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Research Article

Joint radar and communication system: Pre-processing method with OFDM Radar waveform

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ABSTRACT

In this paper, we investigate a Joint Radar and Communication (JRC) system that utilizes a standard Orthogonal Frequency Division Multiplexing (OFDM) signal to enable efficient spectrum sharing. The increasing demand for spectrum efficiency has driven the development of JRC systems, which allow simultaneous sensing and data transmission while maintaining reliable communication. However, spectrum resource allocation remains challenging due to interference between radar and communication signals, which may degrade target detection performance and communication reliability. Therefore, spectrum management and interference mitigation are essential for improving JRC performance. To address this issue, we propose an OFDM packet structure that enhances detection accuracy, along with a pattern matrix that optimizes spectrum allocation to prevent interference. The proposed packet structure enables radar and communication functions to share the spectrum more efficiently while maintaining compatibility with conventional OFDM signaling. In addition, the proposed pattern matrix provides a mechanism for allocating spectrum resources, thereby reducing the overlap between radar and communication transmissions and improving sensing robustness. The proposed framework enhances spectrum utilization without introducing significant changes to the standard OFDM waveform. Simulation results demonstrate the impact of the proposed method on radar performance under various detection algorithms, including Two-Dimensional Fast Fourier Transform, Multiple Signal Classification, and Estimation of Signal Parameters via Rotational Invariance Techniques. Performance comparisons show that the proposed packet structure and spectrum allocation strategy improve target detection capability while effectively suppressing interference. The results further confirm that, at node Radar, target detection can be enhanced and interference reduced, making the proposed approach well-suited for JRC applications in dynamic wireless environments. These findings indicate that the proposed method provides a practical solution for improving sensing performance while preserving reliable communication in future spectrum-sharing JRC systems.

Key words: Joint Radar and Communication (JRC) system, Orthogonal Frequency Division Multiplexing (OFDM) Signal, Target Detection, Two-Dimensional Fast Fourier Transform (2D-FFT), Multiple SIgnal Classification (MUSIC), Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT), Pattern Matrix Design

INTRODUCTION

The JRC system has received a lot of interest because of its high spectrum efficiency, which makes it an attractive option for a variety of developing applications [1]. These include autonomous vehicles, where accurate sensing and reliable communication are crucial for navigation and safety [2], as well as aviation systems, which require a seamless joint of radar for object identification and communications for aircraft [3]. The JRC system also paves the way for developments in intelligent transportation, next-generation aviation technology, and other industries that require dual-functionality by enabling effective spectrum sharing and reducing interference [4]. This novel system uses advanced signal processing and resource allocation algorithms to ensure effective spectrum usage, allowing radar and communication capabilities to coexist within the same bandwidth [5]. Reliable performance is ensured in complicated settings by their capacity to respond dynamically to changing environmental conditions and operational needs.

OFDM is a widely used multi-carrier modulation technique that enhances spectral efficiency and robustness in modern communication systems. By transmitting data over multiple orthogonal subcarriers in parallel, OFDM mitigates frequency-selective fading and intersymbol interference (ISI) [6–8]. Each subcarrier can be individually modulated using Quadrature Amplitude Modulation (QAM), providing adaptability to varying channel conditions [9]. Its orthogonality minimizes interference, making OFDM ideal for wireless communication, 5G net-

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works, and digital television [10] . Beyond communications, OFDM is highly suitable for the JRC system, allowing simultaneous target detection and data transmission within the same spectrum [11–15] . Its high spectral efficiency, robustness against multipath fading, and flexible subcarrier allocation enable accurate range and velocity estimation while maintaining reliable data transmission [16]. While Frequency-Modulated Continuous Wave (FMCW) radar [17] is traditionally used for target detection due to its high range resolution and simple implementation, it lacks the flexibility required for JRC applications. FMCW requires dedicated spectrum allocation, reducing efficiency in shared environments. In contrast, OFDM enables dynamic spectrum sharing, improving efficiency while maintaining high-resolution sensing. Additionally, OFDM is more resilient to multipath fading and better suited for high-mobility scenarios, where FMCW struggles with Doppler shifts. These advantages make OFDM a superior choice for the JRC system, providing a unified framework for spectrum-sharing applications.

The authors in [13,18,19] suggested a technique that divides the received modulation symbols by the transmitted modulation symbols, followed by the application of the inverse discrete Fourier transform (IDFT) and the discrete Fourier transform (DFT) to estimate the range and velocity using an OFDM-based integrated radar and communication waveform. The coherent processing interval (CPI) determines the velocity resolution in these approaches, whereas the signal bandwidth determines the range resolution. The signal bandwidth and CPI must be increased to increase the range and velocity resolution. Increasing the signal bandwidth, however, raises the cost of hardware implementation and frequency resource consumption even when raising the CPI decreases the update rate. Furthermore, in some situations, the target oscillation prevents the CPI from expanding, which restricts its use. On the other hand, super-resolution techniques are very successful in improving the resolution of parameter estimates. Numerous super-resolution methods for angle estimation have been developed in array signal processing [20].

The pattern matrix often represented as a structured mathematical construct such as a Gram matrix [21] , Identity matrix [22], Random matrix [23] , Kronecker matrix [24], or Toeplitz matrix [25], plays a critical role in facilitating the JRC system in an OFDM-based framework. It is intended to assign certain OFDM subcarriers for communication and radar functions, guaranteeing effective coexistence free from interference. The pattern matrix makes it possible for both radar sensing and communication to be seamlessly joined into a single system by carefully determining which subcarriers are used for radar sensing and which are set aside for communications [5]. Separating the individual signal components improves spectrum efficiency while preserving signal clarity. Radar performance is further enhanced by the pattern matrix capability for sophisticated signal processing methods such as Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) [26] and Multiple SIgnal Classification (MUSIC) [27] for super-resolution target identification. The pattern matrix offers an effective and adaptable structure for resource allocation, which is crucial for improving the dual functioning of the JRC system in difficult situations, such as wireless communications and the military field.

This paper presents two key contributions to enhancing the JRC system. First, we propose a design of OFDM waveform specifically for JRC applications, ensuring efficient spectrum utilization while improving radar sensing and communication performance. This design enhances signal robustness, enabling accurate target detection and reliable data transmission within shared spectrum environments. Second, we propose a pattern matrix for pre-processing radar signals, which optimizes resource allocation, prevents interference, and improves sensing accuracy. To validate the effectiveness of these contributions, we perform simulations to evaluate radar performance using three detection methods: Two-Dimensional Fast Fourier Transform (2D-FFT) [28] , MUSIC, and ESPRIT. The Mean Squared Error (MSE) and Signal-to-Noise Ratio (SNR) evaluations are used to compare the accuracy of these methods, demonstrating the improvements achieved through the proposed OFDM waveform and pattern matrix design.

The rest of the paper is organized as follows: in Section II, the system model will be introduced, along with the proposed OFDM waveform design, the proposed pattern-structured matrix, and the application of the pattern-structured matrix to radar signal pre-processing. Section III applies the pattern structured matrix with three algorithms: 2D-FFT, MUSIC, and ESPRIT, and introduces the MSE metrics for evaluating. Numerical results to demonstrate the performance of the system will be evaluated in Section IV. Finally, the conclusions and potential future work are discussed in Section V.

SYSTEM MODEL AND PROPOSED METHOD

The JRC system in Figure 1 consists of three nodes: a radar (R), a target (T), and a base station (B), each

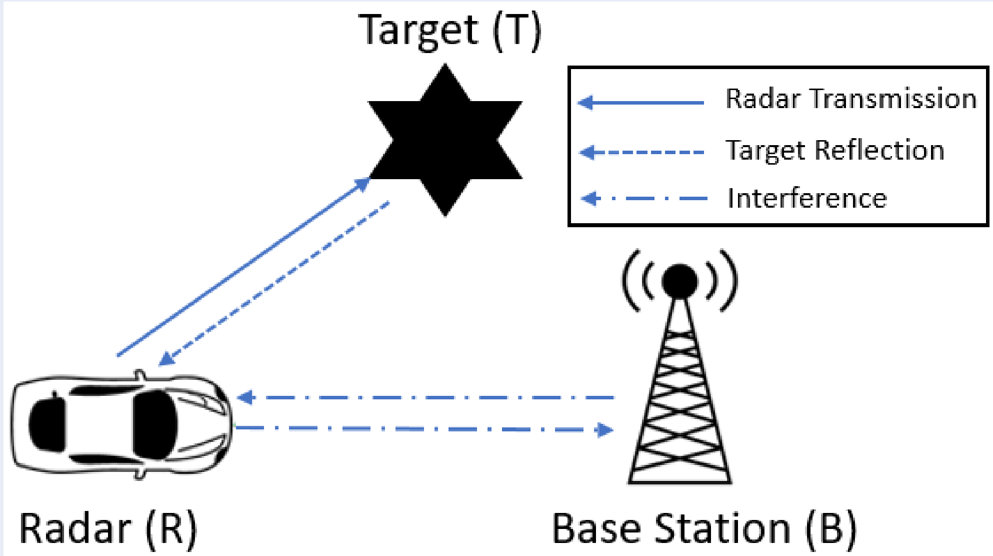

Figure 1: System Model of Joint Radar and Communication System [Source: Linh et.al.]

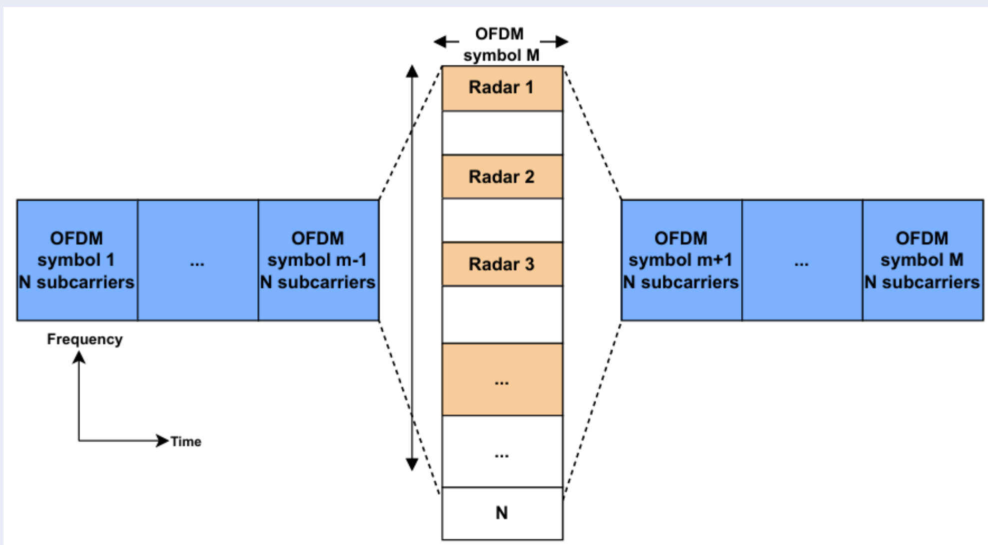

Figure 2: OFDM Radar Signal Packet Structure [Source: Linh et.al.]

equipped with a single antenna. The radar (R) transmits signals toward the target (T) through the radar channel, and the target reflects the signal back to the radar. By analyzing the received echo, the radar extracts information about the target's range and velocity. The target (T) acts as a passive reflector, ensuring that the radar signal is returned with minimal distortion, which allows for precise sensing at the radar. Simultaneously, the base station (B) transmits communication signals, which act as interference at the radar. Both the radar and the base station operate concurrently, requiring the radar to process both the reflected radar signal and the communication interference. Additionally, the base station (B) receives interference from the signals transmitted by the radar, leading to mutual interaction between the two nodes. The system is designed to allow the efficient coexistence of radar and communication functionalities without interference. The use of OFDM waveforms facilitates accurate target detection while supporting reliable communication performance. The mathematical formulation, detailing the signal transmission, received signal, and signal analysis methods, will be presented in Section II-C of this paper.

Designed OFDM Signal Packet Structure

This subsection outlines the essential characteristics of an OFDM signal, emphasizing its packet structure and its dual role in radar and communications applications. The JRC system employs a fixed OFDM framework, where both radar and communication signals share the same OFDM structure but are independently modulated. This approach ensures spectral coexistence while maintaining high-resolution sensing and reliable data transmission. The radar packet is designed to facilitate target detection and estimation using structured subcarrier allocation as shown in Figure 2. The signal is generated by randomly modulating a subset of N subcarriers with 16-QAM symbols. The total bandwidth is $W = N\Delta f$, with Δf the frequency spacing required for orthogonality, ensuring spectral efficiency while preserving orthogonality. Radar transmission follows an OFDM frame structure with M symbols, where a cyclic prefix (CP) of length $N/10$ is appended to mitigate ISI. The radar transmitted signal propagates through a sensing channel characterized by a target distance r and velocity v, introducing a round-trip delay and Doppler shift. The received radar signal undergoes CP removal and FFT processing to recover frequency-domain information, enabling precise target range and velocity estimation. The communications OFDM packet operates independently within the same bandwidth as the radar. Data symbols are randomly mapped onto subcarriers which are not allocated to the radar symbols, ensuring interference prevention.

The structure is shown in Figure 3. Similar to the radar packet, the communication signal undergoes IFFT modulation, CP insertion, and transmission over a Rayleigh fading channel. The radar and communication signals are independently generated but transmitted simultaneously. A subcarrier pattern matrix in the following subsection ensures that radar subcarriers are distinct from communication subcarriers, enabling seamless coexistence. In this paper, we consider the radar and communications nodes that transmit signals simultaneously. The received signals are processed separately; radar signals undergo matched filtering for target detection, while communication signals are equalized and demodulated for data recovery. By leveraging a fixed OFDM waveform, this design achieves efficient spectrum sharing between sensing and communication without requiring additional spectral resources.

Designed Pattern Matrix

The proposed OFDM packet structure introduces a signal pre-processing matrix to suppress interference from communication subcarriers at the radar node. Subcarrier allocation in the JRC system relies on a pattern matrix, which ensures effective coexistence of radar and communication functions by designating specific subcarriers for radar detection (P_{rad}) and communication. A triangular matrix is employed for this allocation due to its advantages over unstructured alternatives like Gaussian random matrices. This matrix provides a deterministic, systematic approach, balancing resource allocation, minimizing interference, and simplifying implementation. It sequentially assigns high-priority radar subcarriers first, followed by communication subcarriers, ensuring mutual exclusivity to prevent signal overlap. The triangular matrix offers several benefits: First, it ensures high spectral efficiency by avoiding redundancy seen in identity or Toeplitz matrices. Second, its modulo-based structure enables computational simplicity for real-time hardware implementation. Third, it provides flexibility and scalability by tuning OFDM parameters M and N. Last, its predictable structure supports advanced signal processing techniques. Compared to random or overlapping matrix designs, the triangular matrix offers a structured, practical, and efficient solution for joint radar-communication subcarrier allocation. The pattern matrix for the radar pre-processing is expressed as:

$$P_{rad}(m,n) = \begin{cases} 1, & if\ mod(n,\mathscr{M}) > m \\ 0, & otherwise, \end{cases}$$

where M is the symbol of the OFDM signal ($m = 1,2,\cdots,M$), and N is the subcarriers of the OFDM Signal ($n = 1,2,\cdots,N$).

To compare with other matrices, the triangular matrix provides a clear division of subcarriers resources. Unlike the Toeplitz matrix or Kronecker product matrix, which introduces overlapping or repeated patterns. This improves signal processing efficiency for radar and communication functions by lowering ambiguity in subcarriers utilization. While the top triangular form fits in well with the simplicity and flexibility of contemporary OFDM-based systems, Toeplitz and Kronecker patterns may also make receiver design more difficult because of their inherent periodicity or redundancy. A Toeplitz matrix is a matrix with constants for each descending diagonal from left

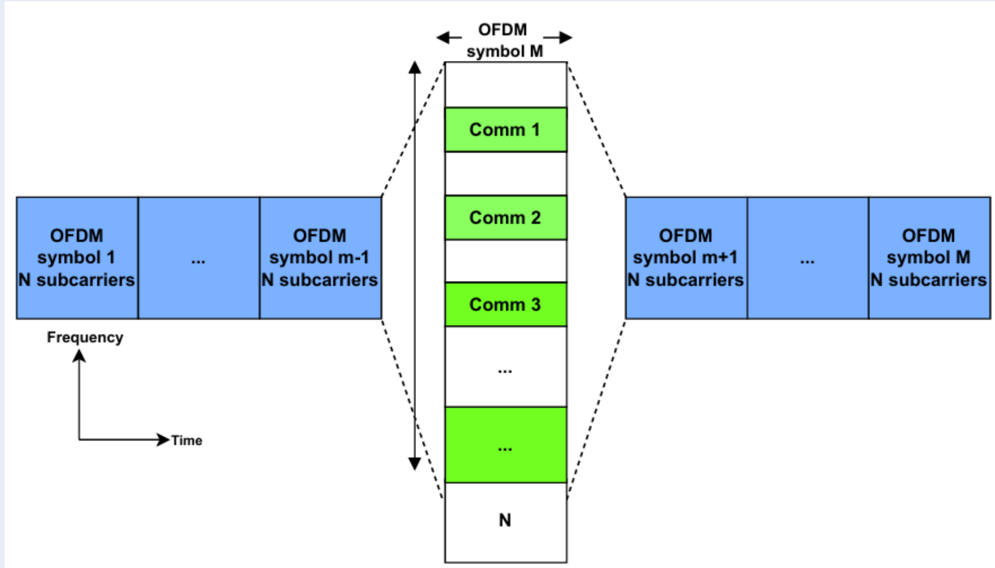

Figure 3: OFDM Communication Signal Packet Structure [Source: Linh et.al.]

to right. Furthermore, the Kronecker product of two matrices A (of size $a \times b$) and B (of size $c \times d$) is denoted as $A \otimes B$.

Despite providing absolute resource separation, the usage of an Identity Matrix severely reduces spectral efficiency since each subcarrier is assigned uniquely, leaving many unused. In a similar vein, a Gaussian random matrix may provide great unpredictability, albeit at the expense of computational complexity and hardware implementation impracticality. The triangular matrix optimizes the usage of available subcarriers while providing an organized allocation that is easy to implement and computationally efficient. Higher communication throughput at higher subcarriers and improved radar sensing resolution at lower subcarriers are made possible by its non-overlapping, gradually rising allotment. This feature is especially helpful in situations with shifting priorities when it's critical to adjust between radar and communication requirements.

Application of proposed method to Radar signal pre-processing

The radar pre-processing step with the pattern matrix for the designed OFDM signal plays an important role in the JRC system. The standard OFDM symbol is mathematically defined as [29]:

$$s(t) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} c(m,n) e^{j2\pi n \Delta f (t - mT_s)}.$$

Here, Δf is the frequency spacing required for orthogonality, T_s is the OFDM symbol duration including CP, $c(m,n)$ represents the complex data symbol transmitted on the m OFDM symbols, and n subcarriers, including the radar at the time of positioning on the pattern matrix and the communication signal on the remaining subcarriers of the radar at node B. Subsequently, the received signal at node R can be expressed as:

$$r(t) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} c(m,n) e^{j2\pi n \Delta f (t - \tau - mT_s)} e^{j2\pi f_D t} + w(t).$$

where f_D is the Doppler shift, τ is the round-trip propagation delay of the target, and $w(t)$ is the complex Gaussian noise. In the JRC system, the standard OFDM signals (illustrated in Figure 4) ensure consistent and reliable performance by employing fixed subcarrier allocations with predetermined parameters [30]. This dual-purpose signal structure allows the seamless coexistence of communication and radar functionalities without requiring separate spectral resources. The information of the subcarriers is then obtained by performing an FFT over each OFDM signal in the block by dividing the received signal by the transmit signal, which can be shown as:

$$C(m,n) = e^{-j2\pi \Delta f \tau} e^{j2\pi f_D t}.$$

The received frame comprising M OFDM symbols and N subcarriers is given in the matrix representation:

$$C = [C(m,n)]|_{m=0,\dots,M-1|n=0,\dots,N-1}^{M \times N}.$$

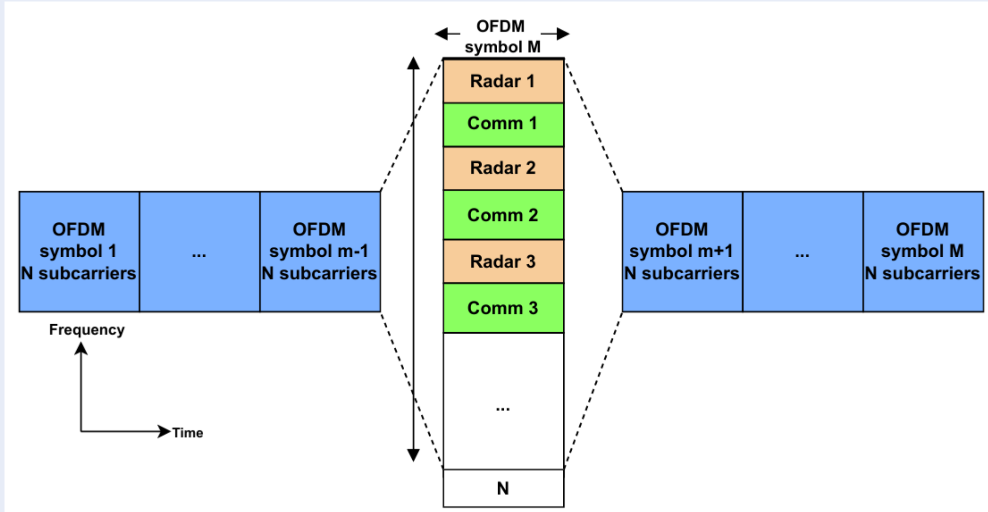

Figure 4: Standard OFDM Signal Packet Structure [Source: Linh et.al.]

Afterward, a pattern matrix for the radar signal preprocessing step is applied. The method entails multiplying the data transmit signals by the corresponding pattern matrix P_{rad} for radar. Radar and communication activities are successfully isolated by this procedure, which ensures that each capability processes only the subcarriers assigned to it. In radar, subcarriers assigned to radar detection are highlighted by multiplying the data transmission signal by P_{rad}, which filters out any contributions of communication signals. Finally, the received signal includes the information of the communication and radar signals with fixed subcarriers location distribution and environmental noise. Then, it is multiplied by the pattern-structured matrix P_{rad} to get the available position of the radar signal for target estimation. The received signal can be shown in the matrix representation as:

$$y = C \odot P_{rad},$$

where $y \in C^{M\times N}$ is the received signal at node S, $C \in C^{M\times N}$ represents the normalized received signal that combines both radar and communication signals, along with noise, $\odot$ represents element-wise multiplication, and $P_{rad} \in C^{M\times N}$ is the proposed pattern matrix.

PERFORMANCE ANALYSIS WITH PATTERN MATRIX

This section introduces the radar signal processing algorithms, 2D-FFT, MUSIC, and ESPRIT, chosen to evaluate the proposed OFDM waveform and pattern matrix in the JRC system due to their complementary capabilities and previous use in radar applications. 2D-FFT offers computational efficiency and real-time capability for range-Doppler mapping. MUSIC provides high-resolution estimation in low-SNR and multi-target scenarios, while ESPRIT balances high resolution with lower complexity by exploiting rotational invariance in certain scenarios. The goal is to evaluate radar performance obtained from these algorithms under MSE measures. The examination identifies each algorithm's strengths and limits in effectively calculating target parameters.

2D-FFT

An effective signal processing algorithm for estimating a target's range and velocity in OFDM radar is the 2D-FFT. It is made up of two FFTs that are consecutive. When applied to subcarriers, the first FFT analyzes frequency changes to obtain range information. When applied to time samples, the second FFT detects Doppler shifts to record velocity. Through this procedure, the received signal is converted into a Range Doppler Map (RDM), where the peaks represent the objects that have been identified and provide information about the target's velocity and distance. To estimate the target's range and velocity, a 2D-FFT method is applied. The received signal in discrete form is expressed, sampled at time indices $t = kT_s$, where k is an integer, and frequency-domain samples $f_n = n\Delta f$:

$$r[k] = P_{rad} \odot [\sum_{m=0}^{M-1} \sum_{n=0}^{N-1} c(m,n) e^{-j2\pi n\Delta f \tau} e^{j2\pi f_D kT_s} \times e^{j2\pi n\Delta f (kT_s - mT_s)} + w[k]].$$

The first FFT is applied across subcarriers to extract the range:

$$R[k,f_n] = \sum_{n=0}^{N-1} r[k] e^{-j2\pi n f_n t}.$$

This transformation provides a set of range bins where peaks correspond to different targets. To extract velocity, a second FFT is applied across time samples:

$$\widetilde{R}(f_D, f_n) = \sum_{k=0}^{M-1} R[k,f_n] e^{-j2\pi f_D k T_s}.$$

Finally, a 2D-FFT representation, which combines both FFT steps, the RDM is obtained as:

$$\widetilde{R}(f_D, f_n) = FFT_k\left(FFT_n\left(r[k]\right)\right).$$

MUSIC

The MUSIC algorithm is a high-resolution approach for determining the frequencies or Directions Of Arrival (DOA) of numerous signals impinging on a network of sensors, even in the presence of noise. It works by examining the eigen-structure of the covariance matrix of the received signal. The covariance matrix is divided into two orthogonal subspaces: the signal subspace (spanned by eigenvectors associated with the largest eigenvalues, corresponding to signal components) and the noise subspace (spanned by eigenvectors associated with the smallest eigenvalues, representing noise). MUSIC takes use of the fact that the genuine signal directions or frequencies are orthogonal to the noise subspace. To estimate parameters, the approach uses a pseudo-spectrum function that is defined as the reciprocal of a hypothetical signal steering vector projection over the noise subspace. The peaks in this pseudo-spectrum represent the calculated parameters. First, the covariance matrix is estimated by processing the received OFDM data, which helps in extracting essential signal characteristics:

$$R_{range} = \frac{1}{\mathscr{M}} C \cdot C^H,$$

where C is the channel information matrix constructed by the received OFDM symbols multiplying by the pattern matrix P_{rad}. Eigen-decomposition is performed to separate the signal and noise spaces, extracting eigen-values and eigen-vectors for accurate parameter estimation:

$$R_{range} = V_{range} \Lambda V_{range}^H,$$

where V_{range} contains eigen-vectors and eigen-values of the range. The noise subspace matrix U_n is formed by selecting the eigen-vectors corresponding to the smallest eigen-values. For range estimation, the MUSIC algorithm utilizes a steering vector to compute the pseudo-spectrum, identifying target distances with high resolution:

$$a(\tau) = e^{-j2\pi n \Delta f \tau}.$$

The MUSIC pseudo-spectrum is computed as:

$$P_{MUSIC,range}(\tau) = \frac{1}{a(\tau)^H U_n U_n^H a(\tau)}.$$

Similarly, we have the covariance matrix for velocity estimation:

$$R_{velocity} = \frac{1}{N} C^T \cdot C^*.$$

Eigen-values and eigen-vectors are derived for accurate parameter estimation by applying eigen-decomposition to separate the signal and noise subspaces:

$$R_{velocity} = V_{velocity} \Lambda V_{velocity}^H,$$

where $V_{velocity}$contains eigen-vectors and contains eigen-values of the velocity. After that, the steering vector is determined:

$$b(f_D) = e^{j2\pi f_D n T_s}.$$

The MUSIC pseudo-spectrum for velocity is:

$$P_{MUSIC,velocity}(f_D) = \frac{1}{b(f_D)^H U_n U_n^H b(f_D)}.$$

ESPRIT

The ESPRIT algorithm is a high-resolution approach for estimating the frequencies or DOA of signals based on noisy data. It makes use of the rotational invariance characteristic of the signal subspace, which results from the structure of the observed data. ESPRIT starts by generating a Hankel matrix from the received signal and then does a Singular Value Decomposition (SVD) to separate the signal and noise subspaces. ESPRIT detects a shift-invariant connection using signal subspace sub-matrices and formulates it as an eigen-value problem. The eigen-values represent signal properties such as frequencies and angles of arrival. The round-trip delay τ introduces a phase shift across subcarriers in the frequency domain:

$$\phi_\tau = -2\pi\tau\Delta f.$$

To estimate τ, the data matrix is constructed from the received OFDM symbols and compute its covariance matrix:

$$R_{zz} = \frac{1}{\mathscr{M}} Z \cdot Z^H,$$

where Z is formed from the received OFDM symbols after FFT processing and multiplied by the pattern matrix P_{rad}. Using SVD, the signal subspace can be extracted:

$$[U,\Sigma,V] = SVD(R_{zz}).$$

The phase shift is obtained using the ESPRIT shift-invariance property:

$$\Psi = -F_1 \cdot F_2^{-1},$$

where F_1 *and* F_2 are sub-matrices derived from U. The eigenvalues of Ψ provide ϕ_τ, from which τ is estimated as:

$$\tau = -\frac{\phi_\tau}{2\pi\Delta f}.$$

The corresponding range is then given by:

$$r = \frac{\tau c_0}{2}.$$

After that, the Doppler shift f_D introduces a phase shift across consecutive OFDM symbols:

$$\phi_D = 2\pi f_D T_s.$$

Following a similar ESPRIT procedure on the time-domain correlation matrix, the phase shift ϕ_D is extracted and the Doppler shift is estimated:

$$f_D = \frac{\phi_D}{2\pi T_s}.$$

The velocity of the target is then computed

$$v = \frac{f_D \lambda}{2}.$$

This ESPRIT-based approach enables high-resolution range and velocity estimation for the OFDM-based JRC system.

MSE-Based Radar Performance

The MSE is often chosen to evaluate radar system performance due to its ability to comprehensively assess system accuracy. By capturing the magnitude of errors, the MSE plays a critical role in robust performance evaluation.

$$MSE(\widehat{s}) = \frac{1}{M}\sum\nolimits_{q=1}^{M} ||\widetilde{s_q}||^2.$$

where $\widetilde{s_q}$ is the estimation error, which respectively with $\widetilde{s_q} = s_q - \widehat{s_q}$, where $\widehat{s_q}$ is the estimator, s_q is the quantity to be estimated; M is the Monte Carlo runs. The MSE has the ability to penalize large errors, which is critical in evaluating system performance.

NUMERICAL RESULTS AND DISCUSSION

In this section, numerical results are shown by simulation to evaluate the proposed method. The comparison of 2D-FFT, MUSIC, and ESPRIT, for range and velocity estimation, are shown to demonstrate the proposed method. Then, a detailed examination of the MSE for range and velocity estimation over different SNR levels as well as communications power levels are highlighted.

To ensure the reliability and relevance of these simulation results, the parameters and performance metrics, summarized in Table 1, were carefully selected to reflect realistic JRC scenarios. The environmental noise is modeled as Additive white Gaussian noise (AWGN), and an SNR of 30 dB is considered for specific high-SNR tests to evaluate performance under optimal conditions. The carrier frequency of f_c = 24 (GHz) aligns with automotive radar standards, providing high range resolution[31]. A subcarrier spacing of Δf = 60 (kHz) ensures orthogonality, with the effective OFDM symbol length $T = \frac{1}{\Delta f}(\mu s)$, a CP of $T_{cp} = \frac{1}{10}(\mu s)$, and total frame time $T_s = T + T_{cp}(\mu s)$,balancing spectral efficiency and robustness against Doppler shifts, consistent with 5G OFDM frameworks. The number of subcarriers ($N = 2048$) and symbols ($M = 512$with a CP size of $CP_{size} = \frac{N}{10}$was selected to achieve sufficient resolution for range and velocity estimation (e.g., target at 12 m and 0 m/s) while maintaining computational feasibility for real-time systems. The wavelength is $\lambda = \frac{c_0}{f_c}(m)$,where c_0 = 3 x 10^8 (m/s), and 16-QAM modulation is utilized for both radar and communication signals[32]. The MSE and Bit Error Rate (BER) were chosen as primary metrics due to their widespread adoption in the JRC system[13]. MSE measures radar accuracy, while BER evaluates communication reliability.Simulation parameters and metrics

Performance of Radar Sensing

Figure 5 illustrates the periodogram of target estimation using a fully OFDM radar signal. In this method, the radar transmits a waveform composed of multiple orthogonal subcarriers, enabling detailed analysis in both time and frequency domains. The figure likely demonstrates how the returned OFDM signal is processed to estimate the periodic motion or time-varying characteristics of a target. This technique allows for accurate detection and tracking, including the presence of noise. The use of a fully OFDM signal may help enhance resolution and provide useful

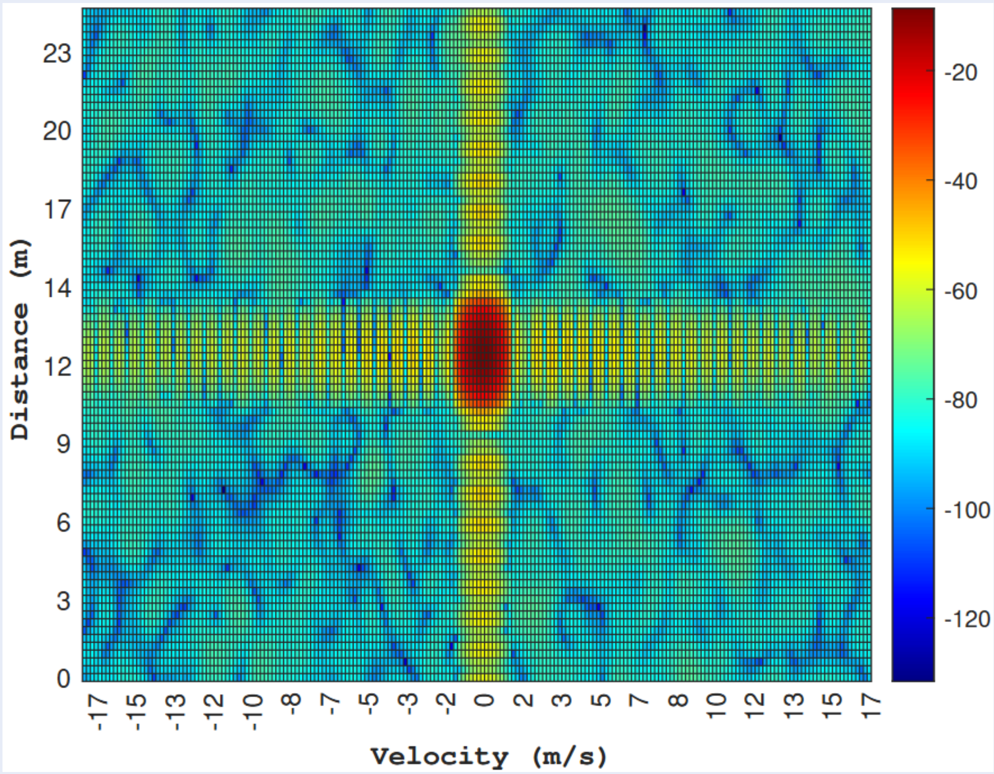

Figure 5: Range and Velocity Target Estimation with Full OFDM Radar signal [Source: Linh et.al.]

Table 1: Simulation parameters and metrics

Parameter	Value
Noise model	Additive white Gaussian noise (AWGN)
Carrier frequency (GHz)	f_c = 24
Subcarrier spacing (kHz)	Δf = 60
OFDM symbol duration (μs)	$T = 1/\Delta f$
Cyclic prefix duration (μs)	T_{cp} = T/10
Total symbol duration (μs)	$T_s = T + T_{cp}$
Radar-to-noise power ratio (dB)	p_{rad} = 0
Number of subcarriers	N = 2048
Number of OFDM symbols	M = 512
Target	Range = 12 m, Velocity = 0 m/s
Cyclic Size	$CP_{size} = N/10$
Wavelength (m)	$\lambda = c_0/f_c$
Modulation	16-QAM
Performance metrics	MSE, BER

[Source: Linh et.al.]

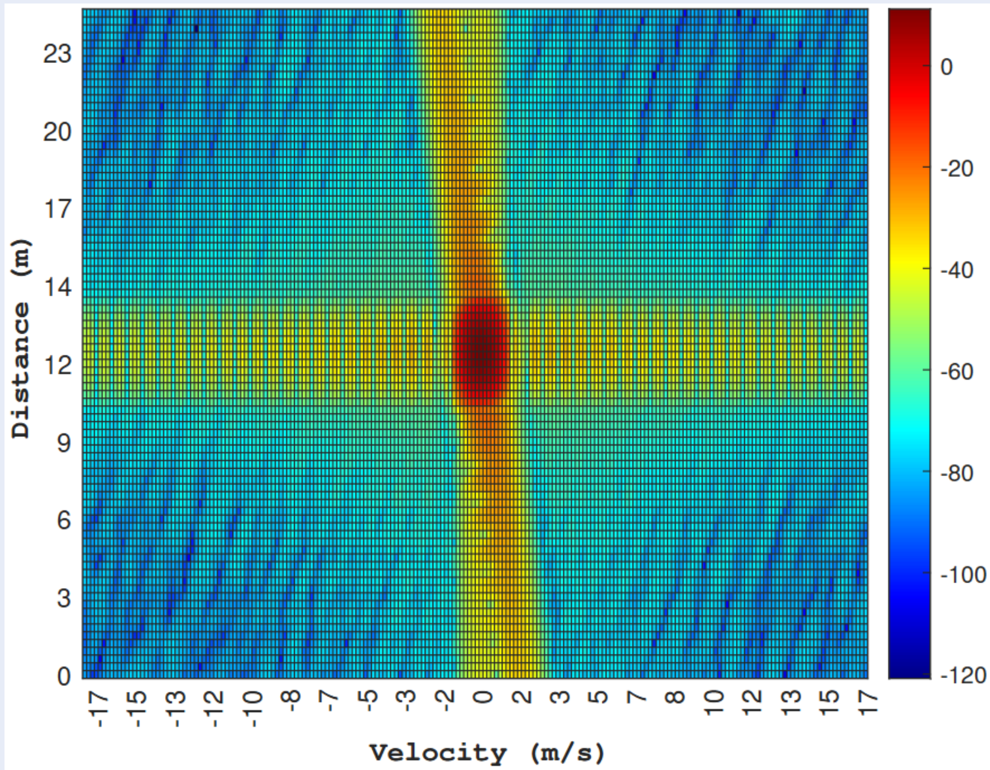

Figure 6: Range and Velocity Estimation with designed OFDM signal and proposed pre-processing method. [Source: Linh et. al.]

insights for applications such as motion observation and target monitoring.

However, Figure 6 shows the periodogram of target estimation with the designed OFDM signal. The designed OFDM signal in the JRC system is intended to support improved spectral efficiency management, reduce the likelihood of interference, and allow for more adaptable waveform design for radar target identification. Within this framework, efforts may be made to reduce the Peak-to-Average Power Ratio (PAPR), which is often a consideration in OFDM-based systems. By adjusting subcarrier allocation or applying signal shaping techniques, it might be possible to lower the PAPR, potentially leading to more power-efficient transmission. Additionally, the design could provide opportunities to embed more information within the transmitted signal, supporting communication functions alongside radar sensing. Maintaining consistent subcarrier assignment may also help reduce synchronization complexity and computational overhead, contributing to a more balanced operation between radar and communication tasks. The overall performance of the system appears to remain relatively stable when compared with the use of a full OFDM radar signal.

Figure 7 shows the MSE performance for range and velocity estimation (in case of no environment noise) using three algorithms: 2D-FFT, MUSIC, and ESPRIT. The upper sub-figure shows the MSE for range estimation, while the lower sub-figure illustrates the MSE for velocity estimation, both plotted against p_{com} (communication-to-noise power ratio) in decibels (dB).

In the range estimation plot, the 2D-FFT algorithm exhibits the most stable performance, maintaining a consistently low MSE in the range of p_{com}, indicating its robustness to power variations. Similarly, the MUSIC algorithm achieves a slightly higher MSE compared to 2D-FFT but remains relatively stable. However, the ESPRIT algorithm shows a noticeable increase in MSE as p_{com} exceeds 1 dB, suggesting a reduced accuracy under higher power conditions. In addition, in the velocity estimation plot, a similar trend is observed. The 2D-FFT algorithm demonstrates the most consistent performance with the lowest MSE across all values of p_{com}. The MUSIC algorithm shows a slightly higher MSE but remains stable.

In contrast, the ESPRIT algorithm exhibits a significant increase in MSE when p_{com} is greater than 1 dB, suggesting a significant sensitivity to communication power in the estimation of velocity. The lowest error occurs in the MUSIC algorithm compared to two remains in the MSE Range and in the MSE Velocity. Specifically, the MSE values for MUSIC remain minimal and steady throughout the p_{com} range (from -5 dB to 3 dB). This indicates that MUSIC is the most accurate among the three metrics under the given conditions. Overall, Figure 7 shows the stability and accuracy of the proposed pre-processing method applying to the JRC system.

The SNR shown in Figure 8 are the sum of environmental and communication noise at node Radar. The radar-to-noise power ratio is fixed at 0 dB. This composite noise depicts the entire interference influencing the system, including both background ambient noise and noise caused by the communication signal. Environmental noise affects both radar and communication signals by introducing unwanted interference that can distort signal detection and estimation processes. For the radar signal, environmental noise can degrade the accuracy of range and velocity estimations, making it more challenging to distinguish targets from the background.

In the upper sub-figure, the MSE performance for range estimation is illustrated for the three algorithms over SNR_{noise} from -30 dB to 30 dB. Both 2D-FFT and MUSIC achieve consistently low MSE values across the entire SNR range. In contrast, ESPRIT exhibits high sensitivity to low-SNR conditions, with its MSE peaking near 30 at SNR_{noise}< -20 dB. However, once SNR_{noise} exceeds -20 dB, ESPRIT's MSE decreases rapidly, approaching the near-zero performance of 2D-FFT and MUSIC. In the lower sub-figure, the MSE performance for velocity estimation, 2D-FFT and ESPRIT maintain low MSE over most of the SNR range; ESPRIT shows a brief elevation only at very low SNR_{noise}(around -30 to -25 dB) before converging to near zero for $SNR_{noise} \gtrsim -20$ dB. By contrast, MUSIC exhibits consistently high MSE across the entire range and decreases only marginally with increasing SNR_{noise}. These observations highlight that 2D-FFT and ESPRIT achieve accurate velocity estimation at moderate-to-high SNR levels, while MUSIC shows limited variation in performance across the SNR_{noise} range.

Performance of Communication Signal

The BER vs. SNR plot in Figure 9 illustrates the communication performance of the designed OFDM for the JRC system. With communication-to-noise power ratio fixed at 0 dB, the graph shows an exponential decrease in BER as the SNR increases. At low SNR values (0–5 dB), the BER remains high, indicating frequent bit errors. However, as SNR is greater than 20 dB, the BER drops below 10^{-3}, marking this the threshold for reliable communication. Beyond 30 dB, BER reaches very low values (less than 10^{-6}), ensuring highly accurate data transmission. This BER proves that the designed OFDM signal can be deployed efficiently for the JRC system, both for radar and communication nodes without mutual interference.

Discussion

The proposed OFDM-based JRC framework effectively balances radar sensing and communication functions while maintaining reliable overall system performance. The designed waveform, together with the proposed pre-processing method, preserves accurate target estimation despite the coexistence of radar and communication signals, demonstrating its capability for efficient spectrum sharing. The comparative evaluation also highlights the different characteristics of the considered estimation algorithms. While MUSIC provides the highest estimation accuracy under favorable conditions, 2D-FFT exhibits greater robustness against communication power variations and environmental interference. ESPRIT, on the other hand, is more susceptible to adverse channel conditions, although its performance improves as the signal quality increases. These observations indicate that the proposed framework remains compatible with different estimation techniques and offers flexibility for various JRC deployment scenarios. Furthermore, the communication performance confirms that the waveform design supports reliable data transmission without compromising radar sensing capability. Overall, the proposed approach provides an effective solution for joining radar sensing and wireless communication within a shared OFDM framework, demonstrating its potential for future spectrum-efficient JRC systems.

CONCLUSIONS

In conclusion, this paper proposed an OFDM waveform design and a signal pre-processing method for radar detection within a JRC system. Radar and communication subcarriers are strategically assigned using a proposed pattern matrix, ensuring effective coexistence and enhanced system performance. The adaptability of this matrix contributes to improved target detection and interference mitigation while maintaining efficient spectrum utilization. The

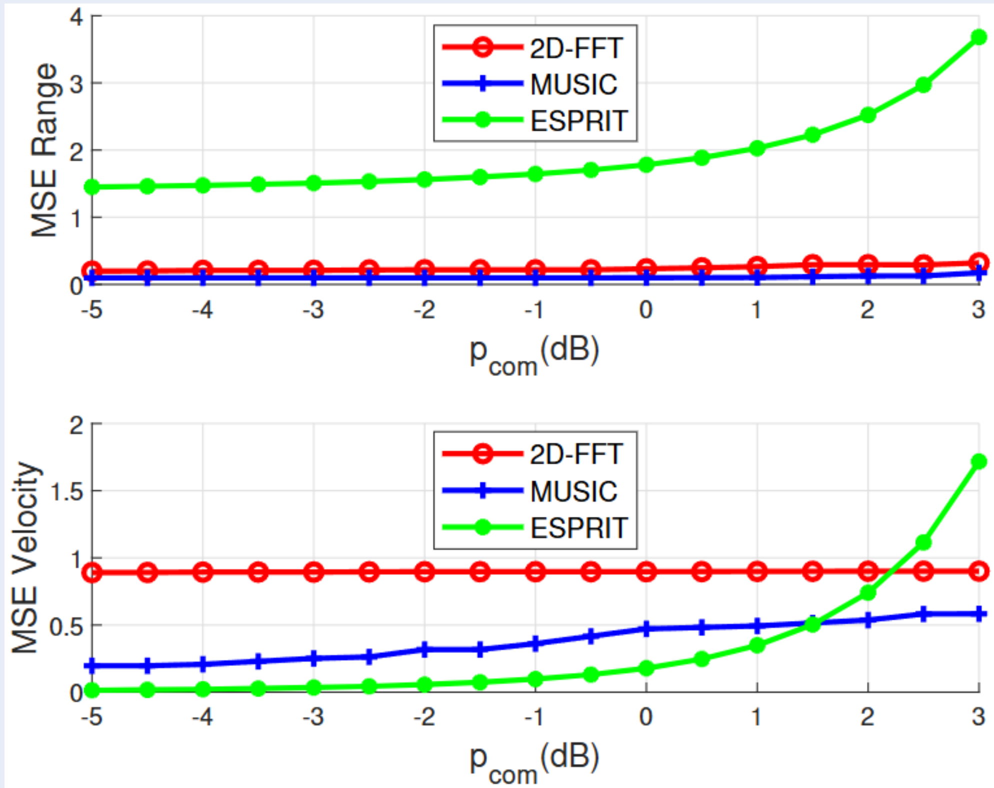

Figure 7: MSE Range and Velocity of 3 Metrics in case of Fix OFDM Signal [Source: Linh et. al.]

system's performance was thoroughly evaluated using the MSE metric to estimate range and velocity, alongside the BER to assess communication reliability across various scenarios. The results demonstrate that the proposed method enhances radar accuracy and achieves low BER for reliable data transmission in the JRC framework. Based on these observations, we conclude with a consideration for future work, which will involve applying the pre-processing method to a practical Integrated Sensing and Communication (ISAC) system. This includes evaluating its performance under varying environmental conditions and with random OFDM waveforms at the radar receiver, as well as exploring the integration of techniques such as Index Modulation, which may enhance data rates through subcarrier indexing, and Compressed Sensing, which could assist in target estimation by leveraging signal sparsity.

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COMPETING INTERESTS

We declare that: in this paper, there is no conflict of interests.

AUTHORS' CONTRIBUTIONS

Mai Linh Pham contributed to the conceptualization of the study, methodology development, and manuscript preparation. Thuan Kinh Quang Nguyen designed and implemented the simulation framework, conducted performance evaluations, and contributed to manuscript writing. Quoc Nam Le assisted in creating system modeling, data analysis, and result interpretation. Hien Q. Ta contributed to the research design, technical review, and validation of the proposed approach. Lap Luat Nguyen supervised the research, provided technical guidance, reviewed the manuscript, and secured the overall direction of the study. All authors discussed the results and approved the final manuscript.

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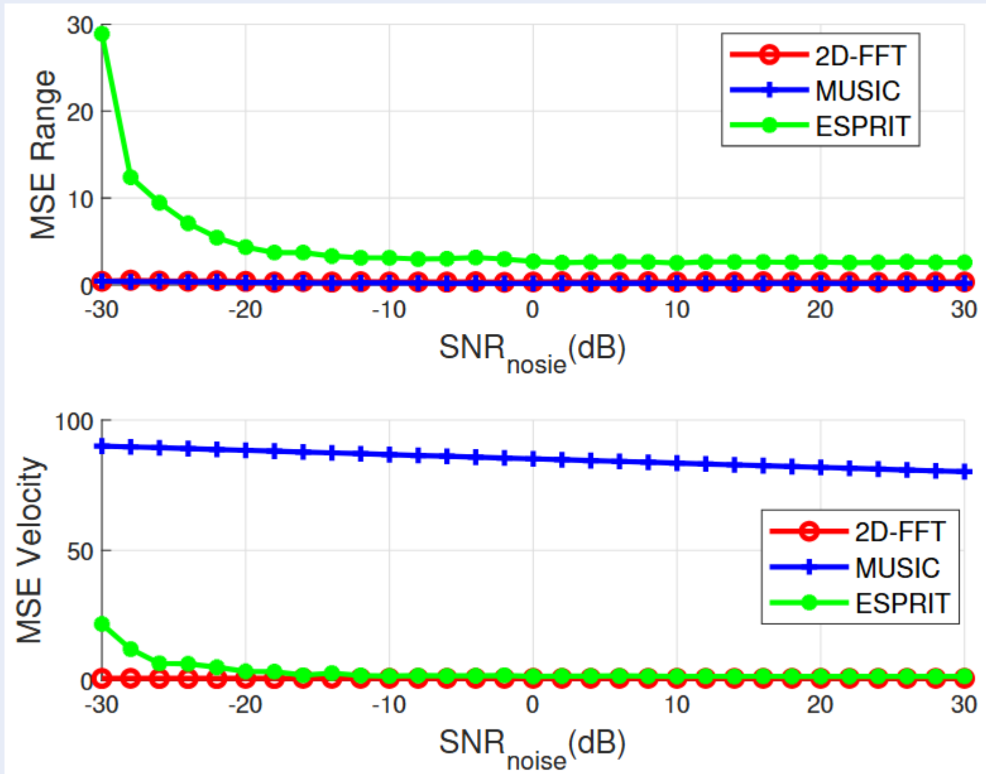

Figure 8: MSE Range and Velocity of 3 Metrics in case of Fix OFDM Signal with AWGN [Source: Linh et. al.]

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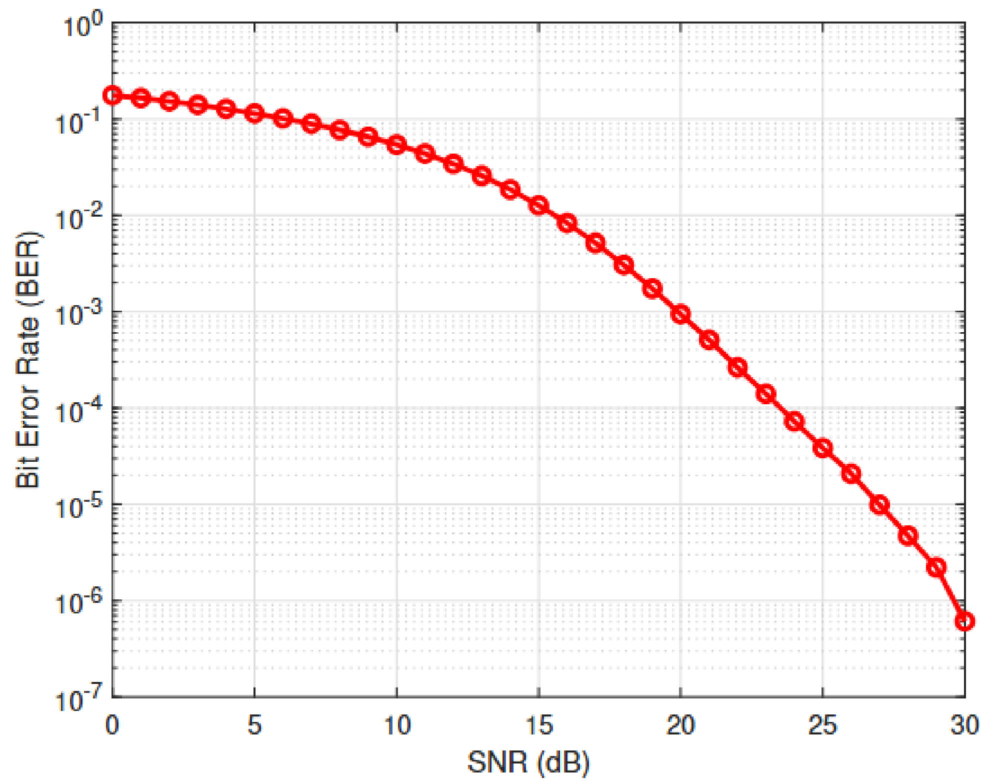

Figure 9: BER of Communication signal with proposed OFDM-based JRC System [Source: Linh et. al.]

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Bài nghiên cứu

Hệ thống kết hợp Radar và Truyền tin: Phương pháp tiền xử lý với tín hiệu OFDM tại Radar OFDM

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TÓM TẮT

Trong bài báo này, chúng tôi nghiên cứu một hệ thống Joint Radar and Communication (JRC) sử dụng tín hiệu Orthogonal Frequency Division Multiplexing (OFDM) tiêu chuẩn nhằm cho phép chia sẻ phổ tần một cách hiệu quả. Nhu cầu ngày càng tăng về hiệu quả sử dụng phổ tần đã thúc đẩy sự phát triển của các hệ thống JRC, cho phép thực hiện đồng thời chức năng cảm nhận và phát hiện (sensing) và truyền dữ liệu trong khi vẫn duy trì khả năng truyền thông tin cậy. Tuy nhiên, việc phân bổ tài nguyên phổ tần vẫn là một thách thức do sự can nhiễu giữa tín hiệu radar và tín hiệu truyền thông, có thể làm suy giảm hiệu năng phát hiện mục tiêu cũng như độ tin cậy của hệ thống truyền thông. Do đó, quản lý phổ tần và giảm thiểu can nhiễu là những yếu tố thiết yếu để nâng cao hiệu năng của hệ thống JRC. Để giải quyết vấn đề này, chúng tôi đề xuất một cấu trúc gói tin OFDM giúp nâng cao độ chính xác phát hiện, cùng với một ma trận mẫu (pattern matrix) nhằm tối ưu hóa việc phân bổ phổ tần để tránh can nhiễu. Cấu trúc gói tin được đề xuất cho phép các chức năng radar và truyền thông chia sẻ phổ tần hiệu quả hơn trong khi vẫn đảm bảo tính tương thích với tín hiệu OFDM truyền thống. Bên cạnh đó, ma trận mẫu được đề xuất cung cấp một cơ chế phân bổ tài nguyên phổ tần, qua đó giảm sự chồng lấn giữa các tín hiệu radar và truyền thông và nâng cao độ bền vững của quá trình cảm nhận và phát hiện. Khung phương pháp được đề xuất giúp nâng cao hiệu quả sử dụng phổ tần mà không làm thay đổi đáng kể dạng sóng OFDM tiêu chuẩn. Kết quả mô phỏng cho thấy ảnh hưởng của phương pháp đề xuất đến hiệu năng radar dưới nhiều thuật toán phát hiện khác nhau, bao gồm Two-Dimensional Fast Fourier Transform (2D-FFT), Multiple SIgnal Classification (MUSIC) và Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT). Kết quả so sánh cho thấy cấu trúc gói tin và chiến lược phân bổ phổ tần được đề xuất giúp cải thiện khả năng phát hiện mục tiêu đồng thời triệt tiêu can nhiễu một cách hiệu quả. Hơn nữa, kết quả cũng xác nhận rằng tại nút Radar, phương pháp đề xuất có thể nâng cao khả năng phát hiện mục tiêu và giảm can nhiễu, cho thấy đây là một giải pháp phù hợp cho các ứng dụng JRC trong môi trường vô tuyến động. Những kết quả này cho thấy phương pháp đề xuất là một giải pháp thực tiễn nhằm nâng cao hiệu năng cảm nhận và phát hiện trong khi vẫn duy trì khả năng truyền thông tin cậy cho các hệ thống JRC chia sẻ phổ tần trong tương lai.

Từ khoá: Hệ thống radar và truyền thông chung (JRC), tín hiệu ghép kênh phân chia tần số trực giao (OFDM), phát hiện mục tiêu, Two-Dimensional Fast Fourier Transform (2D-FFT), Multiple SIgnal Classification (MUSIC), Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT), thiết kế ma trận mẫu

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