

Joint Precoding And Power Optimization for Full-Duplex Cell-Free MIMO ISAC System

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Abstract—This work considers a joint sensing and communication sum rate maximization problem in a full-duplex (FD) cell-free (CF) multiple-input multiple-output (MIMO) system. The setup consists of FD multi-antenna access points (APs) that send integrated sensing and communication (ISAC) data in the downlink (DL) for both communication and target localization. The APs simultaneously receive uplink (UL) data from multiple single-antenna users and target echoes same time-frequency resources. The concurrent data transmission and reception results in self-interference (SI), inter-AP interference (IAI) and cross-link interference overhead. An optimization technique is proposed to provide optimal UL/DL transmit and receive beamformers. The half-duplex (HD) variant of the model is used as a benchmark for the communication case. For the sensing scenario, a variant of the proposed model which considers a sum rate maximization of the communication functionality with an unconstrained sensing component is considered as a baseline. For both sensing and communication setups, the proposed model outperforms the benchmark cases significantly in terms of spectral efficiency (SE) gain.

Index Terms—Integrated sensing and communication, cell-free multiple-input multiple-output systems, sum rate maximization, full-duplex.

I. INTRODUCTION

INTEGRATED Sensing and Communication (ISAC) is a paradigm shift in wireless system architecture wherein radio frequency (RF) hardware, spectral bands, and signal waveforms are natively shared to simultaneously execute data transmission and radar-like environmental sensing. Rather than operating as decoupled, self-contained systems, ISAC converges these functionalities to optimize mutually restricted physical resources, transforming the wireless network into a dual-functional ecosystem that provides both high-capacity connectivity and high-precision localization, tracking, and imaging [1].

A single base station (BS) serving as an ISAC transceiver

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results in geographical constraints and signal processing complexity [2]. To resolve this, cell-free (CF) multiple-input multiple-output (MIMO) technology is employed which considers geographically distributed access points (APs) cooperatively serving a number of user equipment (UE) within the same time-frequency resource blocks. The AP coordination is handled by a central processing unit (CPU) [3], [4]. The advantages offered by the CF MIMO system are spatial degrees of freedom (DoF) and macro-diversity gain due to the distributed antenna system. Combining this architecture with the ISAC technology results in effective target sensing and better uplink/downlink (UL/DL) communication [2], [5], [6].

Due to the transmission and reception of both communication and sensing signals, there is a need for effective interference management and resource allocation [7], [8]. A number of literature have delved into optimal beamforming and power allocation schemes for CF ISAC systems. The work in [5] designed a beamforming technique for CF ISAC MIMO systems. The authors in [6] proposed a transmit beamforming scheme for an CF massive MIMO ISAC system within the communication-sensing domain. These aforementioned works however consider half-duplex (HD) mode operations. This scheme does not efficiently use the available bandwidth due to the transmission and reception of signals in different resource blocks [9].

Thus, practical ISAC systems can consider full-duplex (FD) technologies, where we have concurrent DL transmission of ISAC signals and UL reception of communication and target echo signals [10], [11]. The introduction of FD transmission in CF ISAC comes with a self-interference (SI) cost. Few works have tackled this issue due to the complexity it presents. In [12], the authors solved a weighted maximization problem of sensing and communication signal-to-interference-plus-noise ratios (SINRs) in a reconfigurable intelligent surface-aided FD CF MIMO integrated cooperative sensing and communication system. This was achieved by the joint optimization of the UL/DL beamformers and UL transmit powers. However, DL communication was not studied in this work. In [8], an interference management scheme was proposed for an FD multi-static ISAC system. In order to avoid SI, [8] considered

a network-assisted FD technology which deploys half-duplex (HD) APs.

This work considers an FD CF ISAC MIMO system, where the FD APs transmit ISAC signals for both DL communication and sensing while simultaneously receiving UL communication signals. This results in SI at each AP, inter-AP interference (IAI) and UL-to-DL interference (UDI) between the UL and DL users. We formulate a sum-rate maximization problem of the UL/DL communication rate and sensing rate. We jointly optimize the DL communication and sensing precoders, UL communication and sensing receive filters and UL transmit power allocation. The proposed optimization scheme shows a significant SE gain over the HD counterpart and the system that maximizes the total communication SE while neglecting the sensing constraint.

The rest of the paper is structured as follows: Section II provides the system model. SE analysis for both UL/DL communication and sensing is elaborated in Section III. Numerical results are discussed in Section IV and the conclusion is provided in Section V.

Notation: Bold lower and upper case letters represent vectors and matrices, respectively. $\mathcal{CN}(0, \sigma)$ signifies a circularly symmetric complex Gaussian random variable with variance σ and zero mean. The Hermitian, trace and expectation operators are denoted by $(\cdot)^H$, $\text{Tr}(\cdot)$, and $\mathbb{E}\{\cdot\}$, respectively.

II. SYSTEM MODEL

We consider an FD CF MIMO system consisting of M FD MIMO APs, L single antenna DL users, K single antenna UL users and one target. The m -th AP possesses N_t transmit antennas and N_r receive antennas. The m -th AP sends ISAC signals to L -single antenna DL users and a sensing target while simultaneously receiving communication signals and reflected sensing signals from the K UL users and the target in the UL. The users in this system operate in an HD mode. There is an SI/IAI bottleneck due to the concurrent data transmissions and receptions at the APs on the same frequency band. We assume the conventional block-fading model.

The communication channels from the k -th UL and l -th DL users to the m -th AP are defined as $\mathbf{h}_{mk} \in \mathbb{C}^{N_r \times 1}$ and $\mathbf{g}_{ml} \in \mathbb{C}^{N_t \times 1}$, respectively. They are modeled as line of sight (LoS) channels with $[\mathbf{h}_{mk}]_n = e^{-j(n-1)(2\pi d/\lambda) \sin(\theta_{mk})}$ where d , λ , and θ_{mk} represent the antenna spacing, wavelength, and angle of arrival (AoA) from the k -th UL user to the m -th AP. Also, $[\mathbf{g}_{ml}]_n = e^{-j(n-1)(2\pi d/\lambda) \sin(\theta_{ml})}$ with θ_{ml} denoting the AoA from the m -th AP to the l -th DL user. Also, we define $d = \lambda/2$, for simplicity.

It is assumed that the radar channel consists of LoS paths and both the transmit and receive uniform linear arrays at the m -th AP have half-wavelength antenna spacing. The transmit array steering vector is given as $\mathbf{a}_t(\theta_{ms}) \triangleq [1, e^{j\pi \sin(\theta_{ms})}, \dots, e^{j\pi(N_t-1)\sin(\theta_{ms})}]^T$. The receive array steering vector is denoted as $\mathbf{a}_r(\theta_{ms}) \triangleq [1, e^{j\pi \sin(\theta_{ms})}, \dots, e^{j\pi(N_r-1)\sin(\theta_{ms})}]^T$. The radar channel between the transmit and receive antennas of the m -th AP is expressed as $\mathbf{G}_m = \alpha_m \mathbf{A}_m(\theta_{ms})$, where $\alpha_m \sim \mathcal{CN}(0, c_m^2)$ is

the sensing channel gain [8]; $\mathbf{A}_m(\theta_m) \triangleq \mathbf{a}_r(\theta_{ms}) \mathbf{a}_t^H(\theta_{ms})$; θ_{ms} is the angle between the target and m -th AP.

The ISAC signal $\mathbf{x}_m \in \mathbb{C}^{N_t \times 1}$ is sent by the m -th AP for DL communication and target localization. The integrated signal is given as $\mathbf{x}_m = \sum_{l=1}^L \mathbf{v}_{ml} s_l + \mathbf{v}_{ms} s_s$, where $\mathbf{v}_{ml} \in \mathbb{C}^{N_t \times 1}$ and $s_l \in \mathbb{C}$ denote the DL communication transmit beamformer and the data symbol of the l -th DL user, respectively. It should be noted that $s_l \sim \mathcal{CN}(0, 1)$. Also, $\mathbf{v}_{ms} \in \mathbb{C}^{N_t \times 1}$ represents the sensing beamforming vector and $s_s \in \mathbb{C}$ denotes a sensing signal with covariance $\mathbb{E}\{|s_s|^2\} = 1$. The signals $\{s_l\}_{l=1}^L$ and s_s are assumed to be mutually independent. The signal received at the l -th DL user is given as

$$y_l^d = \sum_{m=1}^M \mathbf{g}_{ml}^H \mathbf{x}_m + \sum_{k=1}^K q_{kl} d_k + n_l, \quad (1)$$

where $d_k \sim \mathcal{CN}(0, p_k)$, $n_l \in \mathcal{CN}(0, 1)$ and $q_{kl} \sim \mathcal{CN}(0, \sigma_{kl}^2)$ are the UL communication signal, noise and the UL-to-DL interference (UDI) channel from the k -th UL user to the l -th DL user, respectively. $\sigma_{kl}^2 = \epsilon_{kl} \xi_{SI}^2$, where ϵ_{kl} represents the large-scale fading between the l -th DL user and the k -th UL user and ξ_{SI}^2 denotes the residual SI. The UDI channel is modeled according to Rayleigh fading. This is justified by considering that the LoS components can be eliminated by exploiting the surrounding buildings and properly separating the transmit and receive antenna chains.

Moreover, $0 \leq p_k \leq P_{u,k}^{\max}$ denotes the transmit power of UL user k , where $P_{u,k}^{\max}$ is the maximum available power.

The received signal at the m -th AP is written by

$$\mathbf{y}_m = \sum_{k=1}^K \mathbf{h}_{mk} d_k + \mathbf{G}_m \mathbf{x}_m + \sum_{n=1}^M \mathbf{H}_{mn} \mathbf{x}_n + \mathbf{n}_m, \quad (2)$$

where $\mathbf{n}_m \in \mathbb{C}^{N_r \times 1}$ denotes AWGN with covariance $\sigma_r^2 \mathbf{I}_{N_r}$; $\mathbf{H}_{mn} \in \mathbb{C}^{N_r \times N_t}$ is the residual SI channel at the m -th AP whose elements are modeled as $\mathcal{CN}(0, \sigma_{mn}^2)$, where $\sigma_{mn}^2 = \epsilon_{mn} \xi_{SI}^2$; ϵ_{mn} denotes the large-scale fading from the n -th AP to the m -th AP. The SI and IAI channels are Rayleigh distributed based on the assumption of antenna isolation and exploiting nearby structures. At the m -th AP, the receive beamformers $\mathbf{u}_{mk} \in \mathbb{C}^{N_r \times 1}$ and $\mathbf{w}_m \in \mathbb{C}^{N_r \times 1}$ are employed to decode the data signal sent by the k -th UL user and echo from the target, respectively, before forwarding to the CPU. Hence, the CPU receives the UL data and echo signals

$$y_k^u = \sum_{m=1}^M \mathbf{u}_{mk}^H \mathbf{y}_m \text{ and } y^s = \sum_{m=1}^M \mathbf{w}_m^H \mathbf{y}_m, \quad (3)$$

respectively.

III. UL/DL COMMUNICATION & SENSING SE

For the k -th UL user, the communication SINR is derived from (3) as

$$\gamma_k^u = \frac{p_k |\mathbf{u}_{mk}^H \mathbf{h}_k|^2}{\sum_{j=1, j \neq k}^K p_j |\mathbf{u}_{mk}^H \mathbf{h}_j|^2 + |\mathbf{u}_{mk}^H \mathbf{G}_m \mathbf{x}|^2 + |\mathbf{u}_{mk}^H \mathbf{H}_m \mathbf{x}|^2 + |\mathbf{u}_{mk}^H \mathbf{n}_m|^2}, \quad (4)$$

where $\mathbf{u}_k = [\mathbf{u}_{1k}^H, \dots, \mathbf{u}_{Mk}^H]^H \in \mathbb{C}^{MN_r \times 1}$, $\mathbf{h}_k = [\mathbf{h}_{1k}^H, \dots, \mathbf{h}_{Mk}^H]^H \in \mathbb{C}^{MN_r \times 1}$, $\mathbf{G} = [\mathbf{G}_1^H, \dots, \mathbf{G}_M^H]^H \in \mathbb{C}^{MN_r \times MN_t}$, $\mathbf{H} = [\mathbf{H}_{m1}^H, \dots, \mathbf{H}_{mM}^H]^H \in \mathbb{C}^{MN_r \times MN_t}$, and $\mathbf{x} = [\mathbf{x}_1^H, \dots, \mathbf{x}_M^H]^H \in \mathbb{C}^{MN_t \times 1}$.

Similarly, the sensing SINR can be obtained from (3) as

$$\gamma^s = \frac{|\mathbf{w}^H \mathbf{G} \mathbf{x}|^2}{\sum_{k=1}^K p_k |\mathbf{w}^H \mathbf{h}_k|^2 + |\mathbf{w}^H \mathbf{H} \mathbf{x}|^2 + |\mathbf{w}^H|^2}, \quad (5)$$

where $\mathbf{w} = [\mathbf{w}_m^H, \dots, \mathbf{w}_M^H]^H \in \mathbb{C}^{MN_r \times 1}$.

Using (1), the communication SINR of the l -th DL user is written by

$$\gamma_l^d = \frac{|\mathbf{g}_l^H \mathbf{v}_l|^2}{\sum_{l' \neq l}^L |\mathbf{g}_l^H \mathbf{v}_{l'}|^2 + |\mathbf{g}_l^H \mathbf{v}_s|^2 + \sum_{k=1}^K p_k |q_{kl}|^2 + 1}, \quad (6)$$

where the numerator represents the desired l -th DL communication signal gain and the denominator denotes the interference-plus-noise power. Moreover, $\mathbf{v}_l = [\mathbf{v}_{1l}^H, \dots, \mathbf{v}_{Ml}^H]^H \in \mathbb{C}^{MN_t \times 1}$, $\mathbf{g}_l = [\mathbf{g}_{1l}^H, \dots, \mathbf{g}_{Ml}^H]^H \in \mathbb{C}^{MN_t \times 1}$, and $\mathbf{v}_s = [\mathbf{v}_{1s}^H, \dots, \mathbf{v}_{Ms}^H]^H \in \mathbb{C}^{MN_t \times 1}$.

IV. SUM RATE MAXIMIZATION

To maximize the total communication and sensing rates of the proposed FD CF ISAC MIMO system, we jointly optimize the UL transmit power p_k , receive beamformers $\mathbf{u}_k$, $\mathbf{w}$, and the DL transmit beamformers $\mathbf{v}_l$, $\mathbf{v}_s$. The problem is formulated as

$$\begin{aligned} & \max_{\{\mathbf{v}_l\}, \{\mathbf{v}_s\}, \{\mathbf{u}_k\}, \{\mathbf{w}\}, \{p_k \geq 0\}} \sum_{k=1}^K \log_2(1 + \gamma_k^u) + \sum_{l=1}^L \log_2(1 + \gamma_l^d) \\ & + \log_2(1 + \gamma^s), \text{ s.t. C1: } \sum_{l=1}^L \|\mathbf{v}_{ml}^H \mathbf{v}_{ml}\| + \|\mathbf{v}_{ms}\|^2 \leq P_m^{\max}, \\ & \text{C2: } p_k \leq P_{u,k}^{\max}, \forall k \in K, \end{aligned} \quad (7)$$

where $P_m^{\max}$ is the total power budget per AP. The problem proposed in (7) is non-convex due to coupled optimization variables in the objective function and NP-hard. To solve it, we first determine the optimal UL receive communication/sensing filters. Implementing the generalized Rayleigh quotient [13], the optimal UL communication filter is derived from (4) as

$$\mathbf{u}_k^* = \left(\sum_{j=1, j \neq k}^K p_j \mathbf{h}_j \mathbf{h}_j^H + \mathbf{G} \mathbf{Q} \mathbf{G}^H + \mathbf{H}^H \mathbf{Q} \mathbf{H} + \mathbf{I}_{MN_r} \right)^{-1} \mathbf{h}_k, \quad (8)$$

where $\mathbf{Q} \triangleq \mathbb{E}\{\mathbf{x} \mathbf{x}^H\} = \sum_{l=1}^L \mathbf{v}_l \mathbf{v}_l^H + \mathbf{V}_0$ and $\mathbf{v}_s \mathbf{v}_s^H = \mathbf{V}_0$. Similarly, we define the optimal UL sensing receive filter based on (5) as

$$\mathbf{w}^* = \left(\sum_{k=1}^K p_k \mathbf{h}_k \mathbf{h}_k^H + \mathbf{H} \mathbf{Q} \mathbf{H}^H + \mathbf{I}_{MN_r} \right)^{-1} \mathbf{a}_r(\theta), \quad (9)$$

where $\mathbf{a}_r(\theta) = [\mathbf{a}_r^H(\theta_{1s}), \dots, \mathbf{a}_r^H(\theta_{Ms})]^H \in \mathbb{C}^{MN_r \times 1}$. Substituting (8) and (9) into (4) and (5), respectively, the UL communication and sensing SINR expressions are reformulated as $\bar{\gamma}^s =$

$\mathbf{a}_t(\theta)^H \mathbf{Q} \mathbf{a}_t(\theta) \mathbf{a}_r(\theta)^H \Psi^{-1} \mathbf{a}_r(\theta)$, and $\bar{\gamma}_k^u = p_k \mathbf{h}_k^H \Phi_k^{-1} \mathbf{h}_k$, where $\mathbf{a}_t(\theta) = [\alpha_1 \mathbf{a}_t^H(\theta_{1s}), \dots, \alpha_M \mathbf{a}_t^H(\theta_{Ms})]^H \in \mathbb{C}^{MN_t \times 1}$, $\Psi = \left(\sum_{k=1}^K p_k \mathbf{h}_k \mathbf{h}_k^H + \mathbf{H} \mathbf{Q} \mathbf{H}^H + \mathbf{I}_{MN_r} \right)$ and $\Phi_k = \left(\sum_{j \neq k}^K p_j \mathbf{h}_j \mathbf{h}_j^H + \mathbf{G} \mathbf{Q} \mathbf{G}^H + \mathbf{H} \mathbf{Q} \mathbf{H}^H + \mathbf{I}_{MN_r} \right)$.

To reformulate the problem (7) into a convex form, we introduce the auxiliary variables $z_k \geq 0$ and $r \geq 0$ for the UL communication rate and sensing rate in (7). Thus the problem (7) is reformulated by

$$\begin{aligned} & \max_{\{\mathbf{V}_l\}_{l=0}^L, \{\mathbf{z}_k \geq 0\}, \{r \geq 0\}, \{p_k \geq 0\}} \sum_{k=1}^K \log_2(1 + z_k) + \sum_{l=1}^L \log_2(1 + \bar{\gamma}_l^d) \\ & + \log_2(1 + r), \text{ s.t. C1, C2, C3: } r \leq \bar{\gamma}^s, \text{ C4: } z_k \leq \bar{\gamma}_k^u, \end{aligned} \quad (10)$$

where $\bar{\gamma}_l^d = \frac{\mathbf{g}_l^H \mathbf{V}_l \mathbf{g}_l}{\sum_{l'=0, l' \neq l}^L \mathbf{g}_l^H \mathbf{V}_{l'} \mathbf{g}_l + \sum_{k=1}^K p_k |q_{kl}|^2 + 1}$. We now focus on the DL communication SE $\sum_{l=1}^L \log_2(1 + \bar{\gamma}_l^d)$ which is a non-concave expression due to the variables $\{\mathbf{V}_l\}_{l=0}^L$ and $\{p_k\}_{k=1}^K$. To resolve this, we first define the variable $c = \sum_{l'=0, l' \neq l}^L \mathbf{g}_l^H \mathbf{V}_{l'} \mathbf{g}_l + \sum_{k=1}^K p_k |q_{kl}|^2 + 1$. We employ the successive convex approximation (SCA) technique to linearize the DL communication SE expression with respect to $\{\mathbf{V}_l\}_{l=0}^L$ and $\{p_k\}_{k=1}^K$ by using the first-order Taylor expansion. Thus, a lower bound on the l -th DL user rate is given by

$$\log_2(1 + \bar{\gamma}_l^d) \geq \log_2 \left(1 + \frac{\mathbf{g}_l^H \mathbf{V}_l \mathbf{g}_l}{c^{(j-1)}} - a_l \right), \quad (11)$$

where $a_l = \frac{\mathbf{g}_l^H \mathbf{V}_l^{(j-1)} \mathbf{g}_l}{(c^{(j-1)})^2} \left(\left(\sum_{l'=0, l' \neq l}^L \mathbf{g}_l^H \mathbf{V}_{l'} \mathbf{g}_l - \sum_{l'=0, l' \neq l}^L \mathbf{g}_l^H \mathbf{V}_{l'}^{(j-1)} \mathbf{g}_l \right) + \left(\sum_{k=1}^K p_k |q_{kl}|^2 - \sum_{k=1}^K p_k^{(j-1)} |q_{kl}|^2 \right) \right)$ and the $(j-1)$ -th iteration $c^{(j-1)}$.

We now seek to resolve the non-convex constraints. Starting with the radar constraint C3 in (10), we can state $\mathbf{Q} \succcurlyeq 0$ and $\mathbf{a}_t^H(\theta) \mathbf{Q} \mathbf{a}_t(\theta) \geq 0$ since $\{\mathbf{V}_l \succcurlyeq 0\}_{l=0}^L$. Thus, by dividing both sides of C3 by $\mathbf{a}_t^H(\theta) \mathbf{Q} \mathbf{a}_t(\theta)$, it results in

$$\mathbf{a}_r^H(\theta) \Psi^{-1} \mathbf{a}_r(\theta) \geq r (\mathbf{a}_t^H(\theta) \mathbf{Q} \mathbf{a}_t(\theta))^{-1}, \quad (12)$$

The expression on the left-hand side of (12) shows that Ψ is an affine function with respect to $\{\{\mathbf{V}_l\}_{l=0}^L, \{p_k\}_{k=1}^K\}$ which is a convex expression. Moreover, the right hand side of (12) is convex with respect to $\{\{\mathbf{V}_l\}_{l=0}^L\}$ which makes the constraint in (12) a difference of convex function. We use the first-order Taylor expansion to derive a lower bound for the left-hand side. At the j -th iteration, the following lower bound is obtained

$$\begin{aligned} & \mathbf{a}_r^H(\theta) \Psi^{-1} \mathbf{a}_r(\theta) \geq \mathbf{a}_r^H(\theta) (\Psi^{(j-1)})^{-1} \mathbf{a}_r(\theta) - \mathbf{a}_r^H(\theta) \\ & \times (\Psi^{(j-1)})^{-1} (\Psi - \Psi^{(j-1)}) (\Psi^{(j-1)})^{-1} \mathbf{a}_r(\theta) \\ & \triangleq f(\Psi, \Psi^{(j-1)}), \end{aligned} \quad (13)$$

where $\Psi^{(j-1)} = \sum_{k=1}^K p_k^{(j-1)} \mathbf{h}_k \mathbf{h}_k^H + \mathbf{H} \mathbf{Q}^{(j-1)} \mathbf{H}^H + \mathbf{I}_{MN_r}$ and $\mathbf{Q}^{(j-1)} = \sum_{l=0}^L \mathbf{V}_l^{(j-1)}$ with $\{p_k^{(j-1)}\}_{k=1}^K$ and $\{\mathbf{V}_l^{(j-1)}\}_{l=0}^L$ being the solutions derived in the $(j-1)$ -th

iteration. The radar constraint C1 in (10) is now reformulated into a convex subset which is given as

$$f(\Psi, \Psi^{(i-1)}) \geq r(\mathbf{a}_t^H(\theta)\mathbf{Q}\mathbf{a}_t(\theta))^{-1}. \quad (14)$$

Considering constraint C2 in (10), it can be proved that for each k , $\mathbf{h}_k^H \Phi_k^{-1} \mathbf{h}_k$ is convex with respect to Φ_k . We employ the first-order Taylor expansion to attain an affine approximation as

$$\begin{aligned} \mathbf{h}_k^H \Phi_k^{-1} \mathbf{h}_k &\geq \mathbf{h}_k^H (\Phi_k^{(j-1)})^{-1} \mathbf{h}_k - \mathbf{h}_k^H (\Phi_k^{(j-1)})^{-1} \times \\ &(\Phi_k - \Phi_k^{(j-1)}) (\Phi_k^{(j-1)})^{-1} \mathbf{h}_k \triangleq f_k(\Phi_k, \Phi_k^{(j-1)}), \forall k, \end{aligned} \quad (15)$$

where $\Phi^{(j-1)} = \sum_{j \neq k}^K p_j^{(j-1)} \mathbf{h}_j \mathbf{h}_j^H + \mathbf{G} \mathbf{Q}^{(j-1)} \mathbf{G}^H + \mathbf{H} \mathbf{Q}^{(j-1)} \mathbf{H}^H + \mathbf{I}_{MN_r}$ is obtained from the $(j-1)$ -th iteration. Using the results in (15), the constraint C2 in (10) is given as

$$\frac{z_k}{p_k} \leq f_k(\Phi_k, \Phi_k^{(j-1)}), \forall k. \quad (16)$$

However, the fractional part of (16) makes the constraint still non-convex. To overcome this challenge, we introduce a real-valued auxiliary variable $\{t_k\}_{k=1}^K$. This is used to equivalently convert (16) into two separate constraints as

$$\begin{cases} \frac{t_k^2}{p_k} \leq f_k(\Phi_k, \Phi_k^{(j-1)}), \\ z_k \leq t_k^2, \end{cases} \quad \forall k \quad (17)$$

where $\frac{t_k^2}{p_k}$ is convex with regards to $p_k > 0$. This equivalence can be proved by contradiction. The convex function t_k^2 is substituted by its first-order Taylor expansion to derive an approximate convex expression of (17) as

$$\begin{cases} \frac{t_k^2}{p_k} \leq f_k(\Phi_k, \Phi_k^{(j-1)}), \\ z_k \leq (t_k^{(j-1)})^2 + 2t_k^{(j-1)}(t_k - t_k^{(j-1)}), \end{cases} \quad \forall k \quad (18)$$

The problem (10) is now resolved by using the SCA framework. We solve the following convex problem in the j -th iteration

$$\begin{aligned} \max_{\substack{\{\mathbf{V}_l \succcurlyeq 0\}_{l=0}^L, \{r \geq 0\}, \\ \{z_k \geq 0, t_k \geq 0, p_k > 0\}}} & \sum_{k=1}^K \log_2(1 + z_k) + \sum_{l=1}^L \log_2 \left(1 + \mathbf{g}_l^H \mathbf{V}_l \mathbf{g}_l \right. \\ & \left. \times (c^{(j-1)})^{-1} - a_l \right) + \log_2(1 + r), \text{ s.t. C1, C2, (14), (18),} \end{aligned} \quad (19)$$

It should be noted that the rank-1 constraint is removed in (19), i.e., $\text{rank}(\mathbf{V}_l) \leq 1, \forall l \geq 1$, based on rank relaxation. The solutions $\{\{\hat{\mathbf{V}}_l\}_{l=0}^L, \{\hat{p}_k\}_{k=1}^K\}$ can be obtained at convergence. It is possible to attain a rank-1 solution for (19) based on [11, Theorem 1] without performance loss.

The algorithm required to provide the optimal solutions of the convex problem (19) is provided in Algorithm 1. The computational complexity of Algorithm 1 is given as $\mathcal{O}(I(M^3 L^4 K^5 + \log(1 + \chi)))$.

Algorithm 1 SCA Algorithm for solving (19)

Initialization: $\{\{\mathbf{V}_l^{(0)} \succcurlyeq 0\}_{l=0}^L, \{p_k^{(0)} \geq 0, z_k^{(0)} \geq 0, t_k^{(0)} \geq 0\}_{k=1}^K, r \geq 0\}$ with iteration index $j = 0$, and convergence value ϵ .

1: **repeat**

2: Solve (19) and update $\{\{\mathbf{V}_l^{(j)} \succcurlyeq 0\}_{l=0}^L, \{p_k^{(j)} \geq 0, z_k^{(j)} \geq 0, t_k^{(j)} \geq 0\}_{k=1}^K\}$.

3: **until** Convergence.

4: Compute the DL transmit beamformer and the UL transmit power using [11, Theorem 1].

5: Compute the receive beamformers using (8) and (9).

Output: $\{\mathbf{v}_l^*\}_{l=1}^L, \mathbf{V}_0^*, \{\mathbf{u}_k^* \geq 0, p_k^* \geq 0, z_k^* \geq 0, t_k^* \geq 0\}_{k=1}^K$.

V. NUMERICAL RESULTS

We employ the following parameters unless otherwise stated: A cell size of 200×200 m², $M = 4$ APs, $K = 3$ UL users, $L = 3$ DL users, and $N_t = N_r = 8$ per-AP transmit and receive antennas, respectively. The path-loss for the LoS channels between the APs and the UL/DL users and LoS channels to the target are computed using the 3GPP Urban Micro-Street Canyon model [14, Table 7.4.1-1]. The non-LoS version of this model is used to determine the inter-AP and UL-to-DL user path-loss. The noise power $N_o = -96$ dBm, transmit powers $\tilde{P}_m^{\max} = \tilde{P}_m^{\max}/N_o$, and $\tilde{P}_{u,k}^{\max} = \tilde{P}_{u,k}^{\max}/N_o$ as the maximum power per AP and k -th UL user power, respectively. The powers are allocated as $\tilde{P}_{u,k}^{\max} = 100$ mW and $\tilde{P}_m^{\max} = 1$ W. The normalized residual SI is given as $\xi_{\text{SI}}^2/N_o = 40$ dB, respectively.

Remarks: For a fair analysis, we compare the communication functionality of the proposed FD CF MIMO ISAC system with its HD counterpart. The HD setup is attained by assuming a time division duplex system in which UL and DL communication functionalities occur in different time resource blocks. For the DL case, the APs perform both target localization and DL data transmission. In the UL, there is simultaneous reception of UL data signals and target sensing by the APs. The UDI term is set to zero and a pre-log value of 1/2 is allocated to the UL and DL communication sum SE. The HD scheme is labeled as ‘‘HD Opt’’ in the plots. For a baseline scheme for the sensing case, we consider a variation of the optimization problem where only communication sum SE is maximized with no constraint on the sensing [11]. This scheme is denoted as ‘‘FD Opt (no SC)’’ in the plots. The derivations for the proposed baseline schemes for comparison are omitted due to space constraints. It should be noted that ‘‘Communication’’ is denoted as ‘‘Comm’’ in the plots. We represent the optimized proposed model as ‘‘FD Opt’’ in the simulation results. In Fig. 1, the total communication and sensing sum SEs are plotted against number of APs, for varying number of users. For both the communication and sensing cases, there is an increase in the sum SE for high number of APs M for all schemes being compared. This is due to the consequent increase in macro-diversity gain which is a

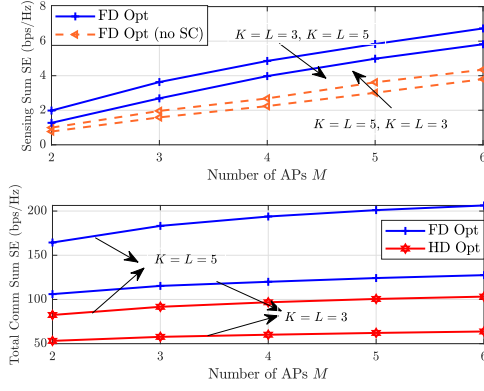


Fig. 1: Sensing/Total Communication Sum SE vs Number of APs M .

crucial benefit in CF MIMO systems. For the communication case, it can be observed that the FD case possesses a significant SE gain over the HD counterpart. Also, a high number of UL/DL users K, L results in a higher sum SE for both the FD and HD setups. For the sensing functionality, the “FD Opt” scheme outperforms the “FD Opt (no SC)” case. This is because the “FD Opt” case ensures the attained macro-diversity gain benefits both ISAC functionalities whilst the “FD Opt (no SC)” scheme seeks to benefit communication only at the expense of sensing. Also, for increasing number of UL/DL users K, L , there is a decrease in the sensing SE for both schemes. This is due to the growth in the UL user interference which causes SE degradation.

The Fig. 2 considers a plot of the total communication and sensing sum SEs against UL/DL transmit power budgets for varying number of UL/DL users. For both ISAC functionalities, an increase in the maximum UL/DL powers $P_{u,k}^{\max}, P_m^{\max}$ results in improved sum SEs. This is due to the simultaneous increase in distributed beamforming gain. One significant point of note is that the “FD Opt” case outperforms the baseline schemes for both communication and sensing setups. This affirms the robustness and feasibility of our proposed model and optimization scheme.

VI. CONCLUSION

This work studied a FD CF MIMO ISAC model, where the sum rate maximization of both the UL/DL communication and sensing sum SEs was solved with our proposed optimization algorithm. The proposed FD setup attained a significant SE gain over its HD counterpart for the communication case for both varying number of APs and UL/DL power budgets. A similar pattern was attained in the sensing case where the proposed model outperforms its variant which considers only communication maximization devoid of a sensing constraint. This proves the stability and viability of our proposed FD CF ISAC MIMO system.

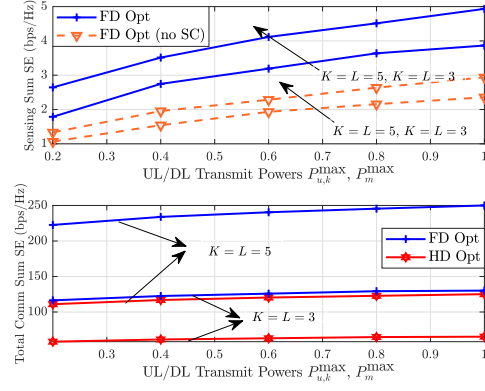


Fig. 2: Sensing/Total Communication Sum SE vs UL/DL Transmit Powers $P_{u,k}^{\max}, P_m^{\max}$.

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