

Joint Power Allocation Strategies for Integrated Sensing and Communication Systems

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Abstract—This paper investigates the joint design of through an angular-domain power allocation framework. Considering a multi-user scenario with a single sensing target, we formulate the original optimization problem and derive a tractable convex approximation that enables efficient power allocation across spatial directions to balance communication rate and sensing performance, quantified through the target illumination power. By introducing a weighting parameter, the framework characterizes the trade-off between sum-rate maximization and sensing gain, leading to a set of optimal operating points. Numerical results demonstrate that the optimal solution exhibits sparse and highly directional power allocation, focusing energy on critical angular directions associated with users or the sensing target. Therefore, the proposed method significantly improves system efficiency by exploiting spatial selectivity.

Keywords—ISAC, power allocation, convex optimization, target illumination

I. INTRODUCTION

A promising paradigm for sixth-generation (6G) wireless systems is Integrated Sensing and Communication (ISAC), which unifies sensing and communication within a common signaling framework, enabling networks to simultaneously transmit information and extract environmental awareness from the same waveform. This dual capability supports a wide range of applications, including autonomous systems, smart environments, and context-aware communications.

In the literature, the ISAC paradigm has been extensively investigated from various perspectives. In [1], the authors study a Cell-Free ISAC (CF-ISAC) scenario, where multiple access points (APs) collaboratively serve users while performing sensing tasks. Specifically, hybrid beamforming architectures, combining analog and digital processing, are employed to enable simultaneous communication with users and radar target detection in the environment. In [2], the authors derive closed-form expressions for the achievable communication rate and the Cramér–Rao lower bound (CRLB), respectively. Based on this framework, a power allocation strategy is developed using successive convex approximation to maximize communication rate under sensing and power constraints.

In this work, we propose an angular-domain optimization framework for multi-user ISAC systems with a single sensing target. The key idea is to reformulate the joint communication and sensing design as a power allocation problem over spatial directions, enabling a unified and tractable approach. By

introducing a weighting factor, the proposed method balances the communication sum-rate and sensing performance, leading to a set of optimal solutions. The framework reveals that the optimal strategy naturally concentrates power on a few angular directions, and improved efficiency compared to conventional approaches.

II. SYSTEM MODEL

A. Network architecture

We consider a downlink (DL) ISAC system, where a single base station (BS) equipped with a uniform linear array (ULA) of N_t antennas simultaneously serves K communication users and senses a radar target. The BS is connected to a central processing unit (CPU) via ideal backhaul links, and full statistical channel state information (CSI) of all K user equipments (UEs) is available at the CPU. We adopt a monostatic radar configuration, in which the transmitter and receiver are co-located at the base station. This assumption is consistent with most ISAC systems, where a single platform performs both communication and sensing.

B. Signal model

The transmitted signal vector $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$ at the BS is modeled as:

$$\mathbf{x} = \sum_{k=1}^K \sqrt{\rho_k} \mathbf{w}_k s_k = \mathbf{W} \mathbf{\Lambda} \mathbf{s}, \quad (1)$$

where $\mathbf{w}_k \in \mathbb{C}^{N_t \times 1}$ is the unit-norm beamforming vector for UE k (i.e., $\|\mathbf{w}_k\|^2 = 1$), s_k is the transmitted symbol satisfying $\mathbb{E}[|s_k|^2] = 1$, and $\rho_k \geq 0$ is the power allocated to UE k . The matrix $\mathbf{W} \triangleq [\mathbf{w}_1, \dots, \mathbf{w}_K] \in \mathbb{C}^{N_t \times K}$ collects the beamforming vectors, $\mathbf{s} \triangleq [s_1, \dots, s_K]^T \in \mathbb{C}^{K \times 1}$ is the symbol vector, and $\mathbf{\Lambda} \triangleq \text{diag}(\sqrt{\rho_1}, \dots, \sqrt{\rho_K})$ is a diagonal matrix encoding the power allocation [3]. The total transmit power constraint is given by:

$$\mathbb{E}[\|\mathbf{x}\|^2] = \sum_{k=1}^K \rho_k \leq P_{\text{total}}. \quad (2)$$

Under this model, the BS simultaneously serves K communication users while exploiting the transmitted waveform for radar sensing, following the dual-function ISAC paradigm.

C. Sensing Model

We consider a monostatic radar setup, where the BS acts as both transmitter and receiver. The transmitted signal is reflected by a target located at direction θ_0 and propagates

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back to the BS. Under this single-path propagation model, the sensing channel between the BS and the target is given by [4]:

$$\mathbf{G}_r = \alpha \mathbf{a}(\theta_0) \mathbf{a}(\theta_0)^H \in \mathbb{C}^{N_t \times N_t} \quad (3)$$

where α denotes the complex reflection coefficient of the target and $\mathbf{a}(\theta_0) \in \mathbb{C}^{N_t \times 1}$ is the array steering vector toward the target direction. The received radar signal at the BS is modeled as:

$$\mathbf{y}_r = \mathbf{G}_r \mathbf{x} + \mathbf{n}_r \in \mathbb{C}^{N_t \times 1} \quad (4)$$

where $\mathbf{n}_r \sim \mathcal{CN}(\mathbf{0}, \sigma_r^2 \mathbf{I})$ denotes additive white Gaussian noise, with σ_r^2 being the noise variance.

The sensing performance is quantified by the transmit power projected onto the target direction. Specifically, the power observed along direction θ_0 is given by:

$$S = \mathbb{E} \left[|\mathbf{a}(\theta_0)^H \mathbf{x}|^2 \right]. \quad (5)$$

Substituting the transmit signal model $\mathbf{x}$ with independent unit-power data symbols, i.e., $\mathbb{E}[|s_k|^2] = 1$ and $\mathbb{E}[s_k s_j^*] = 0$ for $k \neq j$, the expression simplifies to:

$$S = \sum_{k=1}^K \rho_k |\mathbf{a}(\theta_0)^H \mathbf{w}_k|^2. \quad (6)$$

To connect this metric with the proposed framework, we reformulate the sensing performance in the angular domain. Let $\{\theta_\ell\}_{\ell=1}^L$ be a discrete grid of spatial directions, and define the per-user angular power distribution as:

$$P_k(\theta_\ell) \triangleq \rho_k |\mathbf{a}(\theta_\ell)^H \mathbf{w}_k|^2, \quad (7)$$

which represents the power radiated by beamformer $\mathbf{w}_k$ toward direction θ_ℓ . The aggregate transmit beampattern is then:

$$P(\theta_\ell) = \sum_{k=1}^K P_k(\theta_\ell), \quad (8)$$

which represents the total power radiated toward direction θ_ℓ . The sensing metric can then be expressed as:

$$S = \sum_{\ell=1}^L P(\theta_\ell) g(\theta_\ell), \quad (9)$$

where,

$$g(\theta_\ell) = \frac{|\mathbf{a}(\theta_\ell)^H \mathbf{a}(\theta_0)|^2}{\|\mathbf{a}(\theta_\ell)\|^2 \|\mathbf{a}(\theta_0)\|^2} \quad (10)$$

is the normalized angular response of the target.

D. Communication Model

The received signal at UE k is given by:

$$y_k = \mathbf{h}_k^H \mathbf{x} + n_k, \quad (11)$$

where $\mathbf{h}_k \in \mathbb{C}^{N \times 1}$ denotes the channel vector between the BS and UE k , and $n_k \sim \mathcal{CN}(0, \sigma^2)$ represents additive white Gaussian noise. By substituting the transmit signal, the received signal can be expressed as:

$$y_k = \underbrace{\mathbf{h}_k^H \mathbf{w}_k s_k}_{\text{desired signal}} + \underbrace{\sum_{j \neq k} \mathbf{h}_k^H \mathbf{w}_j s_j}_{\text{multi-user interference}} + n_k. \quad (12)$$

Due to the presence of multi-user interference, the signal-to-interference-plus-noise ratio (SINR) at UE k is defined as:

$$\text{SINR}_k = \frac{\rho_k |\mathbf{h}_k^H \mathbf{w}_k|^2}{\sum_{j \neq k} \rho_j |\mathbf{h}_k^H \mathbf{w}_j|^2 + \sigma^2}. \quad (13)$$

Assuming Gaussian signaling and treating interference as noise, the achievable rate for UE k is given by:

$$R_k = \log_2(1 + \text{SINR}_k). \quad (14)$$

E. Communication Metric in the Angular Domain

To express the achievable rate in the angular domain, we leverage the per-user angular power distribution $P_k(\theta_\ell)$ introduced in Section II-C. The angular channel gain of UE k toward direction θ_ℓ is defined as:

$$h_k(\theta_\ell) = \frac{|\mathbf{h}_k^H \mathbf{a}(\theta_\ell)|^2}{\|\mathbf{a}(\theta_\ell)\|^2}, \quad (15)$$

which measures the projection of UE k 's channel onto each spatial direction. Under the dense-grid approximation, the desired signal power and interference power at UE k decompose as:

$$|\mathbf{h}_k^H \mathbf{w}_k|^2 \approx \sum_{\ell=1}^L P_k(\theta_\ell) h_k(\theta_\ell), \quad (16)$$

$$\sum_{j \neq k} |\mathbf{h}_k^H \mathbf{w}_j|^2 \approx \sum_{j \neq k} \sum_{\ell=1}^L P_j(\theta_\ell) h_k(\theta_\ell). \quad (17)$$

The achievable rate for UE k is therefore:

$$R_k \approx \log_2 \left(1 + \frac{\sum_{\ell=1}^L P_k(\theta_\ell) h_k(\theta_\ell)}{\sum_{j \neq k} \sum_{\ell=1}^L P_j(\theta_\ell) h_k(\theta_\ell) + \sigma_k^2} \right). \quad (18)$$

III. PROPOSED ANGULAR-DOMAIN ISAC FRAMEWORK

In this section, we propose a resource allocation framework that operates in the angular domain. Rather than directly optimizing the beamforming vectors $\{\mathbf{w}_k\}$, the framework focuses on the per-user transmit power distribution across spatial directions, where each angle is interpreted as a virtual resource. The individual rates R_k are computed from the per-user allocations $\{P_k(\theta_\ell)\}$, while the sensing metric S depends on the aggregate beampattern $P(\theta_\ell)$, both expressed through the shared angular-domain variables. The trade-off between the two functionalities is controlled via a weighted objective function:

$$\max_{\{P_k(\theta_\ell)\}} \gamma \sum_{k=1}^K R_k + (1 - \gamma) S, \quad (19)$$

subject to:

$$P_k(\theta_\ell) \geq 0, \quad \forall k, \ell, \quad (20)$$

$$\sum_{k=1}^K \sum_{\ell=1}^L P_k(\theta_\ell) \leq P_{\text{total}}, \quad (21)$$

where $\gamma \in [0, 1]$ is a weighting factor that balances communication and sensing priorities.

IV. NUMERICAL RESULTS

This section evaluates the proposed angular-domain resource allocation framework through numerical simulations in a multi-user ISAC system with $K = 2$ communication users and a single sensing target. The angular domain is discretized over the interval $[-90^\circ, 90^\circ]$ with 1° resolution. A single transmitter is considered, with total transmit power $P_{\text{total}} = 10$ W allocated across spatial directions. The users are located at 10° and -20° , while the sensing target is positioned at 0° . Communication performance is evaluated in terms of achievable sum rate, whereas sensing performance is quantified through the target illumination power. The communication–sensing trade-off is controlled by the weighting parameter $\gamma \in [0, 1]$. Since the per-user rates involve SINR expressions with multi-user interference, the resulting optimization problem is non-convex in general. To handle this, a successive convex approximation (SCA) approach is adopted, where the interference term is fixed at each iteration using the current solution and treated as a constant, yielding a convex subproblem solved via the CVX toolbox. This procedure is repeated until convergence to a stationary point.

Fig. 1 shows the Pareto frontier between the achievable sum rate and the target illumination power as γ varies. For low γ , the system prioritizes sensing by focusing power toward the target direction, reducing communication performance. As γ increases, the allocation shifts toward communication, leading to a sharp increase in sum rate. These results confirm that the proposed framework effectively captures the communication–sensing trade-off. $P(\theta_\ell)$

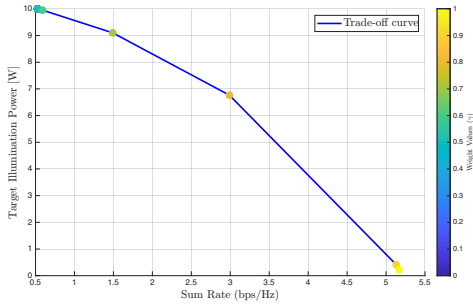


Fig. 1: Pareto Frontier: Communication vs Sensing.

Fig. 2 compares the optimized power allocation against a uniform baseline. The optimized solution concentrates power onto two angular directions at approximately -20 and $+10$, corresponding to the UE locations, while the baseline spreads energy uniformly across all directions. This confirms that the proposed framework effectively exploits spatial selectivity for a more efficient use of the transmit budget.

Fig. 3 shows the achievable rates of both UEs versus the communication weight γ . For low γ , UE 1 maintains a residual rate due to its partial angular overlap with the sensing beam, while UE 2 remains inactive because of its weaker spatial alignment. Around $\gamma \approx 0.6$, the optimizer begins allocating power to UE 2, causing both rates to increase rapidly. As $\gamma \rightarrow 1$, the rates converge to approximately 2.57 bps/Hz, indicating that the system fully prioritizes communication.

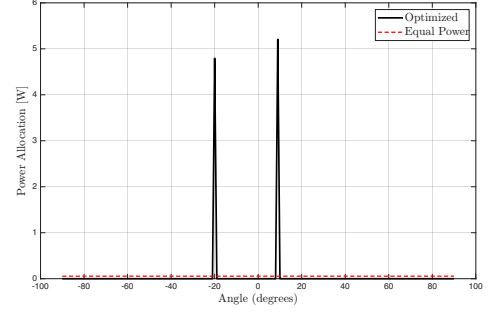


Fig. 2: Power allocation proposed vs baseline.

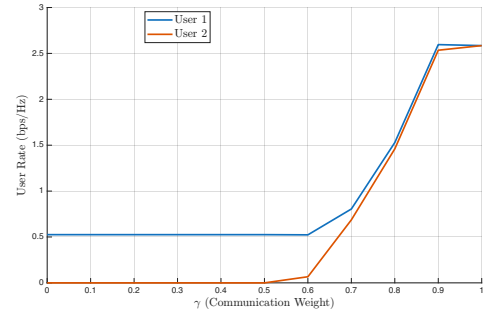


Fig. 3: Achievable rates of UEs vs the communication weight γ .

V. CONCLUSION

We proposed an angular-domain power allocation framework for multi-user ISAC systems, jointly optimizing communication rate and target illumination power through a unified weighting parameter γ . Results showed that the optimized allocation concentrates energy on relevant spatial directions, outperforming the uniform baseline and revealing distinct sensing- and communication-dominant operating regimes. Future work includes multi-target extensions and robust optimization under imperfect CSI.

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