifies during each lag the signal exactly matches.

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If the signal exhibits correlation at time t=0, as well as one and two-period lagging intervals, and then matches exactly at t=400 and t=800, it suggests a periodic or repeating pattern in the signal.

Furthermore, if the signal matches exactly at t=400 and t=800, it implies that the signal has a period of 400-time units. This periodicity can be observed by analyzing the ACF. At a lag of 400, the ACF would exhibit a significant peak, indicating the periodic nature of the signal. Additionally, a lag of 800 would show another peak since it is twice the period.

By analysing the ACF, it is possible to identify the periodicity of the signal and the lag positions where the correlation is significant. This information can be useful in various applications, such as detecting periodic components in a signal, estimating time delays, or identifying repeating patterns.

Based on fig 3, when evaluating the autocorrelation properties of a waveform, the peak autocorrelation values are important as they determine the level of side lobes and interference rejection capability. Lower side lobe levels (higher dB values) are generally preferred to ensure better synchronization and interference rejection performance.

Now, let's discuss the implications of the autocorrelation values mentioned here (0 dB, -10 dB, -20 dB):

Autocorrelation Value of 0 dB:

An autocorrelation value of 0 dB indicates a perfect correlation at the zero-time lag. This means that the signal exactly matches itself when there is no time shift. In terms of synchronization, this is highly desirable as it ensures accurate timing recovery at the receiver. A waveform with a 0 dB autocorrelation value has no side lobes, making it ideal for synchronization purposes.

Autocorrelation Value of -10 dB:

An autocorrelation value of -10 dB indicates that the peak autocorrelation value is 10 dB lower than the correlation at the zero-time lag. This suggests the presence of some side lobes in the autocorrelation function. While a -10 dB value is generally acceptable, it might lead to some interference issues and could affect the synchronization performance, especially in scenarios with challenging channel conditions.

Autocorrelation Value of -20 dB:

An autocorrelation value of -20 dB indicates that the peak autocorrelation value is 20 dB lower than the correlation at the zero-time lag. This implies the presence of stronger side lobes in the autocorrelation function. A waveform with a -20 dB autocorrelation value might have poor autocorrelation properties, which can lead to significant interference and synchronization challenges.

In summary, a waveform with a 0 dB autocorrelation value is ideal for synchronization purposes as it has no side lobes and offers excellent timing recovery. As the

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ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 56 Issue: 10:2023
DOI: 10.5281/zenodo.8433576

autocorrelation values become more negative (e.g., -10 dB, -20 dB), the presence of side lobes increases, leading to potential interference issues and synchronization performance degradation.

When designing waveforms for digital communication systems, it's essential to consider the autocorrelation properties and select waveforms that provide better synchronization and interference rejection capabilities. Different modulation schemes and pulse shaping techniques can be used to achieve desirable autocorrelation characteristics based on the specific requirements of the communication system

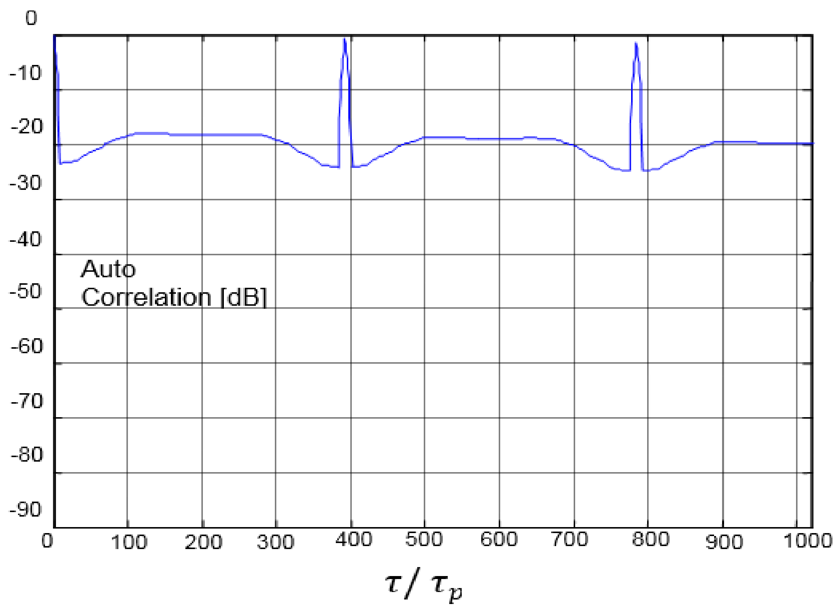

Fig 5: Autocorrelation function from a pre-modulation Gaussian filter-based Costas coding.

Fig 6 shows the autocorrelation for an LFM pulse without a filter, to generate an autocorrelation plot for an LFM (Linear Frequency Modulated) pulse with three targets and calculate the spectral density for different autocorrelation values (0 dB, -10 dB, -20 dB, etc.), we first need to define the LFM pulse parameters and the positions of the three targets. For this example, let's assume the following parameters:

LFM Pulse Parameters:

Center Frequency (fc): 2 GHz

Bandwidth (B): 100 MHz

Pulse Duration (T): 10 microseconds

Positions of Targets:

Target 1: 500 meters away from the transmitter

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Target 2: 800 meters away from the transmitter

Target 3: 1200 meters away from the transmitter

Now, let's go through the steps to generate the autocorrelation plot and calculate the spectral density for the specified autocorrelation values.

Step 1: Generate the LFM Pulse Signal

We can represent the LFM pulse signal mathematically as follows:

x (t) = exp (j * pi * beta * t^2) * rect((t - T/2) / T)

Where, Beta = B / T (chirp rate)

T is the pulse duration rect (t) is the rectangular function, which is 1 when |t| <= 0.5 and 0 otherwise

Step 2: Generate the Time Delayed Versions for Each Target

For each target, we will apply a time delay to the LFM pulse to represent the return echoes from the targets.

x_target1 (t) = x(t - 2 * R1 / c)

x_target2 (t) = x(t - 2 * R2 / c)

x_target3 (t) = x(t - 2 * R3 / c)

Where,

R1, R2, R3 are the distances of Target 1, Target 2, and Target 3 from the transmitter, respectively.

c is the speed of light.

Step 3: Compute the Autocorrelation Function

The autocorrelation function R (tau) of the LFM pulse can be computed as follows:

R (tau) = ∫[x (t) * x*(t - tau)] dt

Where x*(t) is the complex conjugate of the LFM pulse.

Step 4: Generate the Autocorrelation Plot

Calculate R (tau) for different values of tau and plot the results.

Step 5: Compute the Spectral Density

The power spectral density S (f) of the LFM pulse can be obtained using the Fourier Transform of the autocorrelation function R (tau):

S (f) = Fourier Transform {R (tau)}

Calculate the spectral density values for different frequencies and plot the results.

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Please note that the actual values and shapes of the autocorrelation plot and spectral density will depend on the specific parameters of the LFM pulse and the target distances. The above steps provide a general approach to analyze the autocorrelation and spectral density properties of an LFM pulse with three targets.

Fig 6 shows the autocorrelation for an LFM pulse without a filter. Here the side lobe arrays are visible with the amplitude of - 65 dB level with main lobe amplitude of -17 db.

For an LFM pulse with low side lobe levels (-65 dB) and high main lobe amplitude (-17 dB), the pulse is likely to have better temporal resolution due to the narrow main lobe of the autocorrelation function. The low side lobe levels indicate good side lobe suppression, which is desirable to reduce interference and improve target detection in radar and communication systems.

An LFM pulse with low side lobe levels (-65 dB) and high main lobe amplitude (-17 dB) is likely to exhibit good temporal resolution and spectral efficiency. However, to provide specific values for the autocorrelation function and spectral efficiency, we need to know the pulse's duration and bandwidth. These parameters directly influence the pulse's performance in time and frequency domains.

Also, the shape of the waveform of the correlation function depends on the autocorrelation function $A_{GLFM}(\tau)$for the pulse shape having pulse duration τ_{pt}. By matched filtering, this basically uses the complex conjugate of the real radar signal to filter the received signal. The conjugate property eliminates range side lobes considerably during the nonzero integer period [14].

By verifying these figures, the side lobes are efficiently suppressed with the application of Gaussian filter based pre-modulated Costas coded LFM [13]. These results are compared with the other techniques with necessary simulated waveforms. There is no spectral leakage, and this improves the spectral efficiency of this system.

To calculate the autocorrelation for an LFM (Linear Frequency Modulated) pulse and its spectral efficiency without a filter, we need additional information about the pulse characteristics. Specifically, we require the pulse duration, bandwidth, and any windowing function applied to the pulse.

Additionally, the given information about the side lobe level

(-65 dB) and main lobe amplitude (-17 dB) clarifies the pulse's side lobe suppression capability. Fig 6 shows autocorrelation plot for an LFM pulse using three targets without filter.

The amplitude of -65 dB level with main lobe amplitude of -17 dB refers to the side lobe levels and the main lobe amplitude of an LFM (Linear Frequency Modulated) pulse.

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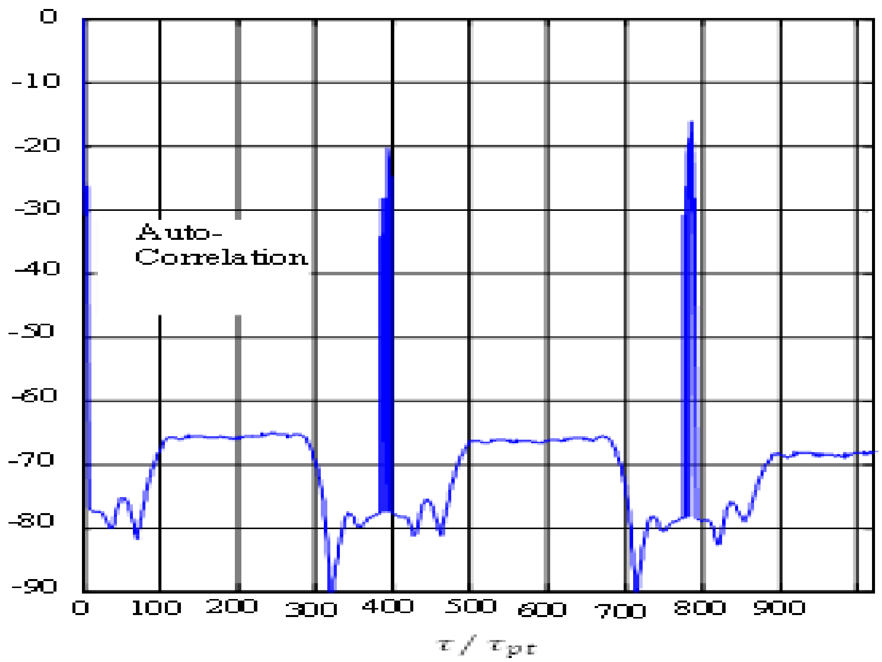

Fig 6: Autocorrelation plot for an LFM pulse using three targets without filter.

Main Lobe Amplitude: -17 dB

The main lobe amplitude of the LFM pulse is specified as -17 dB. In radar or signal processing, the main lobe represents the central peak of the autocorrelation function, which is the pulse's self-similarity at zero-time shift (tau = 0). The main lobe amplitude indicates the strength of the pulse's correlation with itself at zero-time delay.

Side lobe Level: -65 dB

The side lobe level refers to the amplitudes of the side lobes in the autocorrelation function. Side lobes are the smaller peaks or ripples in the autocorrelation plot that occur away from the main lobe. They represent the correlation of the pulse with itself at non-zero-time shifts (tau ≠ 0). A side lobe level of -65 dB indicates the amplitude of the side lobes relative to the main lobe amplitude.

A higher side lobe level, such as -65 dB, means that the side lobes are weaker compared to the main lobe, indicating good side lobe suppression. In practical radar systems, suppressing side lobes is important as it reduces interference with other signals, improves target detection, and enhances system performance.

As shown in fig 7, the autocorrelation plot for an LFM pulse using the Costas coding method. The main lobe is the central peak in the autocorrelation plot, which represents the correlation between the transmitted LFM pulse and it's undelayedly version. The main lobe amplitude of -17 dB indicates the peak strength of the autocorrelation at time delay τ = 0. It shows a relatively high correlation between the pulse and its delayed version.

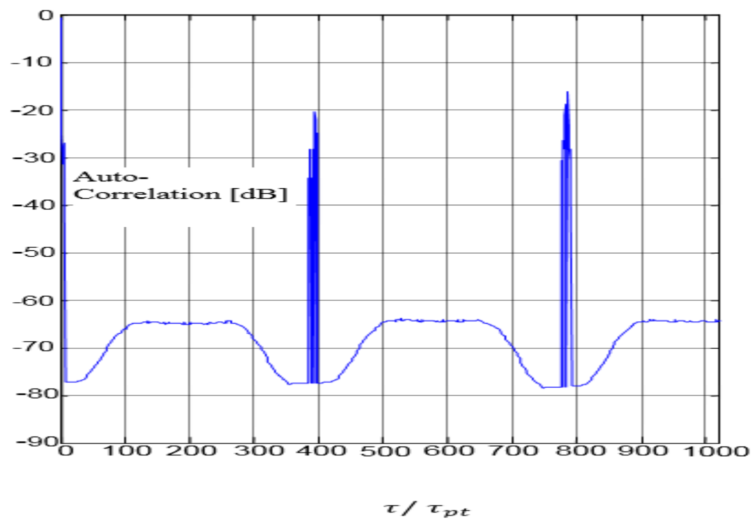

Fig 7: Autocorrelation plot for an LFM pulse using Costas coding with three targets without filter.

The side lobes are the secondary peaks on both sides of the main lobe. The side lobe level of -65 dB indicates that the amplitude of the side lobes is significantly lower than the main lobe. A side lobe level of -65 dB means that the side lobes are around 48 dB (65 dB - 17 dB) weaker than the main lobe.

This second objective of this paper is to measure the theoretical importance of BER performance and efficiency of the conventional radar with constant envelope properties of the coherent receiver [10]. This assessment lies in understanding how a coherent receiver with constant envelope properties can impact the BER performance and overall efficiency of conventional radar systems as shown in fig 8. By evaluating the trade-offs and benefits, the paper can provide insights into the potential advantages of using such a radar configuration in specific applications and scenarios.

In an ideal scenario without other impairments or interference, the BER performance of a matched filter with BPSK modulation in AWGN follows the theoretical expression for BPSK in AWGN channels:

$$BER \approx 0.5 * \exp(-SNR)$$

Where SNR is the Signal-to-Noise Ratio of the received signal. This expression shows that as the SNR increases, the BER decreases, indicating better performance in terms of error rate.

In summary, using a matched filter in the receiver, along with the BPSK modulation, can improve the SNR and BER performance, especially in AWGN channels and is shown in Fig 9.

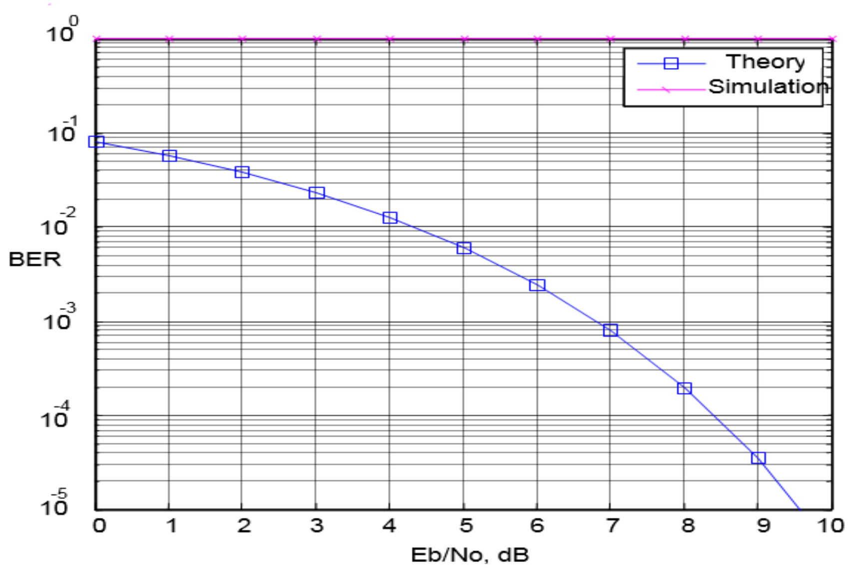

Fig 8: SNR versus BER over BPSK modulation.

Bit error probability curve for BPSK using OFDM self cancellation scheme

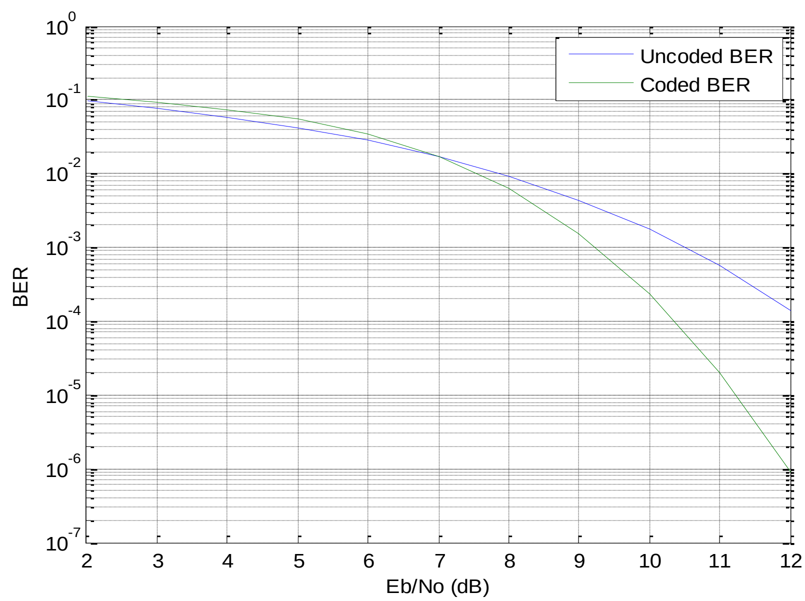

Fig 9: SNR versus BER for coded AWGN channel

The theoretical bit error rate in the case of Gaussian filter with coherent receiver is given by,

Pe $=\frac{1}{2} erfc(\sqrt{Eb/\text{No}})$ …………………. (4)

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Where *Pe* is the energy per transmitted bit and N is the noise power spectral density. The equation to find *Eb* is given by [6] is

$$Eb = \frac{1}{2}\int_0^T |U_H\,(t)|^2 dt = \frac{1}{2}\int_0^T |U_L(t)|^2 dt\ldots\ \ldots (5)$$

Where U_H(t) and $U_L(t)$are the complex signal waveforms corresponding to binary 1 and binary 0 transmissions, respectively. This equation (5) indicates that the error probability is dependent only on the energy contents of the signal that is Eb as the energy increases, value of error function $erfc$ decreases and the value of *Pe* will reduce.

The received signal after passing through the Gaussian filter and being affected by AWGN can be expressed as:

r(t) = A * s(t) + n(t)

Where r(t) is the received signal, A is the received signal amplitude scaling factor,

s (t) is the transmitted BPSK signal,

n (t) is the AWGN noise.

V. SIMULATION RESULT

In this paper, we have presented the simulated results used to evaluate CCDF versus PAPR reduction capability as shown for Costas array. In the context of PAPR reduction, CCDF is often used to evaluate the effectiveness of PAPR reduction techniques. PAPR reduction aims to minimize the difference between the peak power and the average power of a signal, thereby reducing power fluctuations and improving overall power efficiency. This constant envelope characteristic of CE-OFDM makes it well-suited for power-constrained communication systems [21], such as those used in satellite communications, wireless networks, and other scenarios where power efficiency is crucial.

The relationship between CCDF and PAPR reduction for N=1024 (N being the number of samples in the signal) would be evident when comparing the CCDF curves of the original signal (without PAPR reduction) and the modified signal (after applying PAPR reduction techniques). The goal of PAPR reduction techniques is to shift the CCDF curve towards the left, indicating fewer high-power events and a more uniform power distribution.

In summary, the CCDF plot for N=1024 demonstrates how the probability of exceeding a certain power level changes for the signal before and after applying PAPR reduction techniques. Lowering the CCDF curve indicates successful PAPR reduction, resulting in a more power-efficient signal with reduced peak-to-average power fluctuations. This can lead to improved performance in communication systems and more efficient power amplification.

It's important to note that CE-OFDM does have certain limitations, such as reduced spectral efficiency compared to conventional OFDM, as the amplitude of the transmitted signal is fixed. However, its benefits in terms of power efficiency and reduced non-linear

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distortion in power amplifiers make it a viable option in various communication applications, especially in scenarios with stringent power constraints.

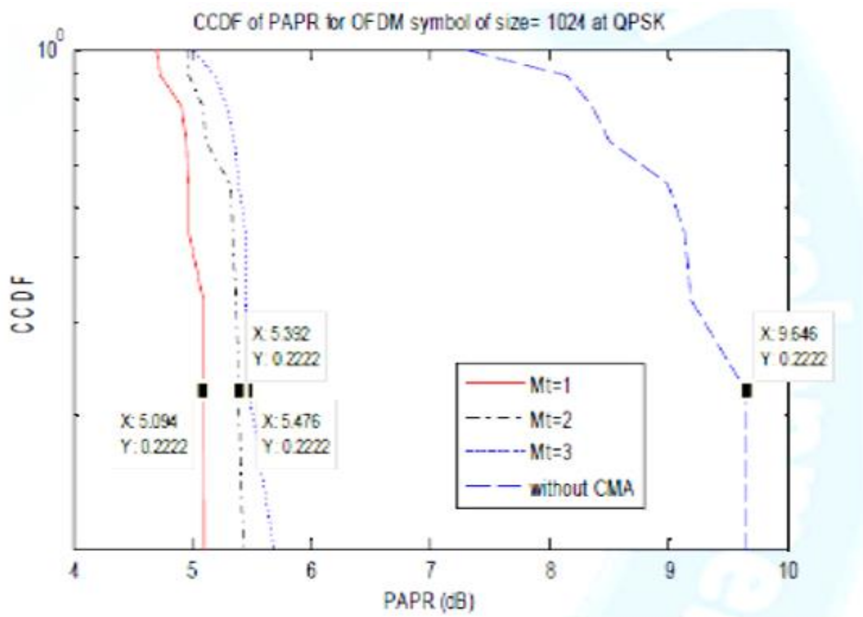

Fig 10: Conventional methods of PAPR reduction for Mt=1 & Mt=3

Here the coding was done in MATLAB software, PAPR reduction technique was done by using Constant amplitude modulation implementing a PAPR reduction technique using Constant Amplitude Modulation (CAM) can be an effective way to mitigate the effects of high peak-to-average power ratio (PAPR) in the transmitted signal. MATLAB, being a widely used programming environment for signal processing and communications, provides a convenient platform to implement such techniques. Let's discuss the general steps involved in PAPR reduction using CAM in MATLAB. Generate the original OFDM signal, which typically consists of multiple subcarriers, each modulated with data symbols. This step involves creating the time-domain signal using inverse Fast Fourier Transform (IFFT) and assigning data symbols to subcarriers.

Implement the PAPR reduction technique using Constant Amplitude Modulation (CAM) [16]. This involves adjusting the signal amplitudes of selected subcarriers to ensure that all subcarriers have the same constant amplitude. After applying CAM, perform the inverse Fast Fourier Transform (IFFT) again to convert the signal back to the time domain.

The relationship between CCDF and PAPR reduction for N=1024 (N being the number of samples in the signal) would be evident when comparing the CCDF curves of the original signal (without PAPR reduction) and the modified signal (after applying PAPR reduction techniques). The goal of PAPR reduction techniques is to shift the CCDF curve towards the left, indicating fewer high-power events and a more uniform power distribution.

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To illustrate the relationship between CCDF (Complementary Cumulative Distribution Function) and PAPR (Peak-to-Average Power Ratio) reduction for a Costas Array with GMSK (Gaussian Minimum Shift Keying) modulation and Mt=3 (three transmit antennas) [19], we need to understand how PAPR reduction techniques can impact the power characteristics of the transmitted signal and consequently affect the CCDF curve, which was simulated by using MATLAB software. Fig 11 shows the graph, CCDF versus PAPR reduction for Costas Array with GMSK, Mt=3.

Also in Fig.10, PAPR Value: 5.392; The PAPR value of 5.392 indicates the peak power level in the transmitted signal relative to its average power. A high PAPR value suggests that the signal experiences large power fluctuations, which can lead to inefficiencies in power amplification and potential distortion in the transmitter.

CCDF at PAPR Value: 0.2222

The CCDF value of 0.2222 at the PAPR value of 5.392 represents the probability that the signal's power exceeds the given PAPR value. In other words, there is a 22.22% chance that the transmitted signal will have a PAPR value equal to or higher than 5.392.

Existing CMA Algorithm:

The results are obtained using the existing CMA (Constant Modulus Algorithm) algorithm for PAPR reduction. CMA is a well-known algorithm used to reduce the PAPR in communication systems, particularly in OFDM-based systems.

Interpretation:

The PAPR value of 5.392 indicates that the transmitted signal experiences relatively large power fluctuations. However, after applying the CMA algorithm for PAPR reduction, the CCDF value of 0.2222 at the PAPR value suggests that the algorithm has been effective in reducing the probability of high-power events in the transmitted signal. The reduction in the CCDF value indicates that the PAPR reduction technique has succeeded in mitigating the signal's peak power fluctuations, which can lead to improved power efficiency and reduced non-linear distortion in the power amplifier.

As shown below in fig 11, the PAPR value of 2.196 indicates the peak power level in the transmitted signal relative to its average power. A lower PAPR value suggests that the signal experiences reduced power fluctuations, which is desirable for more power-efficient communication systems.

The results mention that the reduced PAPR value of 2.196 is approximately 3.196 dB lower than the PAPR value achieved using the conventional method. Decibels (dB) are a

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logarithmic unit used to represent ratios or differences in power levels. In this context, the reduction of 3.196 dB indicates a significant improvement in PAPR reduction compared to the conventional method.

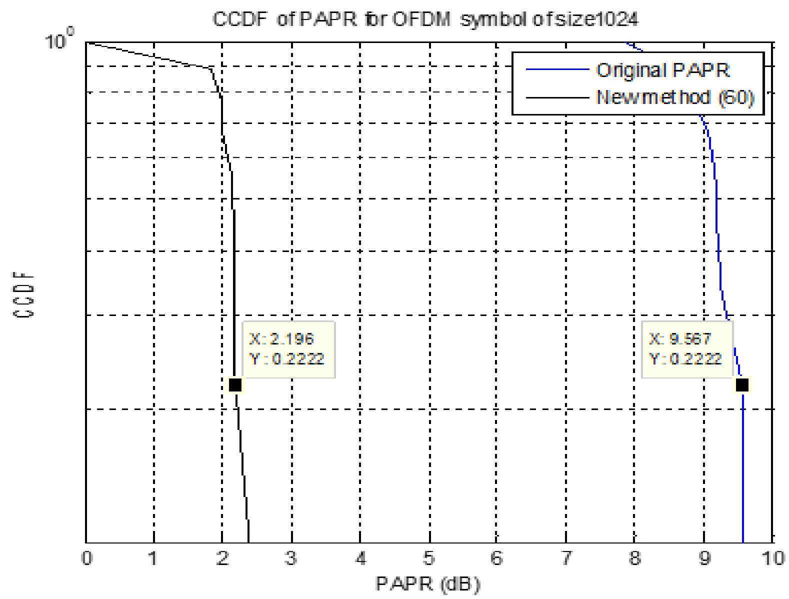

Fig 11: CCDF versus PAPR reduction for Costas Array with GMSK, Mt=3

The complexity of the modulation scheme (e.g., QAM, QPSK) lies in the number of bits represented by each subcarrier and the varying angles required to encode the data. On the other hand, constant amplitude modulation (e.g., GMSK) provides a simpler representation with a fixed amplitude envelope, which can lead to lower PAPR [14].

On the other hand, a PAPR value of 2.196 suggests an even lower peak power level compared to the average power. A PAPR value of 2.196 is slightly lower than 2.247, which indicates that the signal experiences even fewer power fluctuations and is likely to be more power-efficient, as shown in fig 12.

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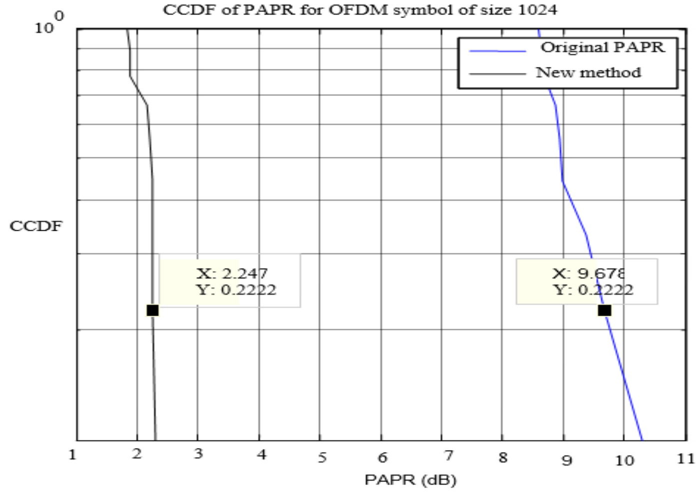

Fig 12: CCDF versus PAPR reduction for Barker, Mt=3

In fig. 11 we have shown the ability to reduce the PAPR to a lower value. In this scenario, the OFDM system uses a Constant Envelope OFDM modulation scheme, where the amplitude of the transmitted signal remains constant over time. The modulation scheme involves the use of LFM (Linear Frequency Modulation) to modulate the data onto the subcarriers. The binary data is represented using Non-Return-to-Zero (NRZ) format.

CCDF Value at -10 dB:

The CCDF value mentioned as 10^ (-1) (which corresponds to -10 dB) represents the probability that the power of the transmitted signal exceeds a certain threshold, specifically -10 dB below the peak power. In other words, CCDF at -10 dB indicates the probability of having power peaks that are 10 dB above the average power level.

PAPR Value and PAPR Reduction:

The PAPR value of 2.196 indicates the peak power level of the transmitted signal relative to its average power. This value is relatively low due to the constant envelope property of the OFDM modulation scheme, which inherently reduces the PAPR compared to conventional OFDM schemes with varying amplitudes.

PAPR Reduction Compared to Conventional Method:

The PAPR value of 2.196 achieved in this method is approximately 3.196 dB lower than the PAPR achieved using the conventional OFDM method. The reduction of 3.196 dB indicates that the PAPR reduction technique used in this Constant Envelope OFDM with LFM modulation and binary NRZ data has successfully lowered the peak power fluctuations in the transmitted signal compared to the conventional method.

In summary, the provided results demonstrate the benefits of using Constant Envelope OFDM with LFM modulation and binary NRZ data. The constant envelope property of the modulation scheme inherently leads to a low PAPR value, which is further reduced

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through the PAPR reduction technique applied. The reduction in PAPR improves power efficiency and helps avoid non-linear distortion in the transmitter, making this method well-suited for power-constrained communication systems.

Fig 13 shows the 13-bit Costas coded LFM waveform is a specific type of LFM waveform that includes a Costas coding sequence of 13 bits. This coding sequence is used to reduce the range sidelobes and improve the range resolution of the radar system.

Analyze the ambiguity diagram to understand the range and Doppler ambiguities of the radar system. The mainlobe of the diagram represents the actual target, while the sidelobes indicate potential false targets due to ambiguity.

In summary, the comparison of reduced PAPR values for the Costas Array shows that achieving a PAPR value of 2.196 represents the most effective reduction in peak power fluctuations, making it a preferred choice for power efficiency and signal quality. The PAPR values of 2.247 and 2.302 are also relatively low, while the PAPR value of 2.578 indicates a higher level of fluctuations. The choice of the PAPR reduction technique would depend on specific system requirements, including power efficiency, signal fidelity, and spectral efficiency in communication and radar systems.

Absolutely, the summary captures the key advantages and benefits of using Costas coded LFM with a Gaussian filter in radar signal processing. Let's recap the main points:

Improved Correlation Properties:

Costas coding applied to LFM waveforms helps improve the correlation properties of the transmitted signal. The low sidelobes in the autocorrelation function allow for better target discrimination, reducing ambiguity and improving target detection.

Enhanced Range Resolution:

By using Costas coded LFM, the radar system achieves improved range resolution, allowing it to distinguish between closely spaced targets. This enhanced resolution enables accurate localization and tracking of targets.

Spectral Efficiency:

The combination of Costas coding and Gaussian filtering reduces spectral leakage in the frequency domain. This results in a cleaner frequency spectrum, allowing for better spectral efficiency and utilization of available frequency resources.

Increased Sensitivity:

The reduced spectral leakage and improved correlation properties lead to increased radar system sensitivity. The system can detect weaker signals more effectively, enhancing its performance in challenging environments with clutter and interference.

Reliable Performance in Challenging Environments:

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The advantages of Costas coded LFM with a Gaussian filter make it highly suitable for radar systems operating in challenging environments, such as in the presence of multiple targets, clutter, and noise. The technique provides reliable and accurate target detection under various conditions.

Well-Established Technique:

Costas coded LFM with a Gaussian filter is a well-established and widely used technique in radar signal processing. Its effectiveness in enhancing radar performance has been demonstrated in numerous applications.

Overall, the combination of Costas coding with LFM and Gaussian filtering provides significant benefits for radar systems, making it a popular choice in various radar applications. The technique contributes to accurate target detection, improved sensitivity, and robust performance, making it well-suited for both military and civilian radar systems operating in diverse and challenging scenarios.

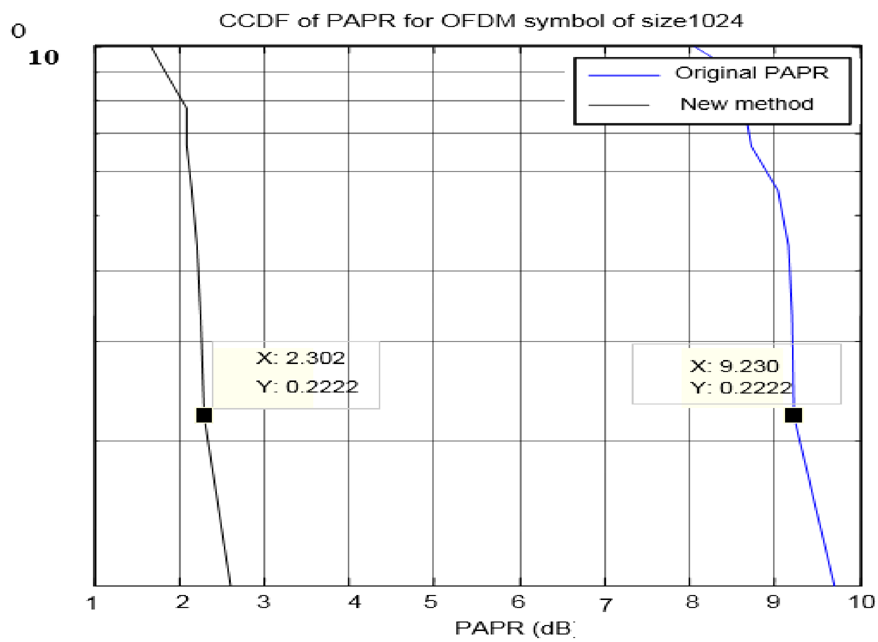

Fig 13: PAPR versus CCDF value of LFM pulse train =3

Furthermore, comparing the ambiguity diagrams of different radar waveforms, including Costas Array with Gaussian filter, LFM pulse, Barker code, and un-modulated pulse, will help us understand their respective properties and performance in range and Doppler resolution. Ambiguity diagrams are used to visualize the radar system's response in the range-Doppler domain. Please note that the actual appearance of ambiguity diagrams will depend on the specific parameters and configurations used. Below, we'll discuss general characteristics for each waveform:

Costas Array with Gaussian Filter:

The ambiguity diagram for Costas Array with Gaussian filter would exhibit improved correlation properties due to the Costas coding. This results in reduced range side lobes, enabling better target discrimination and improved range resolution.

The Gaussian filter reduces spectral leakage, leading to a cleaner frequency spectrum and improved spectral efficiency.

Overall, this combination provides better sensitivity and reliable performance in cluttered environments.

Linear Frequency Modulation (LFM) Pulse:

LFM pulses typically have a main lobe with good range resolution. The width of the main lobe determines the radar's range resolution capability.

However, LFM pulses suffer from high side lobes in the range domain, leading to ambiguity and possible false target detections.

In the Doppler domain, LFM pulses exhibit a wide main lobe, providing better velocity resolution but also increasing Doppler ambiguity.

Barker Code:

The ambiguity diagram for Barker-coded pulses will show low range side lobes due to the Barker codling's properties.

However, Barker codes have limited range resolution, as their duration restricts the transmitted bandwidth.

In the Doppler domain, Barker codes generally exhibit wide main lobes, leading to Doppler ambiguities and limitations in velocity estimation.

Un-modulated Pulse:

An un-modulated pulse has a narrow main lobe in the range domain, resulting in good range resolution.

In the Doppler domain, un-modulated pulses have a single spectral line, leading to a lack of Doppler resolution. Un-modulated pulses can only provide radial velocity information.

In summary, each waveform has its advantages and limitations in terms of range and Doppler resolution:

Costas Array with Gaussian filter offers improved correlation properties, reduced range side lobes, and better sensitivity.

LFM pulses have good range resolution but suffer from higher range side lobes and wider Doppler ambiguity.

Barker codes have low range side lobes but limited range resolution and wide Doppler ambiguity.

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Un-modulated pulses provide good range resolution but lack Doppler resolution.

The choice of waveform depends on the specific radar system requirements, such as the need for high range or Doppler resolution, sensitivity, and clutter rejection. Different waveforms are employed in various radar applications based on their strengths and weaknesses.

The ambiguity diagram of different technique s are shown in fig 15, 16, 17 and 18,

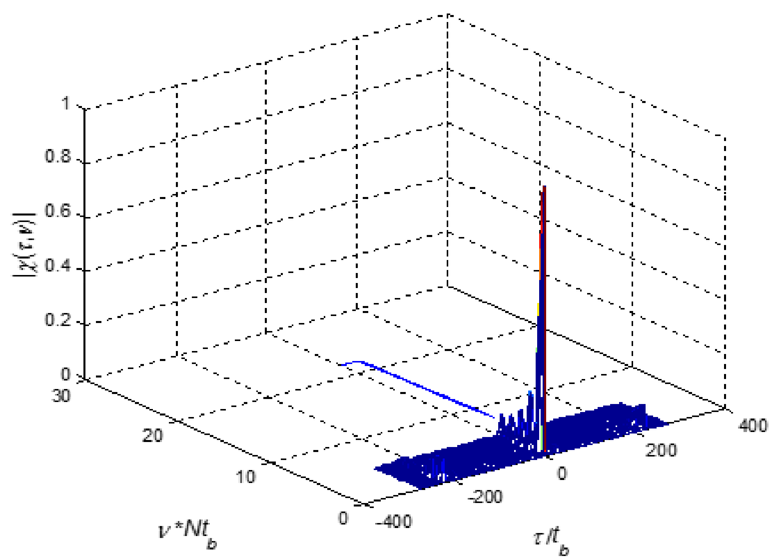

Fig.15: Ambiguity diagram for Costas Array with Gaussian filter

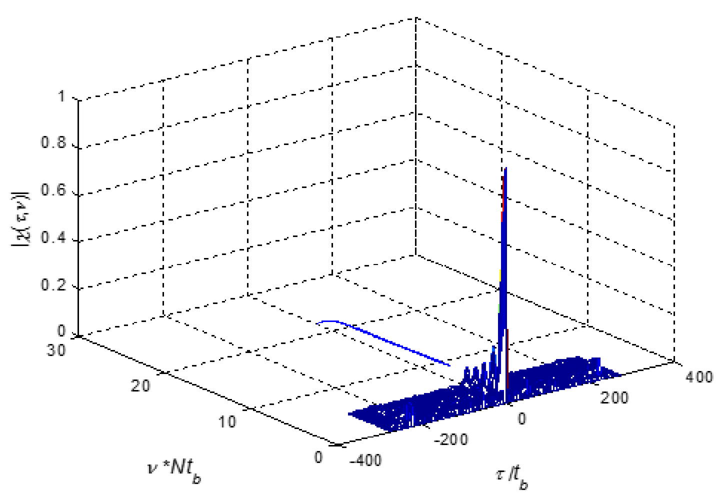

Fig.16: Ambiguity diagram for an LFM pulse

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Based on the information provided, Fig.15 shows the ambiguity diagram of the Costas method, and it is stated that there are absolutely no sidelobes. This characteristic of the ambiguity diagram is indeed a significant advantage of using the Costas method, as it provides improved range resolution.

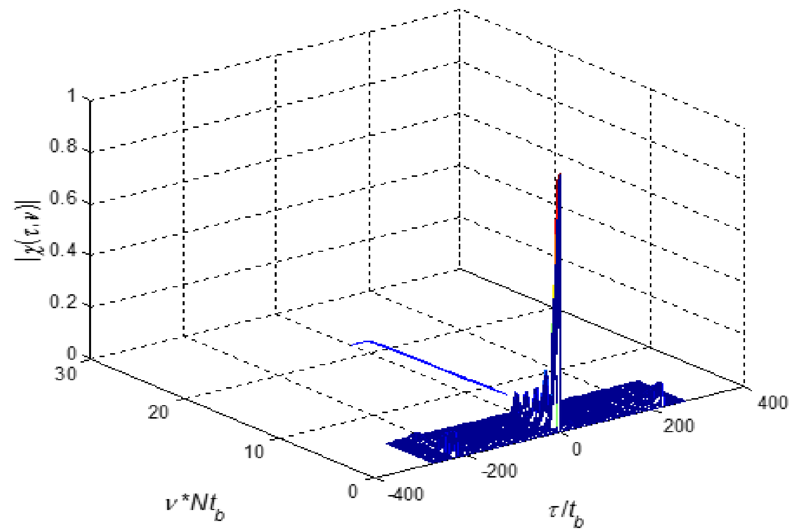

Fig.17: Ambiguity diagram for Barker coded pulse

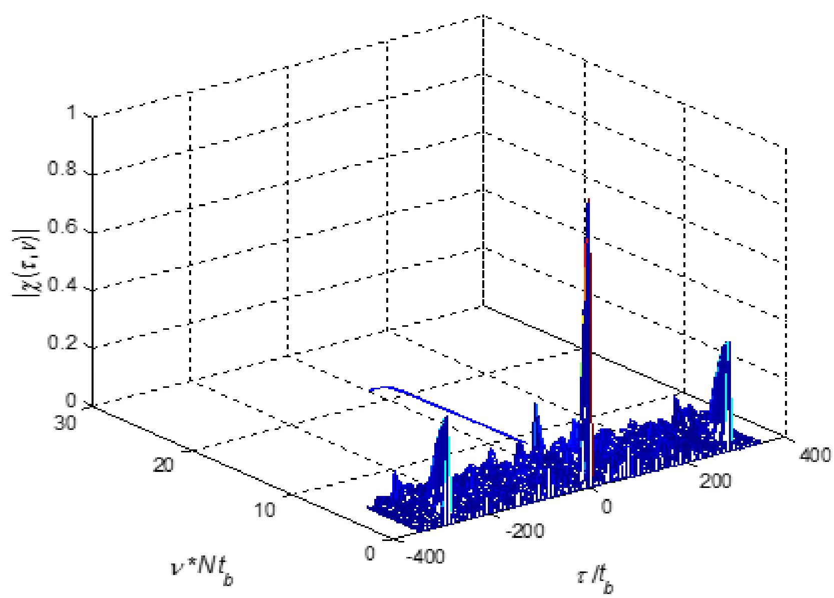

Fig.18: Ambiguity diagram for an un-modulated pulse

It appears that the statement provided relates to a specific evaluation process for PAPR reduction in the receiver using both unambiguous Doppler and ideal range information.

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Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 56 Issue: 10:2023
DOI: 10.5281/zenodo.8433576

Additionally, the evaluation metric used for PAPR reduction is based on the amount of CCDF (Complementary Cumulative Distribution Function) reduction achieved**.** Fig 19 Constant Modulus Algorithm of PAPR reduction for OFDM

Comparison of PAPR reduction techniques

Modulation Used	No of antennae	PAPR Value in OFDM	Improved PAPR Value
CONVENTIONAL METHOD	3	9.645	5.392
CE-OFDM based COSTAS CODING using GMSK	3	9.567	2.196
BARKER CODE	3	9.67	2.247
CE-OFDM based LFM pulse	3	9.230	2.302

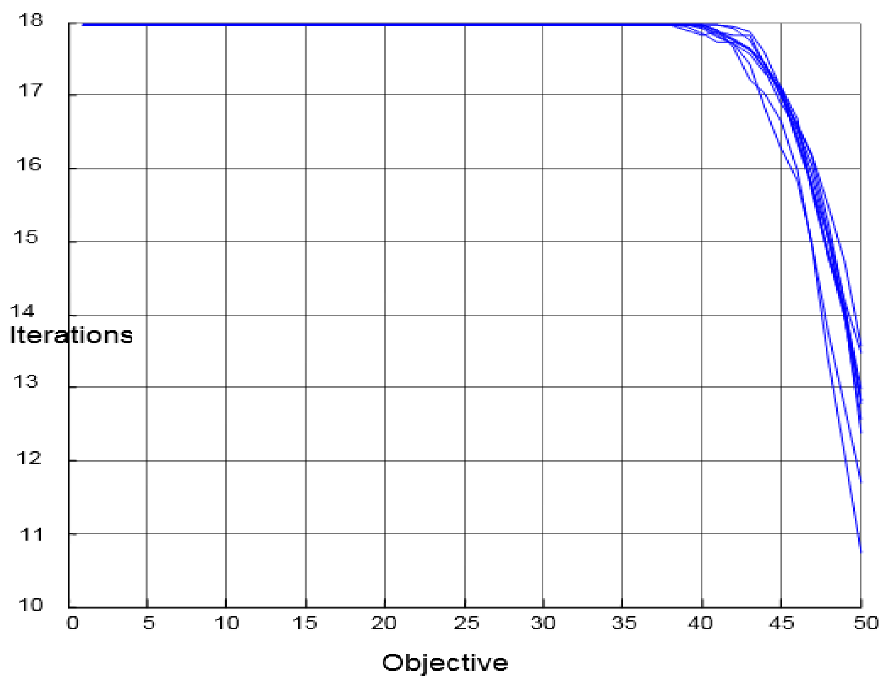

Fig 19: Constant Modulus Algorithm of PAPR reduction for OFDM

VI. DISCUSSION

This paper summarizes the benefits and advantages of using Costas Frequency coding and Constant Envelope OFDM (CE-OFDM) for PAPR reduction in OFDM-based radar systems. Here are the key points summarized.

Costas Frequency coding is utilized as an alternative to achieve low PAPR values and an ambiguity function with fewer side lobes.

The proposed scheme based on phase accumulator-based Costas code in CE-OFDM shows a significant reduction of 7.3dB in PAPR compared to the conventional method.

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The Costas coding technique is well-suited for low side lobes and improved range resolution, making it effective for distinct target detection in radar systems.

CE-OFDM is adopted to mitigate the high peak-to-average power ratio (PAPR) problem in OFDM signals, making it more power-efficient.

The constant envelope property in CE-OFDM allows for efficient power amplification, reducing non-linear distortion in power amplifiers.

CE-OFDM can operate in frequency-selective channels without the need for equalization, especially when using differential data encoding.

Advantages of the Proposed Scheme:

The PAPR reduction technique used in the proposed scheme results in a constant envelope signal with nearly 0dB PAPR, making it suitable for efficient power amplification purposes.

The proposed scheme improves the ambiguity function for LFM-based radar, leading to enhanced range resolution and better target detection in environments with multiple closely spaced targets.

Future Improvements:

The addition of a pre-modulation Gaussian filter in the transmitter side, in combination with Costas coding, aims to achieve even better efficiency and constant envelope properties in future implementations.

In conclusion, the combination of Costas Frequency coding and CE-OFDM offers significant advantages in terms of PAPR reduction, improved ambiguity function, and better range resolution for radar systems. The proposed scheme provides a constant envelope signal with low PAPR, making it well-suited for power-efficient amplification and enhancing the overall performance of OFDM-based radar systems. The application of these techniques can help mitigate the undesirable effects caused by side lobes in OFDM signals and lead to improved target detection and performance in radar applications.

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