A New Method of Integrated Radar-Communication System Waveform Design and Signal Processing Based on OFDM Block Subcarrier Allocation

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Abstract. In the context of the Internet of Vehicles (IoV) and sixth-generation (6G) wireless communication, wireless radar and communication (RadCom) systems face the dual challenges of improving spectrum utilization efficiency and lowering interference levels. The use of orthogonal frequency division multiplexing (OFDM) signals in a shared waveform system has the potential to mitigate mutual interference between communication and radar while also meeting the need for improved range resolution. Some researchers have proposed using the odd and even carriers of OFDM signals to modulate radar and communication functions, intending to achieve integration. Nevertheless, this methodology presents several concerns, such as the potential for interference between radar carriers and communication carriers and the negative impact caused by the cyclic prefix (CP) on radar performance. This study presents a new method that leverages OFDM and block subcarrier allocation techniques to enhance the integration of radar and communication system performance. The primary objective is to mitigate interference by consolidating radar and communication subcarriers while minimizing the detrimental effects of CP on radar performance by utilizing zero padding (ZP) as a replacement for CP. Furthermore, this method reduces pilot tone costs by utilizing radar data to estimate Doppler frequency offsets. It can dynamically adjust the number of radar and communication subcarriers to accommodate evolving performance demands. Simulation results indicate that in the presence of residual frequency offset, this solution enhances communication performance while slightly degrading radar performance.

Keywords: RadCom · OFDM · Block Subcarrier Allocation

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1 Introduction

Due to the rapid advancement of electronic information technology, the utilization of frequency bands, hardware/system design, and signal processing in wireless communications and radar detection exhibit similar development trends [1]. In contemporary and more intricate tasks and situations, conventional radar and communication systems face various obstacles, such as constrained spectrum resources, intensified electromagnetic interference, and heightened system complexity [2]. In order to tackle these concerns, much focus is devoted to investigating radar-communication integration [3,4]. The integration of radar communication holds significant potential in several fields, encompassing but not restricted to earthquake response, vehicle networking, and terrain surveying and mapping.

OFDM is advantageous for applications that need fast transmission and accurate distance resolution because of its exceptional spectral efficiency, robust resistance to multipath effects, flexible subcarrier modulation, and straightforward implementation. As a result, OFDM has emerged as a highly favorable option for integrating radar communication systems [5,6]. Several academics have studied the integrated design of radar communication utilizing OFDM waveform sharing [7,8]. The analysis conducted in reference [9] examined the effects of several carrier allocation techniques on radar mutual information and transmission data rate. The researcher conducted that analysis using conventional cyclic prefix orthogonal frequency division multiplexing (CP OFDM). However, using CP can reduce energy consumption and produce misleading objectives, thus influencing the efficacy of radar systems. In the study conducted by the authors in reference [10], a blank guard interval was utilized as a substitute for the cyclic prefix. The researcher proposed this method in traditional odd-even carrier allocation OFDM technology. Although this methodology improves the performance of radar systems, it concurrently introduces heightened interference between the radar subcarriers and communication subcarriers. Researchers introduced a Chirp signal-based multi-carrier radar communication system in a prior investigation [11] to facilitate signal sharing. However, residual frequency offset compromises the integrity of the signals' orthogonality, leading to the system's overall performance deterioration. Several researchers [12,13] have performed channel estimation and Doppler frequency offset correction by employing training sequences and repeated symbols. It is worth mentioning that these training sequences and repeated symbols also use a portion of the available spectrum resources.

The main contributions of this paper are as follows:

(1) This paper proposes a radar communication system scheme based on block subcarrier allocation of OFDM. By employing block subcarrier allocation, the radar and communication subcarriers are organized into groups, thereby minimizing interference from the radar carrier to the communication carrier and enhancing overall communication performance.
(2) The proposed scheme uses ZP as a substitute for CP. ZP performs a comparable function to CP by reducing Inter-Carrier Interference (ICI) and

Inter-Symbol Interference (ISI). This simultaneous adoption of ZP enhances energy efficiency and mitigates the adverse effects of CP on radar performance.

(3) The scheme presented in this paper employs radar signals to estimate frequency offsets to facilitate cooperative work between radar and communication functionalities.

The primary structure of this paper is organized as follows: In Sect. 2, we present a signal model that utilizes block subcarrier allocation within the framework of OFDM. Moving forward, Sect. 3 offers a comprehensive exposition of the integrated signal design and waveform processing methodology proposed in this study. Section 4 presents detailed simulation experiments that validate the efficacy of the proposed approach. Finally, Sect. 5 provides a succinct summary of the entire body of work.

2 RadCom Integrated Signal Model

OFDM subcarriers exhibit equidistant frequency spacing. As a subcarrier attains its peak value in the frequency domain, the remaining subcarriers assume zero amplitude, thereby ensuring inherent orthogonality among them [14]. As shown in Fig. 1, predefined subcarrier assignment rules determine the allocation of subcarriers for radar signals or communication signals [15]. The orthogonal nature of subcarriers allows for effective concurrent radar detection and communication transmission without reciprocal interference.

The methodology described in this study enables the allocation of extra subcarriers or the increase in energy allocation to subcarriers dedicated to information transmission in situations that need improved communication transmission speeds. Similarly, when faced with situations that need enhanced radar detection capabilities, the approach outlined in this research article facilitates the allocation of additional subcarriers for detection purposes or a higher allocation of energy to subcarriers specifically designated for radar detection.

In this scheme, we denote the total OFDM subcarriers as N_s and categorize them into subcarrier blocks, which we represent as G_B. Specifically, radar detection allocates N subcarriers, while communication transmission allocates $N_s - N$ subcarriers. Within this framework, precisely $\frac{G_B}{2}$ subcarrier chunks serve the purpose of radar detection, leaving the complementary $\frac{G_B}{2}$ subcarrier chunks assigned to the realm of communication transmission. The discrete subcarrier data sequence employed for Inverse Fast Fourier Transform (IFFT) is:

$$\mathbf{Y} = \mathbf{M}_{\mathrm{r}}\mathbf{X}_{\mathrm{r}} + \mathbf{M}_{\mathrm{c}}\mathbf{X}_{\mathrm{c}} \tag{1}$$

where in $\mathbf{X}_{\mathrm{r}} \in \mathbf{C}^{N_{\mathrm{S}} \times 1}$ and $\mathbf{X}_{\mathrm{c}} \in \mathbf{C}^{N_{\mathrm{S}} \times 1}$ represent signals in the radar frequency domain and the communication domain, respectively. The matrices $\mathbf{M}_{\mathrm{r}}$ and $\mathbf{M}_{\mathrm{c}}$ correspond to the subcarrier configurations for radar and communication systems, while matrices $\mathbf{D}_{\mathbf{r}_{-i}}$ and $\mathbf{D}_{\mathbf{c}_{-i}}$ pertain to the subcarrier block configurations specific to radar and communication.

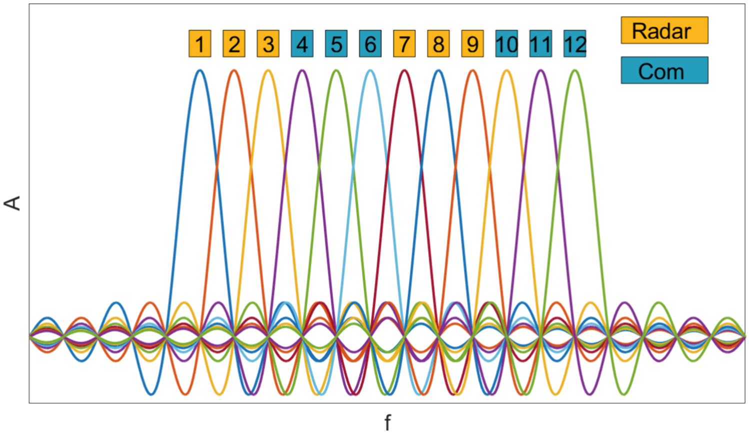

Fig. 1. Block Subcarrier Allocation.

$$\mathbf{M}_{\mathrm{r}} = \operatorname{diag}\left\{\mathbf{M}_{\mathrm{r}}(1), \cdots, \mathbf{M}_{\mathrm{r}}(k), \cdots, \mathbf{M}_{\mathrm{r}}(N_s)\right\} \tag{2}$$

$$\mathbf{M}_{\mathrm{c}} = \operatorname{diag}\left\{\mathbf{M}_{\mathrm{c}}(1), \cdots, \mathbf{M}_{\mathrm{c}}(k), \cdots, \mathbf{M}_{\mathrm{c}}(N_s)\right\} \tag{3}$$

$$\mathbf{D}_{\mathbf{r}_{-i}} = [\mathbf{M}_{\mathrm{r}}((i-1)\frac{N_s}{G_B}+1), \ldots, \mathbf{M}_{\mathrm{r}}(i\frac{N}{G_B})] \tag{4}$$

$$\mathbf{D}_{\mathbf{c}_{-i}} = [\mathbf{M}_{\mathrm{c}}((i-1)\frac{N_s}{G_B}+1), \ldots, \mathbf{M}_{\mathrm{c}}(i\frac{N}{G_B})] \tag{5}$$

The variables $\mathbf{M}_{\mathrm{r}}(k)$ and $\mathbf{M}_{\mathrm{c}}(k)$ take binary values of 0 or 1, subject to the constraint $\mathbf{M}_{\mathrm{r}}(k) + \mathbf{M}_{\mathrm{c}}(k) = \mathbf{I}$, where $\mathbf{I} \in \mathbf{C}^{\frac{N_s}{G_B}\times 1}$ represents the unity array. When $\mathbf{M}_{\mathrm{r}}(k) = 1$ and $\mathbf{M}_{\mathrm{c}}(k) = 0$, the status quo is maintained, indicating the assignment of the kth subcarrier to the radar signal. Similarly, when $\mathbf{M}_{\mathrm{r}}(k) = 0$ and $\mathbf{M}_{\mathrm{c}}(k) = 1$, the status quo is upheld, signifying the assignment of the kth subcarrier to the communication signal. Here, $i = 1, 2, \cdots, \frac{N_s}{G_B}$ represents the subcarrier block sequence. The subcarrier data sequence employed for OFDM modulation can also be represented as

$$\mathbf{Y} = [\mathbf{D}_{\mathbf{r}_{-1}}, \mathbf{D}_{\mathbf{c}_{-1}}, \ldots, \mathbf{D}_{\mathbf{r}_{-i}}, \mathbf{D}_{\mathbf{c}_{-i}}] \tag{6}$$

The radar employs a Chirp signal as its transmission waveform. Given the utilization of N subcarriers for radar detection, the frequency-domain radar signal r exhibits N non-zero spectral components. These spectral components correspond to the discrete spectrum samples of the Chirp signal. $r\,(n)$ can be expressed as

$$r\,(n) = \mathrm{DFT}\left[\exp\left(j\pi k_r\left(\frac{n-1}{F_s}\right)^2\right)\right] \tag{7}$$

where in $n = 1, 2, \cdots, N$, k_r represents the frequency modulation slope, F_s denotes the sampling frequency, which adheres to the condition $N = F_s T$; here, T signifies the period of the Chirp signal.

3 Integrated Signal Design and Processing Method for RadCom

3.1 Integrated Signal Design Method

The multipath effect can give rise to ICI and ISI in conventional multi-carrier communication systems like OFDM, disrupting the orthogonal relationship among subcarriers. Traditional strategies frequently use the CP as a protective interval to address these issues. This methodology ensures that the receiver's window encompasses only a single OFDM symbol, enhancing the system's resistance to interference and the overall transmission quality. However, it is essential to recognize that while using CP improves communication effectiveness, it can potentially lead to reduced energy efficiency and have implications for radar detection.

As seen in Fig. 2, the methodology proposed in this research replaces CP with ZP. Upon reception, the received signal is divided into partitions, ensuring that only the current OFDM symbol is present within the receiving window, which partitioning aids in mitigating ISI. Additionally, the guard interval is obtained from the following OFDM symbols and appended to the beginning of the current signal. This approach ensures the integrity of every character, thereby reducing the impact of ICI.

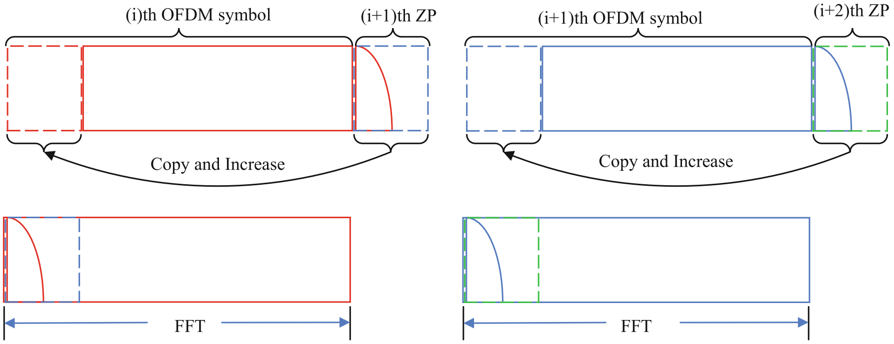

Fig. 2. The replication and addition of ZP.

3.2 Flow of Integrated Signal Processing

As shown in Fig. 3, this paper presents the formation and processing flow of the integrated radar communication signal. The transmitting end combines radar and communication signals to create a subcarrier data sequence. We then transform this sequence into time-domain data using IFFT modulation and insert a guard interval, in the form of ZP, between adjacent OFDM symbols. At the receiving end, the preamble serves the purpose of preliminary frequency offset estimation. Following this, frequency offset correction and guard interval removal are performed separately for each symbol. Later, the Fast Fourier Transform (FFT) is used, facilitating the subsequent segregation of radar and communication carriers. Subsequently, communication information is being recovered via demodulation. Simultaneously, target information is extracted from the radar echo signal through IFFT modulation and pulse compression.

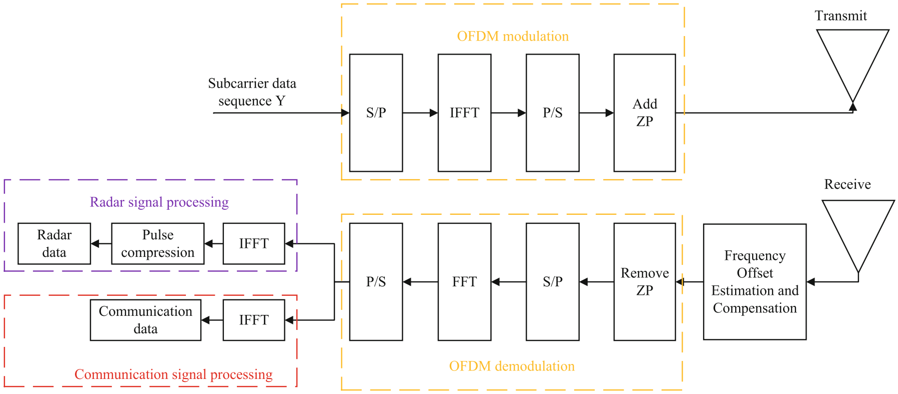

Fig. 3. Process flow of integrated radar communication system.

3.3 Method for Estimation and Compensation of Frequency Offset

In an OFDM system, Doppler frequency shifts can introduce interference, disrupting the orthogonality among subcarriers and causing changes and degradation in the constellation diagram. These changes and degradation detrimentally affect the overall system functioning. The methodology proposed in this study uses radar data to estimate frequency offsets, differing from traditional techniques. Adopting this methodology reduces the need for training sequences and pilot frequencies, preserving system resources.

Within the framework of radar communication integration, a Doppler frequency offset engenders the emergence of two discernible categories of impacts. The first issue is the reciprocal interference between radar and communication subcarriers. The second aspect pertains to self-interference between radar subcarriers and communication subcarriers. The methodology proposed in this research article involves segmenting OFDM subcarriers into distinct blocks. We assign subcarrier blocks of even order for radar detection purposes and designate subcarrier blocks of odd order for communication transmission. This strategy reduces the interference caused by radar signal subcarriers on communication signal subcarriers, improving communication performance.

The process of frequency offset estimation and compensation using radar information is depicted in Fig. 4. In this process, two consecutive OFDM symbols, namely $yi + 1$ and yi, are initially stored in a buffer. Subsequently, the time-domain signal undergoes transformation into a frequency-domain signal through FFT, enabling the extraction of radar-related information. This information includes Y_{i+1} and Y_i, which are calculated to obtain ε.

$$\varepsilon = \arg\left(Y_{i+1} \cdot X_{i+1} \cdot (Y_i \cdot X_i)^*\right) \frac{1}{2\pi} \cdot \frac{N_{fft}}{N_{fft} + N_{zp}} \tag{8}$$

where in ε represents the estimated frequency offset value used to compensate for the frequency offset within the received signal in the time domain. X_{i+1} and X_i denote separate known radar information from different symbols. N_{fft} corresponds to the number of FFT points within a single OFDM symbol, while N_{zp} represents the length of the guard interval.

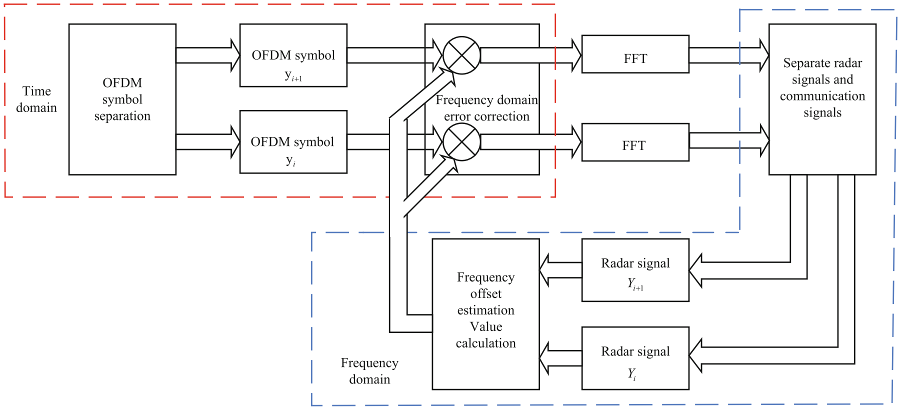

Fig. 4. Frequency offset estimation and compensation process.

4 Simulation

The simulation experiment validated the effectiveness of the radar communication integrated waveform design scheme and processing approach described in this research. The radar signal employs the Chirp signal and modulates the communication information using Quadrature Phase Shift Keying (QPSK) modulation. As seen in Fig. 5, it became apparent that an escalation in residual frequency offset resulted in a progressive displacement of the constellation diagram from its original form. As a result, these changes resulted in a gradual decline in the system's overall effectiveness.

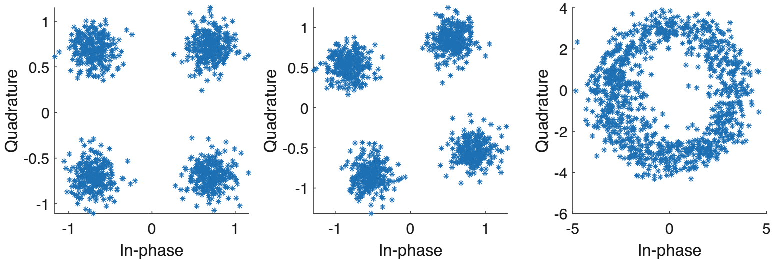

Fig. 5. Influence of Frequency Offset on Signal Constellation Diagram.

The simulation results illustrating the pulse are presented in Fig. 6. Upon reception, the radar echo signals underwent the process of pulse compression. As the residual frequency deviation increased, it led to fluctuations in the pulse compression's location and amplitude. These changes had a detrimental influence on the performance of radar detection performance.

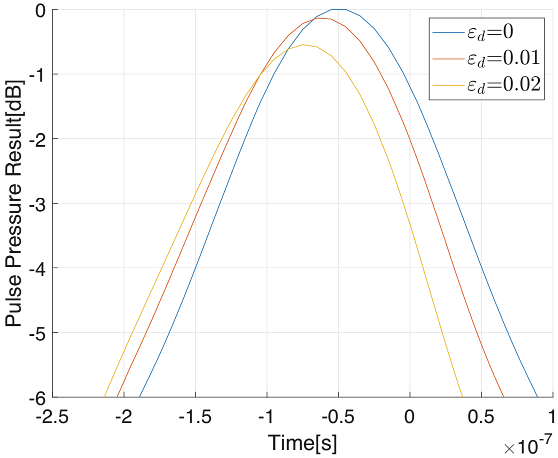

Fig. 6. The Influence of Residual Frequency Deviation on the Peak Amplitude and Position of Radar Pulse Compression.

As seen in Fig. 7, a comparative analysis was conducted between the conventional method employing the odd-even carrier allocation strategy and the new approach introduced in this research, assuming the presence of a residual frequency offset. References [9,10] outlined a methodology that employed OFDM sub-carrier allocation, where in they assigned radar modulation to odd-numbered carriers and communication modulation to even-numbered carriers, successfully integrating radar and communication functionalities. Building upon this foundation, this study proposes a new methodology for enhancing the allocation of subcarriers. The categorization of OFDM subcarriers into different groups assigns some for communication and others for radar. This new methodology facilitates the integration of radar and communication systems and improves overall communication performance.

The residual frequency offset included in radar transmissions has two primary impacts. Firstly, self-interference within the radar carrier results in energy dispersion towards neighboring sub-carriers, thus diminishing the integrated side lobe ratio (ISLR). Secondly, the presence of communication carriers interferes with the radar carrier, leading to altered properties and peak position of radar pulses.

This new methodology aims to mitigate the mutual interference between radar subcarriers and communications subcarriers. Nevertheless, this increased self-interference among radar subcarriers has led to a slight decline in radar performance parameters. For example, the paper's radar signal design yielded a measured peak side lobe ratio (PSLR) of −20.52 dB at a signal-to-noise ratio (SNR) of 3 dB. The result was inferior to the −20.82 dB acquired using the conventional approach. Similarly, ISLR was −10.83 dB for the proposed method, showing a minor decrement compared with the −11.07 dB of the conventional approach.

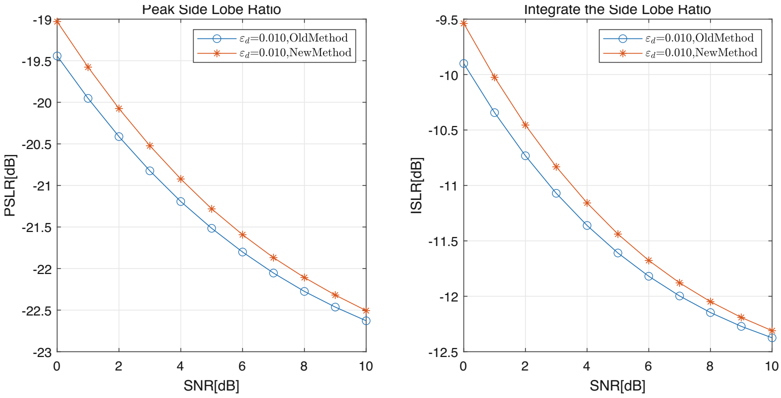

Fig. 7. Influence of Residual Frequency Offset on Radar Peak Sidelobe Ratio and Radar Integral Sidelobe Ratio. The conventional approach(OldMethod). The new approach proposed in this study (NewMethod).

As seen in Fig. 8, an augmentation in the SNR led to a progressive decrease in the communication system's bit error rate (BER). The residual frequency offset has two primary impacts on communication signals. Firstly, this phenomenon induces self-interference within communication carriers, leading to elevated bit error rates due to energy leakage towards neighboring sub-carriers. Secondly, it gives rise to interference between radar carriers and communication carriers, resulting in the distortion of the communication constellation diagram and compromising the overall performance of communication systems. The new approach presented in this research demonstrates superior performance in transmission bit error rate compared to the conventional method, given an equivalent residual frequency offset. This new methodology exhibited enhanced performance during the experiment compared to the conventional approach when the residual frequency offset was set at $\varepsilon_d = 0.025$, and the BER was $1 \cdot 10^{-5}$. This improvement manifested as a gain of 0.75 dB.

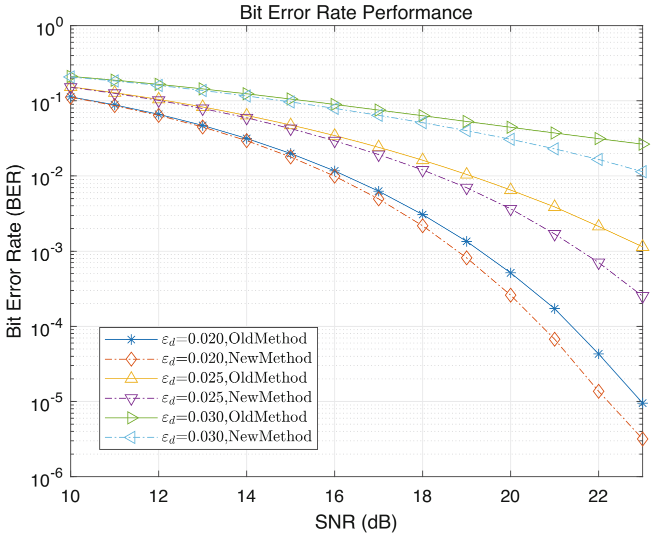

Fig. 8. Communication Bit Error Rate Comparison.

5 Conclusion

This paper delves into waveform design and processing methods for integrating radar and communication systems. It analyzes the limitations of conventional approaches in scenarios involving residual frequency offset and presents a novel integrated waveform design scheme based on OFDM block subcarrier allocation. This paper analyzes the effects of Doppler frequency offset on the radar communication integration signal and presents a corresponding approach for estimating and compensating for the frequency offset. Simulation trials confirmed the efficacy of this methodology. Compared with the traditional OFDM waveform design method, the methodology proposed in this research study utilizes block subcarrier allocation instead of alternating subcarrier allocation. Block subcarrier allocation reduces the interference of radar subcarriers with communication subcarriers. Simulation results indicate that when a residual frequency offset is present, the proposed strategy slightly decreases radar performance but improves communication reliability.

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