Frequency Hopping Joint Radar-Communications With Hybrid Sub-Pulse Frequency and Duration Modulation

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Abstract—Frequency-hopping (FH) joint radar-communications (JRC) can offer excellent security for integrated sensing and communication systems. However, existing JRC schemes mainly embed information using only the sub-pulse frequencies and hence the data rate is limited. In this letter, we propose to use both sub-pulse frequencies and durations for information modulation, leading to higher communication data rates. For information demodulation, we propose a novel scheme by using the time-frequency analysis (TFA) technique and a ‘you only look once’ (YOLO)-based detection system. As such, our system does not require channel estimation, simplifying the transmission signal frame design. Simulation results demonstrate the effectiveness of our scheme, and show that it is robust against the Doppler shift and timing offset between the transceiver and the communication receiver.

Index Terms—Joint radar-communications, waveform design, YOLO.

I. INTRODUCTION

THE FREQUENCY-HOPPING (FH) joint radar-communications systems (JRC) [1], [2], [3], [4], [5], [6] have become more and more prevalent in both military and civil applications, e.g., airborne, shipborne, ground-based combat systems, the connected autonomous vehicle (CAV). The most popular FH JRC systems include multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM), multi-Carrier AgilE phaSed Array Radar (CAESAR), and FH-MIMO [2].

A key challenge in FH JRC is to embed/modulate data (onto sub-pulse frequencies) at the transceiver and demodulate the signal at the receiver. For data embedding, the most dominant technique is the index modulation (IM), which utilizes frequency selection/combinations and/or antenna selection/permutation for data representation. Specifically, the data bits are embedded by selecting different sets of sub-pulse frequency (i.e., frequency combination) and allocating them to different antennas (i.e., antennas permutation). For data demodulation, the optimal demodulator can be based on the maximum likelihood principle [3], while sub-optimal methods, which require lower computation complexities, are based on compressive sensing (CS) or the discrete Fourier transform (DFT) [2]. However, the performance of these methods depends on the accuracy of channel estimation. Unfortunately, a long training sequence necessary for accurate channel estimation is not always feasible. This is because a long training sequence reduces the communication fraction over the whole time frame, thus decreasing the data bit rate. In particular, the data embedding schemes using both sub-pulse frequency combinations and antenna permutations require complex demodulation techniques that are prone to demodulation error. On the other hand, the data embedding scheme using only the sub-pulse frequency combination has a limited data transmission rate.

This letter proposes novel techniques to embed and demodulate data in an FH JRC system to increase the data rate and reduce the demodulation error. For data embedding, we use both sub-pulse frequency and duration, therefore increasing the data transmission rate compared to only using the sub-pulse frequency. For data demodulation, we propose a novel scheme based on the signal’s time-frequency image (TFI) and a ‘you only look once’ (YOLO)-based detection system. This demodulation scheme, instead of requiring a channel estimation, only requires the estimation of the channel delay spread, thus less prone to estimation error. Moreover, the proposed demodulation technique is more robust to the Doppler shift and the timing offset between the transceiver and the communication receiver compared to the existing ones. Additionally, the proposed data embedding and demodulation schemes are spatially flexible and not limited to the sidelobe of the transmit beampattern, since the data is not embedded by utilizing the phase or amplitude of the beampattern sidelobe.

II. SYSTEM AND SIGNALS

A. System Overview

We consider a ground-to-air JRC system, where the JRC transceiver is located on the ground and the communication receiver is mounted on an aircraft or a high-altitude platform (HAP), as illustrated in Fig. 1. For sensing, the JRC transceiver transmits the radio frequency (RF) signal and processes the reflected RF signal to determine target’s position and velocity. For data transmission, the communication receiver obtains the RF signal from the JRC transceiver and demodulate the embedded data. At the transceiver or communication receiver, the received RF signal is down-converted to the intermediate frequency (IF) signal and sampled at sampling frequency $f_s$ to generate a discrete-time signal as

$$r[k] = h[k] * s[k] + w[k].$$

Manuscript received 9 July 2022; accepted 18 August 2022. Date of publication 23 August 2022; date of current version 9 November 2022. This work was supported in part by the Australian Government through the Australian Research Council’s Discovery Projects Funding Scheme under Project DP210101411. The associate editor coordinating the review of this article and approving it for publication was F. Shu. (Corresponding author: Linh Manh Hoang.)

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Digital Object Identifier 10.1109/LWC.2022.3200676

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Here, \( k \) is the sample index which increases every \( T_s = 1/f_s \), \( s[k] \) and \( r[k] \) are the transmitted and received signal samples, respectively, \( h[k] \) denotes a Rician channel model [7], and \( w[k] \) is the complex additive white Gaussian noise (AWGN). The JRC system uses a pulse wave (PW) waveform with a duty cycle \( D = \Delta t_w/(\Delta t_t) \), \( D < 1 \), where \( \Delta t_w \) and \( \Delta t_t \) are the pulse width and pulse repetition intervals, respectively. The received signal at the communication receiver is then used to generate the Choi-Williams distribution time-frequency image (CWD-TFI). Next, the CWD-TFI is preprocessed in the Preprocessing block to generate the training and testing data for the YOLO detection system. The training process of the YOLO detection system is demonstrated by the dashed line in Fig. 1. The trained YOLO detection system and the testing CWD-TFIs are used to generate the annotated CWD-TFIs, which are used to demodulate the embedded data.

B. Signals Model

The JRC system uses FH signals with each signal pulse being divided into \( N_t \) sub-pulses (i.e., hops) with different frequencies and durations. Let \( \mathbf{F} = (f_1, f_2, \ldots, f_{N_t}) \) denote the FH sequence and \( \mathbf{T} = (\Delta t_1, \Delta t_2, \ldots, \Delta t_{N_t}) \) denote the sub-pulse duration sequence. The JRC signal in each pulse is represented by

\[
s[k] = \sum_{n=1}^{N_t} A e^{j2\pi f_n k T_m} \text{rect} \left( \frac{k T_s - \sum_{i=0}^{n-1} \Delta t_i}{\Delta t_n} \right),
\]

where

\[
\text{rect}[k] = \begin{cases} 1, & 0 \leq k \leq 1, \\ 0, & \text{otherwise}, \end{cases}
\]

and \( \Delta t_0 \triangleq 0 \).

III. DATA EMBEDDING SCHEMES

In this letter, we use the Costas arrays to generate the FH sequence of each signal pulse in one of the data embedding schemes. Using the Costas array, an FH signal possesses a narrow peak at the origin of its ambiguity function (AF) and low sidelobes elsewhere, which is desirable for the radar measurement (i.e., range and speed) accuracy. Specifically, the pulse compression ratio (PCR) of a Costas signal is \( N^2 \). Details of the Costas arrays, their construction, and characteristics can be found in [8, Ch. 5].

We propose two data embedding techniques, namely Random and Costas-based schemes. Unlike existing studies that only utilize sub-pulse frequencies to convey information, both sub-pulse frequencies and durations are used in our proposed schemes. We first design the codebooks \( \mathcal{S} \) and \( \mathcal{S}_C \) of the Random and Costas-based schemes, respectively. Then, for each embedding scheme, data bits are embedded by mapping each element of the corresponding codebook to a symbol. Let \( \mathcal{F} \triangleq [(1, 2, \ldots, N_t) \times f_1] \) be the selection set of the sub-pulse frequency, where \( f_1 \) is the fundamental frequency. Let \( \mathcal{D} \triangleq [(\Delta_t_1, \Delta_t_2, \ldots, \Delta_t_{N_t}) \times f_1] \) be the selection set of the sub-pulse duration, where \( N_T \) is the number of sub-pulse duration selections. The codebooks \( \mathcal{S} \) and \( \mathcal{S}_C \) are designed as follows.

- **Random scheme:** \( \mathcal{S} \) is designed by selecting each sub-pulse frequency from the frequency set \( \mathcal{F} \), and selecting each sub-pulse duration from the duration set \( \mathcal{D} \) as

\[
f_i \in \mathcal{F}, \Delta t_i \in \mathcal{D}, \forall i \in (1, 2, \ldots, N_t),
\]

\[
f_i \neq f_{i+1}, \forall i \in (1, 2, \ldots, N_t - 1).
\]

Here, condition (4) means every two consecutive sub-pulse frequencies are not equal, which is necessary for the data demodulation technique that will be presented in Section V.

- **Costas-based scheme:** Unlike the Random scheme, for designing \( \mathcal{S}_C \), each sub-pulse frequency is not individually selected. Instead, the whole FH sequence of each signal pulse is selected from the Costas-based FH sequence defined as follows.

Let \( \mathcal{A}_C \triangleq [(A_1, A_2, \ldots, A_{N_C})] \) be the set of Costas array of length \( N_t \), where \( A_i, \forall i \in (1, 2, \ldots, N_C) \) is an \( N_t \times 1 \) Costas array, and \( N_C \) is the number of Costas sequence with length of \( N_t \). Then, let \( \mathcal{F}_C \triangleq [(A_1, A_2, \ldots, A_{N_C}) \times f_1] \) be the selection set of the Costas-based FH sequence. Then, the FH sequence of each signal pulse is selected from \( \mathcal{F}_C \). On the other hand, similar to the Random scheme, each sub-pulse duration is selected from the sub-pulse duration set \( \mathcal{D} \) as

\[
\mathbf{F} \in \mathcal{F}_C, \Delta t_i \in \mathcal{D}, \forall i \in (1, 2, \ldots, N_t).
\]

Note that for the Costas-based scheme, because the FH sequence is generated using the Costas array, condition (4) is satisfied. The dimensions of \( \mathcal{S} \) and \( \mathcal{S}_C \) are given by

\[
|\mathcal{S}| = N_t^{N_t^2} \times N_t(N_t-1)(N_t-2) \ldots (N_t-N_t+1),
\]

\[
|\mathcal{S}_C| = N_t^{N_t^2} \times N_t(N_t-1)(N_t-2) \ldots (N_t-N_t+1),
\]

As shown in (6), the number of selections of sub-pulse frequencies is \( N_t(N_t-1)(N_t-2) \ldots (N_t-N_t+1) \) instead of \( N_t^{N_t^2} \) due to the requirement in (4).

It follows from (6) and (7) that the maximum number of bits \( C \) and \( C_C \) that can be embedded in each pulse of the two schemes are given by

\[
C = \lfloor \log_2(|\mathcal{S}|) \rfloor = \lfloor \log_2(N_t N_t^2 (N_t-1)(N_t-2) \ldots (N_t-N_t+1)) \rfloor,
\]

\[
C_C = \lfloor \log_2(|\mathcal{S}_C|) \rfloor = \lfloor \log_2(N_t^{N_t^2} N_t) \rfloor.
\]

where \( \lfloor . \rfloor \) denotes the floor function, determining the closest smaller integer. As can be seen, the Random scheme achieves a higher transmission rate than the Costas-based scheme.
IV. SENSING AT THE JRC TRANSCEIVER

This section describes the matched filtering technique used at the JRC transceiver to detect the reflected radar signal. We also demonstrate that by using the sub-pulse frequencies and durations for data embedding as presented in the previous section, the detection probability of the sensing function is not affected.

Let \( P_D \) and \( P_{FA} \) denote the detection and false alarm probabilities of the JRC transceiver, respectively. Let \( E_p \) be the signal energy per each pulse of the JRC signal and \( \sigma_w^2 \) be the noise variance. The energy-to-noise ratio (ENR) of the JRC signal is given by

\[
ENR = 10 \log_{10} \left( \frac{E_p}{\sigma_w^2} \right),
\]

To detect the transmitted signal \( s[k] \) buried in the reflected RF signal \( r[k] \), the JRC transceiver performs the matched filtering. Let \( R_s \) denotes the output of the matched filter. Based on Neyman-Pearson criterion, the transceiver decides a detection if \( R_s \) exceeds a threshold \( \gamma \)

\[
R_s = \sum_{k=0}^{N_p-1} r[k] s[k] > \gamma,
\]

where \( N_p \) is the number of signal sample per pulse,

\[
\gamma = \sqrt{\sigma_w^2 E_p} Q^{-1}(P_{FA}),
\]

\[
Q(x) = \int_{x}^\infty \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2} t^2\right) \, dt
\]

is the complement of the cumulative distribution function (CDF) of the standard Gaussian distribution, and \( Q^{-1}(x) \) denotes the inverse function of \( Q(x) \). The characteristic of \( P_D \) is given in Theorem 1 below.

**Theorem 1:** The value of \( P_D \) is independent from the JRC signal waveform and only depends on \( P_{FA} \) and ENR.

**Proof:** From [9, Ch. 4], \( P_D \) can be expressed by \( P_{FA} \) and ENR as

\[
P_D = Q \left[ Q^{-1}(P_{FA}) - \sqrt{10^{\text{ENR}}/10} \right].
\]

Accordingly, \( P_D \) only depends on \( P_{FA} \) and ENR, and is independent from the JRC signal waveform.

Therefore, varying the sub-pulse frequencies and durations does not affect the detection performance of the sensing function, as long as the signal energy per each pulse is fixed. Note that, however, varying the sub-pulse durations may cause some increase in the peak-to-average power ratio (PAPR), which reduces the efficiency of the power amplifier at the front end of the JRC transceiver and communication receiver. Therefore, the sub-pulse selection set \( D \) should be carefully designed to avoid an excessive PAPR value.

V. DEMODULATION AT THE COMMUNICATION RECEIVER

This section presents the detailed procedure of the proposed data demodulation schemes. First, the CWD is used to generate the received signal’s CWD-TFI, which illustrates the sub-pulse frequency and duration of the signal by the signal objects. Then, we use the ‘you only look once’ (YOLO) detection system to recognize the signal objects on the CWD-TFI. By using the coordinates of the bounding box of the signal objects, the sub-pulse frequencies and durations can be determined. Finally, the embedded symbols are demodulated by comparing the sub-pulse frequencies and durations to the codebook.

A. CWD-TFI Preprocessing

To generate the CWD-TFI, similar to [10], we capture \( N_s = 2048 \) consecutive signal samples, and assume these \( N_s \) samples contain a complete signal pulse, and the signal pulse starts from an arbitrary point within the \( N_s \) samples. Fig. 2(a) and Fig. 2(b) illustrate the CWD-TFIs of a Costas signal travels through an AWGN and a Rician fading channel, respectively. The parameters of the signal includes a frequency of \( f = 5 \) Hz, delay spread of the channel \( \tau_d = 5/16 \), and a starting point of 322.

Fig. 2. CWD-TFIs of a Costas signal with \( F = [(4, 2, 5, 1, 3) \times f], T = (5, 2, 4, 2, 3) \times 80/(f_s), f_s = f_s/16, \) and a starting point of 322.
the resized CWD-TFIs. Then, the signal sub-pulse locations in the CWD-TFI are specified by the bounding boxes (i.e., white-color rectangles in Fig. 3), as a requirement for the training of the YOLO. Note that the localization of the bounding boxes is not needed in the CWD-TFI processing procedure in the testing phase, because the bounding boxes are parts of the output of the trained YOLO detection system.

B. “You Only Look Once” (YOLO) Object Detection System

Among the object detection algorithm for determining the objects types and their locations in the image, YOLO [11] is well-known for its real-time detection speed, which is critical in tactical applications, such as military JRC systems. Details of the YOLO detection system can be found in [11].

Fig. 4 shows the YOLO’s output for the CWD-TFI of a Costas signal with an FH sequence of $F = [(4, 2, 5, 1, 3) \times f_t]$, a sub-pulse duration sequence of $T = (4, 3, 5, 4, 2) \times 80/(f_s)$, $f_t = f_s/16$, and a starting point of 259. As can be seen, the output contains not only the signal type (i.e., “Costas”) but also the locations of the signal objects (i.e., the white-color rectangular bounding boxes) and the probabilities of the detection.

C. Data Demodulation Technique

As aforementioned, the output from the YOLO detection system contains the bounding boxes, which determine the position, horizontal, and vertical width of the signal objects in the CWD-TFI. The $i$th left-most bounding box, corresponds to the $i$th sub-pulse, is localized by a tuple of $(x_i^{min}, x_i^{max}, y_i^{min}, y_i^{max})$. Recall that for the CWD-TFI, $L$ pixels in the vertical axis correspond to a frequency range from 0 to $f_s/2$, while $L$ pixels in the horizontal axis correspond to a time duration of $N_t \times (1/f_s)$, the frequency and duration of the $i$th sub-pulse can be calculated by

$$f_i = \frac{f_s(x_i^{max} - x_i^{min})}{4L},$$

$$\Delta t_i = \frac{N_t(x_i^{max} - x_i^{min}) - \tau_{d}}{L f_s},$$

where $\tau_{d}$ is the channel’s delay spread. To estimate $\tau_{d}$, a training process is performed, where a signal pulse with known FH sequence $F$ and sub-pulse duration $T$ is transmitted by the JRC transceiver and captured by the communication receiver. Then, $\tau_{d}$ can be determined by

$$\tau_{d} = \frac{1}{N_t} \sum_{i=1}^{N_t} (\Delta t_i - \Delta t_i^*),$$

where $\Delta t_i^*$ is the $i$th sub-pulse duration demonstrated on the CWD-TFI of the training signal. By comparing the combination of $f_i$ and $\Delta t_i$ values with the selections in the codebook $S$ or $S_C$, the embedded symbol in each signal pulse can be determined.

VI. PERFORMANCE EVALUATION

Table I shows the parameter values used to produce the simulation results. We use all available Costas sequences (i.e., $N_C = 40$ for $N_t = 5$) for data modulation. The list of available Costas arrays and their construction can be found in [8, Ch. 5]. To train the YOLO detection system, for each data embedding scheme, we generate 2700 signals with SNR ranging from $-6$ dB to 10 dB and a step size of 2 dB. The 2700 signals are divided into a training set of 2160 signals (80% of the total) and a validation set of 540 signals (20% of the total). For the testing data, we generate 3300 signals for each embedding scheme, with SNR ranging from $-10$ dB to 10 dB and a step size of 2 dB.

| Parameter | Description | Value |
|-----------|-------------|-------|
| $N_t$     | Number of sub-pulses per pulse | 5     |
| $N_C$     | Number of Costas pulses | 40    |
| $T$       | Sub-pulse duration selection set | $(1, 1.5, 2, 2.5, 3) \times 80/(f_s)$ |
| $f_t$     | Fundamental frequency | $f_s/16$ |
| $L$       | Resized CWD-TFI width (pixels) | 500   |
| $\tau_{d}$ | Delay spread of the Rician channel | $40/f_s$ |

![Fig. 3. CWD-TFI preprocessing procedure for the Costas signal in Fig. 2(a).](image1)

![Fig. 4. YOLO’s output for a Costas signal with $F = [(4, 2, 5, 1, 3) \times f_t]$, $T = (4, 3, 5, 4, 2) \times 80/(f_s)$, $f_t = f_s/16$, and a starting point of 259.](image2)
Fig. 5 shows the detection probability of the JRC sensing function for different signal waveforms (i.e., Random scheme, Costas-based scheme, and fixed sub-pulse length), $P_{FA}$, and SNR values. The results are obtained by averaging 10,000 independent trials. As can be seen, for each $P_{FA}$ value, the three curves almost overlap, meaning the detection probability only depends on $P_{FA}$ and ENR but not the signal waveform. Therefore, varying the sub-pulse durations does not affect the detection capability of the sensing function of the FH JRC system, as long as the signal energy per each pulse is fixed.

Fig. 6 demonstrates the maximum number of bits that can be transmitted over a signal pulse of the two proposed embedding schemes and those in [3], [5]. As can be seen, the Random scheme can embed a significantly higher amount of data than the Costas-based scheme, while the Costas-based scheme can convey a slightly higher number of data bits than the scheme in [3], [5]. That is because the schemes in this letter use both sub-pulse durations and frequencies to embed signals. On the other hand, the technique in [3] focuses on using antenna permutations for data embedding. Therefore, the proposed techniques are more suitable when the number of antennas is limited, while the technique in [3], [5] is suitable when an extensive number of antennas is available.

Fig. 7 illustrates the symbol error rate (SER) of the two proposed schemes and those of the techniques in [5] as functions of the signal-to-noise ratio (SNR). As can be seen, the two proposed schemes have lower SERs compared to those of the techniques in [5] for all SNRs. Distinctively, at low SNRs (i.e., $\leq -2$ dB), the two proposed schemes have similar SERs, and are about 4 dB and 10 dB better than those of the FH and BPSK techniques in [5], respectively. This is because the proposed techniques use the CWD, which contains the auto-correlation operation, to generate CWD-TFIs of the signals. As such, the proposed techniques are more robust against noise compared to the other techniques in [5].

VII. CONCLUSION

We have proposed novel approaches for embedding and demodulating information bits in FH JRC systems. For data embedding, we have used both sub-pulse durations and frequencies to increase the data transmission rate. For data demodulation, to reduce the error rate, we have proposed a CWD-TFI and YOLO-based demodulation scheme that does not require channel estimation and is robust against Doppler shift and timing offset between the JRC transceiver and communication receiver. Simulation results have shown that our proposed techniques achieve higher data transmission and lower symbol error rates than the existing ones.

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