Concurrent Downlink and Uplink Joint Communication and Sensing for 6G Networks

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Abstract—Joint communication and sensing (JCAS) is a promising technology for 6th Generation (6G) mobile networks, such as intelligent vehicular networks, intelligent manufacturing, and so on. Equipped with two spatially separated antenna arrays, the base station (BS) can perform downlink active JCAS in a mono-static setup. This paper proposes a Concurrent Downlink and Uplink (CDU) JCAS system where the BS can use the echo of transmitted dedicated signals for sensing in the uplink timeslot, while performing reliable uplink communication. A novel successive interference cancellation-based CDU JCAS processing method is proposed to enable the estimation of uplink communication symbols and downlink sensing parameters. Extensive simulation results verify the feasibility of the CDU JCAS system, showing a performance improvement of more than 10 dB compared to traditional JCAS methods while maintaining reliable uplink communication.

Index Terms—Joint communication and sensing, 6G system, concurrent downlink and uplink.

I. INTRODUCTION

Critical machine-type applications of 6th generation (6G) networks, such as intelligent vehicular networks, intelligent manufacturing and smart cities, require terminals and infrastructures to have environmental sensing and machine cooperation capabilities to facilitate automatic control of intelligent machines [1]. Therefore, wireless communication and sensing abilities are indispensable for 6G networks. However, the proliferation of wireless sensing and communication infrastructure and devices will result in severe spectrum congestion problems [2]. In this context, joint communication and sensing (JCAS) has emerged as one of the most promising 6G key techniques due to its potential in improving spectrum and energy efficiency. It can achieve wireless sensing and communication capabilities simultaneously by using the unified spectrum and transceiver with the same signal transmission [3].

Recently, the full-duplex (FD) array and transceiver designs required to implement downlink (DL) active JCAS have been widely studied. In [4], the authors pointed out that the critical enabler for implementing DL active JCAS is the FD operation to simultaneously transmit JCAS signals and receive reflections from the environment. In [5], the authors proposed that a feasible near-term solution for the FD JCAS operation is using two sets of spatially well-separated antenna arrays for transmitting and receiving. In [6], the authors developed an FD JCAS system that detects targets within 20 meters while maintaining an FD link with another communication node. In [7], the authors proposed to apply the successive-interference cancellation (SIC) in FD and D2D communications to suppress the mutual interference.

In this paper, we propose a concurrent downlink and uplink (CDU) JCAS system based on orthogonal frequency-division multiplexing (OFDM) signals, which can double the sensing efficiency of base station (BS) with negligible impact on uplink (UL) communications. It exploits the two-array setup in a JCAS node, and conducts DL active sensing in the UL data communication timeslot while receiving the UL communication signals. It is particularly suitable for millimeter wave (mmWave) signals, given its propagation property of dominated line-of-sight (LoS) path. To our best knowledge, this is the first work that investigates this setup. The main advantage, compared to sensing using the UL signals, is that sensing can be conducted in a well-controlled manner and in a mono-static setup. Therefore, the CDU JCAS is indispensable for sensing environment consecutively. In order to realize CDU JCAS, suppressing the mutual interference between UL communication and DL active sensing signals at the BS is critical. We propose a novel SIC-based method to remove the interference of UL communication to echo sensing signal processing without reducing the reliability of UL communication significantly. This method enables both the effective estimation of UL communication symbols and DL sensing echo channels.

Notations: Bold uppercase letters denote matrices (e.g., \( \mathbf{M} \)); bold lowercase letters denote column vectors (e.g., \( \mathbf{v} \)); scalars are denoted by normal font (e.g., \( \gamma \)); \( (\cdot) \) and \( (\cdot)^H \) denote Hermitian transpose, complex conjugate and transpose, respectively; \( |\gamma| \) represents the modulus of a complex scalar; \( \mathbf{M}_1 \in \mathbb{C}^{M \times N} \) and \( \mathbf{M}_2 \in \mathbb{R}^{M \times N} \) are \( M \times N \) complex-value and real-value matrices, respectively; \( \|
u_k\| \) represents the l-norm of \( \nu_k \); \( \text{Tr}(\mathbf{M}) \) is the trace of \( \mathbf{M} \); \( E(\cdot) \) represents the expectation of random variables; for two given matrices \( \mathbf{S}_1 \) and \( \mathbf{S}_2 \), \( [v_{p,q}]_{p,q=0}^{p,q} \in \mathcal{S}_1 \times \mathcal{S}_2 \) denotes the vector stacked by values \( v_{p,q} \) satisfying \( p \in \mathcal{S}_1 \) and \( q \in \mathcal{S}_2 \); and \( v \sim \mathcal{N}(m, \sigma^2) \) represents that a random variable \( v \) follows a circular symmetric complex Gaussian (CSCG) distribution with mean \( m \) and variance \( \sigma^2 \).

II. SYSTEM MODEL

In this section, we present the CDU JCAS scenario and JCAS channel models to provide fundamentals for the CDU JCAS signal processing.

A. CDU JCAS Scenario

We consider a CDU JCAS scenario, where the BS performs DL active JCAS operation while receiving the UL communication signal from the user, as illustrated in the upper part of Fig. 1. Both the user and BS are used for transmitting sensing signals, and the other array concurrently receives the echo sensing signals and UL communication signals from the user. Our focus here is to enable active sensing at BS in the UL communication period.

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The bottom part of Fig. 1 shows the signal structure and timeline in the CDU JCAS system. In the preamble period, UL communication synchronization and channel estimation are conducted at BS. Then, BS transmits sensing signals when receiving the UL communication data signals. The BS soon receives superimposed UL communication and sensing echo signals. By suppressing the mutual interference, BS can achieve concurrent UL communication and DL active sensing. OFDM signals are used for both UL communication and DL active sensing. The repeated sequences are used for each sensing symbol so that each can be treated as the cyclic prefix of the next symbol, making it easy to align the reception of UL communication and echo signals for OFDM signal processing.

B. UPA Model

The uniform interval between neighboring antenna elements is denoted by $d_a$. The size of UPA is $P \times Q$. We consider the far-field signal models. The two-dimensional (2D) angle-of-arrival (AoA) for receiving or the angle-of-departure (AoD) for transmitting signals is denoted by $p = [\varphi, \theta]^T$, where $\varphi$ and $\theta$ are the azimuth and elevation angles in the spherical coordinates. Let the $(p, q)$th antenna element of UPA denote the antenna element at the $p$th row and $q$th column. The phase difference between the $(p, q)$th antenna element and the reference element (i.e., the $(0,0)$th antenna element) is

$$a_{p,q} (p) = \exp \left[ -\frac{2\pi}{\lambda} d_a (p \cos \varphi \sin \theta + q \sin \varphi \sin \theta) \right], \quad (1)$$

where $\lambda = c/f_c$ is the wavelength of the carrier, $f_c$ is the carrier frequency, and $c$ is the speed of light in vacuum.

The steering vector for the array is given by

$$a(p) = [a_{p,q}(p)]_{(p,q)\in[0,1,\ldots,P-1] \times [0,1,\ldots,Q-1]}, \quad (2)$$

where $a(p) \in \mathbb{C}^{PQ \times 1}$.

C. JCAS Channel Models

Without loss of generality, we assume that two arrays of BS have the same size, denoted by $P_t \times Q_t$, while the size of the user’s array is $P_r \times Q_r$. In the proposed CDU JCAS scenario, the UL communication and the DL echo sensing subchannels are concerned.

1) Downlink Echo Sensing Subchannel Model: The DL sensing subchannel comprises the echo paths of the user and scatterers, as shown in Fig. 1. The channel response of the DL echo sensing subchannel at the $m$th OFDM symbol of the $n$th subcarrier is given by

$$H_D^{S,n,m} = \sum_{l=0}^{L_T-1} \left[ b_{s,l} e^{j2\pi f_s l n T_D} e^{-j2\pi n \Delta f_D^{(s,l)}} \right] \times a(p_{RX,l}) a^T(p_{TX,l}^D), \quad (3)$$

where $L_T$ is the number of scattering targets, and $l = 0$ represents the echo path between BS and the user. $p_{TX,l}$ and $p_{RX,l}$ are 2D AoA and AoD of the JCAS transmitter and sensing receiver, respectively; $a(p_{RX,l}) \in \mathbb{C}^{P_t \times 1}$ and $a(p_{TX,l}^D) \in \mathbb{C}^{P_t \times 1}$ are the corresponding steering vectors as given in (2), since the mmWave array is typically much larger than the CDU JCAS system. In the preamble period, UL communication and multiple non-line-of-sight (NLoS) paths, as shown in Fig. 1. The channel response matrix of the UL communication channel at the $m$th OFDM symbol of the $n$th subcarrier is given by

$$H_U^{C,n,m} = \sum_{l=0}^{L_C-1} \left[ b_{c,l} e^{j2\pi f_c l n T_U} e^{-j2\pi n \Delta f_U^{(c,l)}} \right] \times a(p_{RX,l}^U) a^T(p_{TX,l}^U), \quad (4)$$

where $l = 0$ is for the response of the LoS path and $l = 1, \ldots, L - 1$ are for the responses of the $(L - 1)$ NLoS paths; $a(p_{RX,l}^U) \in \mathbb{C}^{P_t \times 1}$ and $a(p_{TX,l}^U \in \mathbb{C}^{P_t \times 1}$ are the receiving and transmitting steering vectors of the $l$th path, as given in (2), respectively; $p_{RX,l}^U$ and $p_{TX,l}^U$ are the corresponding 2D AoA and AoD of the $l$th path for the receiver and transmitter, respectively; $T_U^C$ and $\Delta f_U^{(c,l)}$ are the time duration and subcarrier interval of each UL OFDM symbol, respectively; $f_{c,0} = \frac{f_c}{2}$ and $\tau_{c,0} = \frac{\tau_c}{2}$ are the Doppler frequency shift and time delay of the LoS path, with $v_0$ and $d_0$ being the relative velocity and distance between the BS and user; $f_{c,l}$ and $\tau_{c,l} (l \geq 1)$ are the Doppler frequency shift and time delay of the $l$th NLoS path, respectively; $\tau_{c,l} = d_{l,1}^r/d_{l,2}^r$ with $d_{l,1}^r$ and $d_{l,2}^r$ being the distances between the user and the $l$th scattering target and between the $l$th scatterer and BS. Moreover, $b_{c,0} = \sqrt{\frac{\lambda^2}{(4\pi d_0^r)}} \beta_{C,0}$ and $b_{c,l} = \sqrt{\frac{\lambda^2}{(4\pi d_{l,1}^r d_{l,2}^r)}} \beta_{C,l} (l \geq 1)$ are the fading factors of the LoS path and the $l$th NLoS path, respectively; $\beta_{C,0} = 1$, and $\beta_{C,l} \sim \mathcal{CN}(0, \sigma_{\beta,l}^2)$ for $l \geq 1$ is the reflection fading at the $l$th scattering target [8]. Note that $H_D^{S,n,m}$ is the sum of multiple independent CSCG distributions.

2) Uplink Communication Channel Model: The UL communication channel comprises a LoS path between the user and BS, and multiple non-line-of-sight (NLoS) paths, as shown in Fig. 1. The channel response matrix of the UL communication channel at the $m$th OFDM symbol of the $n$th subcarrier is given by

$$H_U^{C,n,m} = \sum_{l=0}^{L_C-1} \left[ b_{c,l} e^{j2\pi f_c l n T_U} e^{-j2\pi n \Delta f_U^{(c,l)}} \right] \times a(p_{RX,l}^U) a^T(p_{TX,l}^U), \quad (4)$$

where $l = 0$ is for the response of the LoS path and $l = 1, \ldots, L - 1$ are for the responses of the $(L - 1)$ NLoS paths; $a(p_{RX,l}^U) \in \mathbb{C}^{P_t \times 1}$ and $a(p_{TX,l}^U \in \mathbb{C}^{P_t \times 1}$ are the receiving and transmitting steering vectors of the $l$th path, as given in (2), respectively; $p_{RX,l}^U$ and $p_{TX,l}^U$ are the corresponding 2D AoA and AoD of the $l$th path for the receiver and transmitter, respectively; $T_U^C$ and $\Delta f_U^{(c,l)}$ are the time duration and subcarrier interval of each UL OFDM symbol, respectively; $f_{c,0} = \frac{f_c}{2}$ and $\tau_{c,0} = \frac{\tau_c}{2}$ are the Doppler frequency shift and time delay of the LoS path, with $v_0$ and $d_0$ being the relative velocity and distance between the BS and user; $f_{c,l}$ and $\tau_{c,l} (l \geq 1)$ are the Doppler frequency shift and time delay of the $l$th NLoS path, respectively; $\tau_{c,l} = d_{l,1}^r/d_{l,2}^r$ with $d_{l,1}^r$ and $d_{l,2}^r$ being the distances between the user and the $l$th scattering target and between the $l$th scatterer and BS. Moreover, $b_{c,0} = \sqrt{\frac{\lambda^2}{(4\pi d_0^r)}} \beta_{C,0}$ and $b_{c,l} = \sqrt{\frac{\lambda^2}{(4\pi d_{l,1}^r d_{l,2}^r)}} \beta_{C,l} (l \geq 1)$ are the fading factors of the LoS path and the $l$th NLoS path, respectively; $\beta_{C,0} = 1$, and $\beta_{C,l} \sim \mathcal{CN}(0, \sigma_{\beta,l}^2)$ for $l \geq 1$ is the reflection fading at the $l$th scattering target. When the distances of LoS and NLoS paths are in similar magnitude order, we can see that $|b_{c,0}|^2 = \frac{\lambda^2}{(4\pi d_0^r)}$ is typically much larger than $|b_{c,l}|^2 = \frac{\lambda^2}{(4\pi d_{l,1}^r d_{l,2}^r)} |\beta_{C,l}|^2$, i.e., the path loss of the NLoS path is much larger than the LoS path for mmWave signals.

III. CONCURRENT DOWNLINK AND UPLINK JCAS SIGNAL PROCESSING

This section provides the CDU JCAS processing method to acquire the communication and sensing information from the superposed received signals. We consider the case where the received UL communication signal is significantly larger than the DL echo signals. This is a typical case because the path loss factor of the echo signal is no smaller than...
1) Communication Signal Demodulation: To demodulate the communication signal from the superimposed received signal, a receiving beamforming vector should be used by BS, denoted by \( w_{RX}^{C} \), to equalize the UL communication channel. Here, \( w_{RX}^{C} \) is designed to maximize the signal-to-noise power ratio (SNR) and minimize the communication symbol demodulation error. According to [11], the solution of \( w_{RX}^{C} \) is the linear transform of the channel state information (CSI), i.e., \( w_{RX}^{C} = h_{C,n,m}^{T} B \), where \( B \) is a matrix argument for optimization. Therefore, the problem is formulated as

\[
\begin{align*}
\text{argmin}_{w} & \left\{ \| (w^{H} h_{C,n,m}^{U} P_{T}^{U} d_{n,m}^{S} - d_{n,m}^{U} ) \|^{2} \right\} & \\
\text{s.t. } & w = h_{C,n,m}^{U} B \tag{8}
\end{align*}
\]

The solution to (8) is given in (9), and the detailed derivation is provided in the Appendix.

\[
\begin{align*}
\hat{w}_{RX}^{C} &= \sqrt{P_{T}^{C}} h_{C,n,m}^{C} [ (h_{C,n,m}^{U})^{H} h_{C,n,m}^{C} ]^{-1} \\
& \times \{ P(h_{C,n,m}^{U}) h_{C,n,m}^{U} + \sigma_{N}^{2} \}^{-1} \\
& \times \{ (h_{C,n,m}^{U})^{H} h_{C,n,m}^{C} \}.
\end{align*}
\]

After \( \hat{w}_{RX}^{C} \) is acquired, the superimposed signal, \( \hat{r}_{DU,n,m}^{C} \), is expressed as

\[
\begin{align*}
\hat{r}_{DU,n,m}^{C} &= \sqrt{P_{T}^{U}} d_{n,m}^{U} + h_{C,n,m}^{C} \hat{w}_{RX}^{C} + n_{C,n,m}^{U} + n_{C,n,m}^{U} \\
& \approx \hat{r}_{DU,n,m}^{C} / \hat{h}_{C,n,m}^{C}.
\end{align*}
\]

The estimate of \( \hat{d}_{DU,n,m}^{U} \), denoted by \( \hat{d}_{DU,n,m}^{U} \), can be obtained based on \( \hat{d}_{DU,n,m}^{U} \) by the maximum-likelihood (ML) criterion, which is expressed as

\[
\hat{d}_{DU,n,m}^{U} = \text{arg min}_{d_{DU,n,m}^{U}} \| (\hat{r}_{DU,n,m}^{C} - d_{DU,n,m}^{U} ) \|^{2}.
\]

2) Downlink Echo Sensing Signal Processing: After the communication symbol is estimated, the communication signals can be reconstructed and removed from (7) and we obtain

\[
\begin{align*}
\hat{y}_{DU,n,m}^{C} &= h_{C,n,m}^{D} \sqrt{P_{T}^{D}} d_{n,m}^{S} + e_{DU,n,m}^{U} + n_{C,n,m}^{U} \tag{11}
\end{align*}
\]

where \( \hat{y}_{DU,n,m}^{C} \) is the estimated communication signal. Without loss of generality, we apply the LS beamforming method in this paper and is expressed as

\[
\hat{h}_{C,n,m}^{D} = \arg \min_{\hat{h}_{C,n,m}^{D}} \| (\hat{y}_{DU,n,m}^{C} - \hat{h}_{C,n,m}^{D} d_{n,m}^{S} ) \|^{2}.
\]

Since we are interested in sensing at a specified direction, \( p_{DU}^{S} \), BS can apply a beamforming vector pointing at this specified direction, denoted by \( w_{RX,S}^{D} \), to receive the cleaned echo signals in (12). Here, without loss of generality, we apply the LS beamforming method to obtain \( w_{RX,S}^{D} \). Since the echo AoA is the same as the sensing AoD, \( w_{RX,S}^{D} = (w_{TX}^{D})^{T} \). The echo response estimated at the th subcarrier of the mth OFDM symbol, denoted by \( \hat{h}_{S,x,m}^{E} = }
\[
\hat{\mathbf{h}}_{S,n,m}^D = \sum_{l=0}^{L_T-1} \left[ \sqrt{P_L} b_{S,l} (\pi_{R,S}^D \mathbf{X}_{l,TX,S}^D) \right] + \mathbf{w}_{S,n,m},
\]
where \(\mathbf{w}_{S,n,m} = (\mathbf{w}_{R,S}^D)^H \mathbf{e}_{n,m}^U / \eta_{n,m}^D\) and \(n_{s,n,m} = (\mathbf{w}_{R,S}^D)^H \eta_{n,m}^D / \eta_{n,m}^D\) are the transformed SIC error propagation and noise, respectively, and \(\pi_{R,S}^D = \mathbf{a}^T (\mathbf{p}_{TX,S}^D) \mathbf{w}_{TX,S}^D\) and \(\mathbf{w}_{TX,S}^D = (\mathbf{w}_{R,S}^D|^H \mathbf{a}(\mathbf{p}_{RX,S})\) are the transmit and receive beamforming (BF) gains of DL JCAS. We can see that the smaller array sizes will lead to smaller BF gains.

For JCAS processing, multiple OFDM symbols and subcarriers are required. We use \(M_s\) and \(N_s\) to denote the numbers of OFDM symbols and subcarriers for JCAS operation, respectively. The echo sensing channel response matrix of \(M_s\) echo sensing signals is denoted by \(\mathbf{H}_S\). The (\(n, m\))th element of \(\mathbf{H}_S^D\) is \(\hat{\mathbf{h}}_{S,n,m}^D = \hat{\mathbf{h}}_{S,n,m}^D\).

According to (13), \(\mathbf{H}_S^D\) has column and row vectors with the bases \(e^{-j \pi f_{TX} T_{c}^D / 2 n_{s,n,m}}\) and \(e^{-j \pi f_{TX} T_{c}^D / 2 m_{s,n,m}}\), respectively. Therefore, by applying inverse fast Fourier transform (IFFT) to each column of \(\mathbf{H}_S^D\), we obtain \(\mathbf{H}_S\). Then, the range-Doppler spectrum can be obtained by applying fast Fourier transform (FFT) to each row of \(\mathbf{H}_S\) [8]. Let \((R_l, F_l)\) denote the coordinate of the maximal point of range-Doppler spectrum, the range and radial velocity are given by \(\hat{r}_l = \frac{\lambda}{2 M_s T_c^D}\) and \(\hat{v}_l = \frac{\lambda}{2 M_s T_c^D}\), respectively [8]. Note that we can obtain multiple local maximal points when \(L_T > 1\).

### C. Multiple BS Deployment Scenario

The CDU JCAS signal processing method in Section III-B can also be used in multi-BS scenarios with UL optimal transmit power tuning method referenced to, e.g., the Algorithm 1 in [12]. To apply the optimal power tuning, the UL communication interference channel should be estimated. After the UL transmit power tuning is finished, each BS can demodulate the UL communication data signal and estimate the ranges and Doppler frequencies of targets from the SIC processed echo sensing signals.

### IV. SIMULATION RESULTS AND ANALYSIS

In this section, we present the simulation results to verify the effectiveness of the presented CDU JCAS processing method. The simulation parameters are given as follows. The carrier frequency is 63 GHz [13], and the subcarrier interval is 240 kHz. The subcarrier number and OFDM symbol number for detection are \(N_c = 128\) and \(M_s = 64\), respectively. Therefore, the bandwidth of CDU JCAS is \(B = 30.72\) MHz. The variance of complex Gaussian noise is set to \(\sigma_n^2 = k \beta T B = 1.2294 \times 10^{-12}\) W, where \(k\) is the Boltzmann constant, \(T\) is the noise factor, and \(B\) is the standard temperature. The antenna interval is half the wavelength, and the antenna array sizes of BS and the user are \(P_s \times Q_s = 8 \times 8\) and \(P_u \times Q_u = 1 \times 1\), respectively. The locations of BS and the user are \((50, 4.75, 7)\) m and \((140, 0, 2)\) m, respectively; and the target's location and velocity are \((129, 10.5)\) m and \((5, 0, 0)\) m/s, respectively. Moreover, we set \(\sigma_i^2 = \sigma_j^2 = 1\). Based on the locations of the user, BS, and the scatterer, the AoA, AoD and ranges between the user and BS can be derived to generate the JCAS channel response matrices according to (3) and (4).

The general expression for the range and velocity estimation mean square error (MSE) is given by

\[
MSE_{\xi} = \sum_{l=0}^{L_T-1} \sum_{i=1}^{N_{eir}} \left( \left| \hat{\xi}_{l,i} - \xi_l \right|^2 (L_T N_{eir}), \right.
\]
where \(\hat{\xi}_{l,i}\) is the estimated parameter value of the \(l\)th target in the \(i\)th circulation, \(\xi_l\) is the actual parameter value of the \(l\)th target, and \(N_{eir}\) is the number of trials. Moreover, the bit error rate (BER) is calculated as \(BER = N_c / N_{eir}\), where \(N_{eir}\) is the total numbers of transmitted bits and error bits in \(N_{eir}\) trials, respectively. We set \(N_{eir} = 10^4\).

We choose the DL JCAS method in [10] as a comparison, which only focuses on the sensing echo signal processing and does not consider handling UL communication interference. For simplicity, we define the DL JCAS method in [10] as case 1, the proposed CDU JCAS as case 2, the proposed CDU JCAS with \(P_t^D = 0\) W as case 3, and the CDU JCAS with an additional target as case 4. The location and velocity of the additional target are \((136.9, 10.6, 4.8)\) m and \((-5, 0, 0)\) m/s, respectively. Fig. 3 and Fig. 4 show the range and radial velocity estimation MSEs for cases 1, 2, 3, and 4. When 4-QAM is used for UL communication, as the DL transmit power of BS, \(P_t^D\), increases, the MSEs of all the curves decrease because the received SNRs increase. The value of \(P_t^D\) required to achieve the minimum MSE for case 1 increases by more than 10 dB, compared with case 3. In other words, the range and velocity estimation accuracy of the traditional JCAS method is deteriorated severely in the presence of interference from the UL communication. When \(P_t^D = 20\) and 13 dBm, the values of \(P_t^D\) required for case 2 to achieve the minimum MSE are reduced by 16 and 9 dB, compared with case 1. This is because CDU JCAS can mitigate the impact of UL communication
The BER of CDU JCAS processing method. The solid curves are for case 2, and the dashed curves are for UL communication without echo interference.

Fig. 6. The range estimation MSE of case 2 under various BS array sizes.

Interference on the echo sensing processing. Moreover, when $P_U^D = 20$ dBm, $P_U^D$ required for case 4 to achieve the minimum MSE is slightly higher than that for case 2, since the range-Doppler spectra of multiple targets interfere with each other slightly.

Fig. 5 shows the BER simulation results for case 2. The BER of UL communication with no echo interference is also plotted in dashed curves for comparison. Note that when $P_U^D = 20$ dBm, the BER is too small and the number of error bits is 0 in the limited trials. When the DL transmit power, $P_U^D$, is small, BER of case 2 is close to BER of UL communication without interference, because the echo signal interference endures large loss and is much smaller than the received UL communication signal. As $P_U^D$ increases, BER increases slowly before $P_U^D$ reaches 27 dBm. Because $P_U^D$ is not allowed to exceed 27 dBm in the 3GPP standard [13], the echo signal in CDU JCAS causes negligible degradation of communication performance.

Fig. 6 presents the range estimation MSE for case 2 under various BS array sizes, when 4 QAM is used for UL communication modulation. It can be seen that as the BS array size decreases from $8 \times 8$ to $4 \times 4$, the value of $P_U^D$ required to achieve the minimum MSE increases. This is because the reduced array size leads to the decrease of BF channel gain in (13).

Finally, we show the sensing performance of the proposed CDU JCAS signal processing method in multi-BS scenarios. We introduce another BS-user pair. The locations of BS 2 and user 2 are (260, 4.75, 7) m and (180, 10, 2) m, respectively; and the velocities of user 2 is (5, 0, 0) m/s. We call the above multi-BS scenario as case 5.

The range estimation MSEs for cases 2 and 5. This is because the UL communication interference between two UL links deteriorates the BER and increases the variance of SIC propagation error.

V. CONCLUSION

This paper proposes a CDU JCAS system that can improve the accuracy of environmental sensing for BS while performing reliable UL communication. A novel SIC-based CDU JCAS processing method is proposed to remove the interference of UL communication to echo sensing signal processing without reducing the reliability of UL communication. Simulation results verify the feasibility of the CDU JCAS system. It is shown that the CDU JCAS processing method has significantly improved the range detection accuracy compared to the traditional DL active JCAS method, with negligible performance degradation of UL communications.

APPENDIX

It can be concluded that (8) is a convex problem of $\mathbf{B}$. To simplify the expression, we use $\mathbf{h}$, $P$, and $d$ to replace $\mathbf{h}_{U,n,m}^D$, $P_U^D$, and $d_{n,m}^U$ in (8), respectively. By denoting

$$J = E[\|\mathbf{w}^H\mathbf{h}\sqrt{\mathbf{P}}\mathbf{d} - d\|^2_2 + Tr(\sigma_h^2\mathbf{w}^H\mathbf{w})],$$

the solution of $\frac{\partial J}{\partial \mathbf{B}} = 0$ is the minimum point for (8). By deriving the first-order derivative of $J$ over $\mathbf{B}$, and exploiting $E[\|d_{n,m}^U\|^2] = 1$, we obtain

$$\frac{\partial J}{\partial \mathbf{B}} = 2\mathbf{h}^H\mathbf{h}P\mathbf{h}^H\mathbf{h}\mathbf{B} - 2\sqrt{\mathbf{P}}\mathbf{h}^H\mathbf{h} + 2\sigma_h^2\mathbf{h}^H\mathbf{h}\mathbf{B}.$$  

(16)

We can further derive the minimum point for (8) as

$$\mathbf{B} = (\mathbf{h}^H\mathbf{h})^{-1}(P\mathbf{h}^H\mathbf{h} + \sigma_h^2)^{-1}((\mathbf{h}^H\mathbf{h})\sqrt{\mathbf{P}}).$$

(17)

By applying (17) into (8), we obtain (9).
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