Bistatic Joint Radar and Communication with 5G Signal for Range Speed Angle Detections

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***Abstract*—We propose a bistatic joint radar and communication (JRC) based on standardized 5G new radio (NR) waveform, where the receiver can decode the transmitted signal, and estimate the range, speed, and angle of the radar targets at the same time. The proposed solution consists of several key components, including a) a decision feedback architecture and two JRC algorithms for bistatic radar sensing; b) a multi-user bistatic JRC solution; and c) a direction of arrival (DOA) estimation algorithm based on the range-Doppler map (RDM). We present simulation results to demonstrate the effectiveness of our proposed solution, and its ability to work well in the multi-user scenarios where multiple users share the same spectrum, making it a promising solution for practical applications that require radar sensing in crowded environments.**

I. Introduction

The idea behind joint radar and communication (JRC) is to leverage the same hardware and waveform to perform both sensing and communication functions. This approach has the potential to bring significant savings in terms of spectrum, power, cost, and many benefits to different application areas, including assisted or automated driving systems [1] - [5].

The research on JRC has been active in recent years. Reference [6] provides excellent reviews on this topic with a focus on orthogonal frequency division multiplexing (OFDM) or multi-tone waveforms. References [7] - [10] propose radar detection/estimation algorithms for cyclic prefixed OFDM (CP-OFDM) that use channel estimation and block processing based on the special structure of CP-OFDM. Reference [11] uses the autocorrelation-based method for radar detection/estimation, which relies on the excellent auto-correlation property of the preamble sequence in IEEE 802.11ad waveform. In [12], methods are proposed to achieve superior detection resolution for IEEE 802.11p waveform.

In this paper, we propose an integrated solution for multi-user bistatic JRC systems based on 5G new radio (NR) waveform. The use of multi-user bistatic JRC systems offers several benefits. Firstly, it does not have the self-interference problem that is inherent to monostatic radar [13]. Secondly, it offers increased flexibility in system design. For example, it is possible to deploy multiple receivers at different locations, which allows for more comprehensive coverage of the area under surveillance. Thirdly, it can operate in a cooperative or non-cooperative mode, depending on the specific application requirements. Overall, a multi-user bistatic 5G JRC system is a powerful tool that can provide improved radar target detection and localization, reduced vulnerability to interference, and increased flexibility in system design. The contributions of this paper are summarized as below:

- Decision feedback bistatic architecture. While decision feedback is a well-known scheme in wireless communications, it is less commonly used in radar system due to the lack of demodulation and decoding capability in radar. The unique design of bistatic JRC enables to leverage the decision feedback for radar sensing. In this architecture, the receiver first estimates the channel based on pilots/preambles, then demodulates and decodes the signal for communication purposes, and finally uses the recovered signal samples for radar sensing. Under this architecture, two JRC algorithms are proposed and compared.
- Multi-user JRC solution. When multiple users share the same spectrum, multi-user interference will degrade the accuracy and reliability of radar detection. Therefore, multi-user interference cancellation techniques are essential to improve the radar detection performance in shared spectrum environments.
- DOA estimation based on the range-Doppler map (RDM) and FFT. If the signals reflected by different radar targets have very close direction of arrival (DOA), the DOA of the reflected signals cannot be detected accurately with MUSIC or Capon algorithms. Therefore, a new DOA estimation algorithm based on RDM and FFT is proposed to achieve high DOA estimation accuracy.

Compared with the latest similar work in [14] - [15], our radar sensing makes use of communication data payload besides the known pilots or preambles through decision-feedback. This makes the range and Doppler estimations more reliable due to the availability of more data.

II. System Model

We consider a multi-user bistatic JRC system as shown in Fig. 1, where multiple users share the same 5G NR spectrum, receive data from the communication transmitter (TX) and detect and track the locations and velocities of radar targets independently. In this system model, the TX

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generates a modulated signal based on the 5G NR standard and sends it to radar targets via a TX antenna (ANT). The signal is reflected and received by the receiver antennas of multiple users, where multiple users use the received signal to estimate the range, speed and angle of the radar targets. One of the unique aspects of this system is that the transmitted signal contains modulated data, which allows receiver (RX) to receive useful communication data while performing radar sensing simultaneously. The detection outputs of the multiple users can be combined to provide a complete picture of the environment, enabling improved radar target detection and localization. In the interest of paper length, we will discuss radar detection using one user as an example. Other users will process following the same way. How multi-users cooperate and combine their results will be discussed in a separate paper.

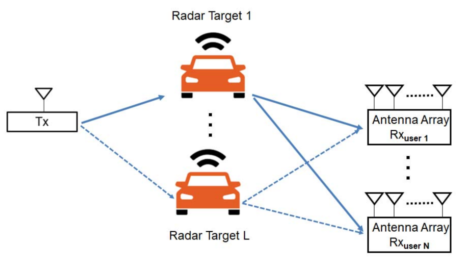

Fig. 1. Illustration of multi-user bistatic 5G JRC system.

The system model is described as follows. Let s(t) be the transmitted baseband signal. The signal reflected from radar targets is received at the receiver of multiple users. Assuming that there are L radar targets, the received baseband discrete signal is given by

$$y(nT_b) = \sum_{l=1}^{L} h_l s(nT_b - \tau_l) e^{j2\pi n\phi_l T_b} + w(nT_b) \quad (1)$$

where $h_l = \alpha_l e^{-j2\pi(f_c+\phi_l)\tau_l + j\omega + j\theta_l}$ is the complex channel gain of radar target l (random phase error is absorbed into this term as well), α_l is the attenuation coefficient of radar target l, f_c is the carrier frequency, $\phi_l = \frac{u_l}{c} f_c$ is the Doppler frequency shift induced by the moving of radar target l, u_l is the relative speed of radar target l , c is the speed of light, τ_l is the trip delay of radar target l, ω is the initial phase, θ_l is a phase error, T_b is the sampling period and $w(nT_b)$ is the noise term.

Radar receiver is to find the delay τ_l (corresponding to range) and Doppler shift ϕ_l (corresponding to the relative speed). Let $\varepsilon_l = \tau_l / T_b$, $v_l = \phi_l T_b$. Note that $\varepsilon_l = \tau_l / T_b$ may not be an integer. If so, we choose ε_l as the nearest integer to τ_l / T_b. To simplify notations, we denote $y(nT_b)$ by $y(n)$, $s(nT_b)$ by $s(n)$, and $w(nT_b)$ by $w(n)$, and will have

$$y(n) = \sum_{l=1}^{L} h_l s(n - \varepsilon_l) \ e^{j2\pi n v_l} + w(n), n = 0, 1, \ldots . \quad (2)$$

The above model is applicable to any waveform. We assume that the transmitted time domain signal has a “block structure” and each block has a CP. The signal $s(n)$ is composed of M blocks with each block having a length of $N_a = N + N_p$, where N is the length of data block and N_p is the length of CP. In each block, the first N_p symbols (the CP) are the repetition of the last N_p symbols. OFDM and CP-SC are the two most popular waveforms with this structure. To cater for this structure, we divide the received discrete signal $y(n)$ into blocks of length N_a. In each block, the first N_p elements (corresponding to the CP of that block) are discarded. The block m (after discarding the CP) is denoted as $y_m(n), n = 0, 1, \ldots, N-1, m = 0, 1, \ldots, \ M-1$. Assuming that the normalized delay is always smaller than the CP length $\varepsilon_l \leq N_p$, the received signal can be expressed as

$$y_m(n) = \sum_{l=1}^{L} \hat{h}_l s_m \left(\langle n - \varepsilon_l \rangle_N \right) e^{j2\pi n v_l} e^{j2\pi m N_a v_l} + w_m(n) \quad (3)$$

where $\hat{h}_l = h_l e^{j2\pi N_p v_l}$ and $\langle n \rangle_K$ denotes the remainder of n modulo K: $\langle n \rangle_K = n \bmod K$.

III. Review of Fast Cyclic Correlation RADAR (FCCR) Algorithm

The Fast Cyclic Correlation Radar (FCCR) was derived from the maximum likelihood (ML) principle and can be used for any waveform with the CP structure [7]. Theoretically, it is nearly optimal given that the delay is within the CP range. In the FCCR algorithm, the received signal is divided into M blocks of length N_a, and the CP is discarded. The signal at block m is denoted as $y_m(p)$. Let the cyclic correlation of the received signal and the transmitted signal be

$$r(n, m) = \sum_{p=0}^{N-1} y_m(p) s_m^* \left(\langle p - n \rangle_N \right), n = 0, 1, \ldots, N-1. \quad (4)$$

Let the DFT of $r(n, m)$ on the second dimension be

$$R(n, k) = \sum_{m=0}^{M-1} r(n, m) e^{j \frac{-2\pi m k}{M_1}} \quad (5)$$

where $M_1 = qM$ with q being a positive integer number. We call $R(n, k)$ the range-Doppler matrix (RDM). It is proved in [7] that the ML estimation for the range and speed can be very well approximated by the maximization below

$$(n_1, \ k_1) = \arg \max_{(n, \ k)} |R(n, k)|. \quad (6)$$

The normalized range and speed are then obtained as: $\varepsilon_1 = n_1$, and $v_1 = k_1 / (M_1 N_a)$.

A very special property of FCCR is that it processes the signal in time domain with optimal performance, which is particularly useful when the receiver can only get data from part of the subcarriers. In 5G NR, the whole bandwidth is usually shared by multiple UEs, where each UE only uses a particular subcarrier set. Thus, in the following, we will use FCCR for the multi-user bistatic radar based on 5G signal.

IV. Bistatic Radar Architecture and Algorithms

A. Decision Feedback Bistatic Radar Architecture

In bistatic radar architecture, the receiver and transmitter are physically separated. As shown in Fig. 2. the receiver utilizes a decision feedback mechanism to improve the accuracy and reliability of radar sensing. Since the receiver does not know the source signal, it needs to estimate the channel and then demodulate and decode the received signal based on the known pilots or preamble information. Once the receiver has recovered the transmitted signal, it can use the received signal samples to perform radar sensing.

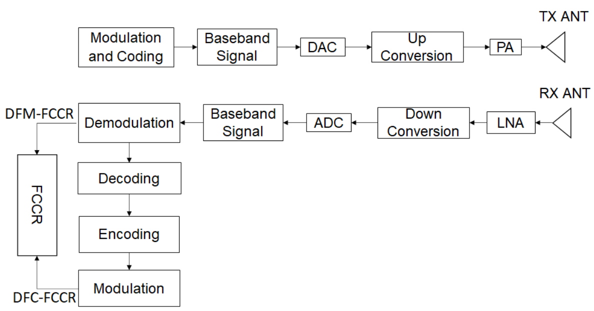

Fig. 2. Decision feedback JRC block diagram.

As shown in Fig. 2, we can use the existing communication receiver to recover the user's data first, and then apply the FCCR based on the recovered data. We propose two methods for this purpose. The two methods differ in terms of complexity and performance.

The first method is called decision feedback with de-Modulation FCCR (DFM-FCCR), where the receiver feeds the demodulated signal directly to the radar sensing block. This approach is relatively simple and straightforward, but it does not take advantage of the coding gain that may be available.

The second method is called decision feedback with de-Coding FCCR (DFC-FCCR), where the receiver performs decoding on the received signal, and then re-encodes and remodulates the decoded bits before feeding the remodulated signal to the radar sensing block. This approach takes advantage of the coding gain, which can significantly improve the radar detection performance, especially in low signal-to-noise ratio (SNR) scenarios. However, the second method is more complex than the first method since it involves additional encoding and modulation steps, which may increase the processing time and power consumption of the system and could be a concern in certain applications.

B. Multi-user Bistatic JRC Solution

When multiple users share the same spectrum, interference between users will occur, which will degrade the accuracy and reliability of radar detection. Therefore, multi-user interference cancellation techniques are essential to improve the performance of JRC systems in shared spectrum environments. Our approach is to use signal processing techniques to cancel the multi-user interference in frequency domain, which involves using digital signal processing techniques such as Fourier transforms or digital filters to separate the desired signal from the interfering signals. The UE only keeps the signal for itself and reset the received signal by putting zeros on the subcarriers used by others. Finally, the FCCR algorithm is used based on the reset signal and the UE's own data. The detail of the algorithm is shown in Algorithm 1.

Algorithm 1 Multi-user Bistatic JRC Solution

1: Perform FFT on receive signal $y_m(n)$, and transmit signal $S_m(k)$ to obtain

$$Y_m(k) = \sum_{n=0}^{N-1} y_m(n)\, e^{j\frac{-2\pi nk}{N}}$$

$$S_m(k) = \sum_{n=0}^{N-1} s_m(n)\, e^{j\frac{-2\pi nk}{N}}.$$

2: Extract user own received signal by setting other users' signal to be zero

$$\widetilde{Y}_m(k) = \begin{cases} Y_m(k), & \text{if k is user's data subcarrier} \\ 0, & \text{else} \end{cases}$$

$$\widetilde{S}_m(k) = \begin{cases} S_m(k), & \text{if k is user's data subcarrier} \\ 0, & \text{else.} \end{cases}$$

3: Compute the cyclic correlation $\widetilde{r}(n,m)$ by IFFT

$$\widetilde{r}(n,m) = \frac{1}{N} \sum_{k=0}^{N-1} \widetilde{Y}_m(k) \widetilde{S}_m^*(k) e^{j\frac{2\pi nk}{N}}.$$

4: Compute FFT of $\widetilde{r}(n,m)$ to get the RDM

$$\widetilde{R}(n,k) = \sum_{m=0}^{M-1} \widetilde{r}(n,m) e^{j\frac{-2\pi mk}{M_1}}.$$

5: Based on the $\widetilde{|R(n,k)|}$, determine which points are radar targets and estimate the range and speed of each detected radar target as

$$(n_1,\ k_1) = \arg \max_{(n,\ \ k)} \left|\widetilde{R}(n,k)\right|.$$

C. DOA based on RDM and FFT

Given the situation that the signals reflected by different radar targets may have close DOA, we cannot detect the DOA of the reflected signals accurately if we directly feed received signal to MUSIC or Capon algorithms. Therefore, we propose a new DOA estimation algorithm based on RDM generated in radar sensing process. Specifically, we first use the radar sensing algorithm to obtain RDM on each antenna. Then, we search for the peak in each RDM along the Doppler and range axis, which corresponds to the Doppler shift and delay of the reflected signals. Finally, at peaks in RDMs taken on different antennas, we use the phase difference to estimate the DOA of signals reflected from different radar targets. This algorithm can achieve high DOA estimation accuracy even when the DOA of the signals reflected from different radar targets are very close. The detail of the algorithm is shown in Algorithm 2.

Algorithm 2 DOA Estimation based on RDM and FFT

1: For each receive antenna i, find RDM $R_i(n,k)$.

2: Find the average of RDMs across all antennas as

$$\bar{R}(n,k) = \frac{1}{N_{\text{antenna}}} \sum_{i=1}^{N_{\text{antenna}}} |R_i\left(n,k\right)|.$$

3: Find the peaks indices of the average RDM $\bar{R}(n,k)$ as

$$(\text{index}_{\text{range}}, \text{index}_{\text{speed}}) = \arg \max_{(n,\ k)} \bar{R}(n,k).$$

4: Find the peak with indices $(\text{index}_{\text{range}}, \text{index}_{\text{speed}})$ in each RDM, store all the peaks in a vector, and perform N_{FFT}-point FFT on the peaks $R_i\left(\text{index}_{\text{range}}, \text{index}_{\text{speed}}\right)$ to obtain

$$X_{\text{FFT}}\left(k\right) = \sum_{i=0}^{N_{\text{antenna}-1}} R_i\left(\text{index}_{\text{range}}, \text{index}_{\text{speed}}\right) e^{j\frac{-2\pi ik}{N_{\text{FFT}}}}.$$

5: Find the peak indices on $|X_{\text{FFT}}(k)|$ as

$$\text{index}_{\text{doa}} = \arg\max_{k} |X_{\text{FFT}}(k)|.$$

6: The final DOA is given by

$$\theta = \frac{180}{\pi} \sin^{-1}\left(\frac{\text{index}_{\text{doa}} - 1}{2N_{\text{FFT}}}\right).$$

V. Simulation Results

In this section, we show simulation results of our proposed bistatic decision feedback JRC algorithms, multi-user JRC solution and DOA estimation algorithm based RDM and FFT using the 5G NR signal generated by the Matlab 5G toolbox. The detailed settings are shown in Table I. For simplicity, we only consider two radar targets in the simulation, with one strong target and one weak target, respectively. We assume the power of the weak target is 10 dB lower than the strong target. The following figures show the range/speed detection performance of the weak target only, as the strong target is easy to detect and all algorithms have similar detection performance for the strong target.

TABLE I
SIMULATION PARAMETERS

Channel bandwidth	48.6 MHz
Carrier frequency	5.9 GHz
Subcarrier spacing	15 kHz
Modulation scheme	QPSK
FFT size	4096
Symbols per slot	14
Slots per subframe	1
Slots per frame	10
LDPC code rate	490/1024
LDPC encoding algorithm	Normalized min-sum
Maximum LDPC iteration count	6
Number of DM-RS symbol	1
Number of transmit antennas	1
Number of receive antennas	3
DOA range of two reflected signals	[0 30] degree
Relative path gains of two reflected signals	[10 0] dB
Range of two radar targets	[90 300] m
Speed of the strong radar target	[0 20] km/h
Speed of the weak radar target	[0 100] km/h

Figs. 3 and 4 demonstrate the range and speed detection performance of the proposed bistatic decision feedback JRC algorithms for the weak target. We can see that both DFC-FCCR and DFM-FCCR have much better performance than CHOR in [8]. The reason is that CHOR is based on channel estimation only. Since there is only one DM-RS symbol for channel estimation in each time slot, the channel estimation for other OFDM symbols is given by 2-D interpolation (time and frequency interpolation) only, resulting in inaccurate channel estimation for other OFDM symbols and inadequacy to detect range/speed of radar targets accurately. Therefore, decision feedback is essential to improve the range/speed detection performance by exploiting the advantage of decoded/demodulated information. These two figures also highlight that DFC-FCCR provides better performance than DFM-FCCR, due to the coding gain introduced. However, DFC-FCCR is more complex, requiring additional encoding and modulation steps, which introduces additional delay in processing time. The choice between the two methods depends on the specific requirements and constraints of the application, such as desired performance, complexity, and processing time. Both methods have their advantages and disadvantages, and the optimal choice will require a careful trade-off analysis.

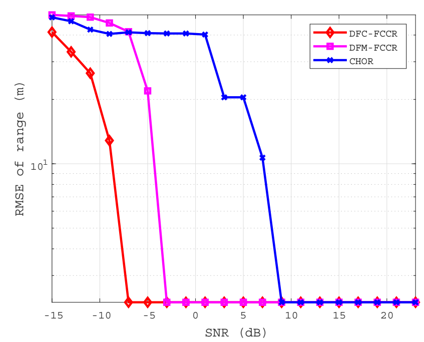

Fig. 3. Range performance of decision feedback JRC.

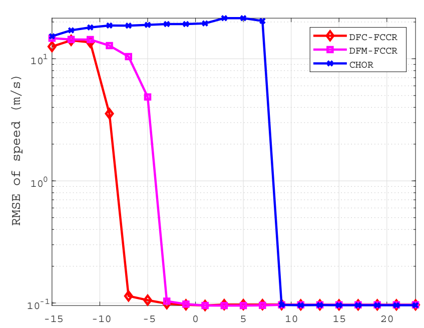

Fig. 4. Speed performance of decision feedback JRC.

Figs. 5 and 6 present a comparison of the performance of DFC-FCCR where multiple users share the same spectrum. It can be observed that the proposed multi-user JRC algorithm shows good performance when there are two or four users. As the number of users sharing the spectrum increases, the performance of the algorithm will degrade, as fewer data subcarriers are available for radar detection for each user. Nevertheless, when there are only two users, the algorithm remains robust and can achieve performance close to that of a single-user scenario when SNR is larger than or equal to -1 dB. Note that in these two figures, SNR is the ratio of received signal (including possible multi-user interferences) power to the noise power.

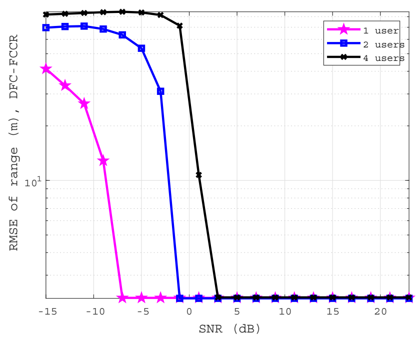

Fig. 5. Range performance of multi-user JRC.

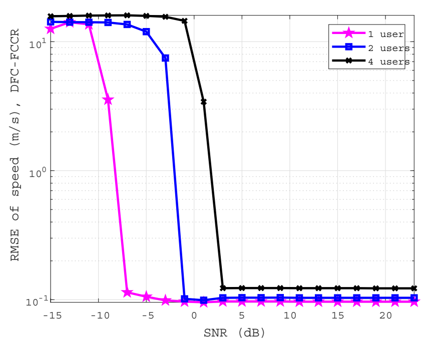

Fig. 6. Speed performance of multi-user JRC.

Fig. 7 shows the performance of the proposed DOA estimation algorithm based on RDM and FFT. We can see that the algorithm can achieve less than 0.5-degree accuracy when a small number of antennas, e.g., 3 antennas, and a small number of FFT points, i.e., 128 points, are used in the algorithm. Since RDM is already obtained during radar sensing process, we only need to perform FFT and 1-D search for this DOA algorithm. So the complexity of this algorithm is very low, which can help reduce computational requirements and potentially lower the cost of implementation.

VI. Conclusions

We have proposed a bistatic JRC based on standardized 5G NR waveform, where the receiver can decode the transmitted signal, and estimate the range, speed, and angle of the radar targets at the same time. The proposed solution includes a decision feedback architecture for bistatic radar sensing, two decision feedback JRC algorithms, a multi-user bistatic JRC solution, and a DOA estimation algorithm based on RDM and FFT. The proposed bistatic decision feedback JRC solutions demonstrate high accuracy in range and speed detection. The DOA estimation based on RDM and FFT achieves high

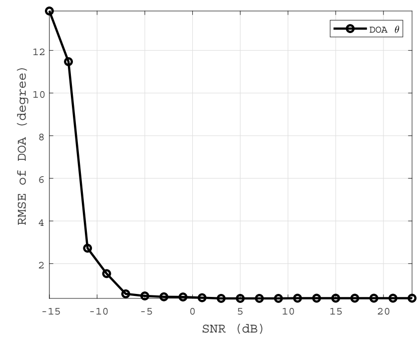

Fig. 7. DOA estimation performance using RDM and FFT.

resolution with a small number of antennas, thanks to the pre-separation of the targets in the RDM. Overall, the proposed decision feedback JRC solution based on the 5G NR waveform and bistatic architecture has the potential to significantly improve the environment awareness of the receiver and boost the sensing and communication performances.

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