

Sum-Rate Maximization for ISAC Systems With Backscatter RFID Tags

Rojith K[†], Raviteja Allu[†], Keshav Singh[†], Saba Al-Rubaye[‡], and Chih-Peng Li[†]

[†]Institute of Communications Engineering, National Sun Yat-sen University, Kaohsiung 80424, Taiwan

[‡]School of Aerospace Transport and Manufacturing (SATM), Cranfield University, Milton Keynes, U.K.

Abstract—This paper investigates an integrated sensing and communication (ISAC) system incorporating backscattering radio frequency identification (RFID) tag. In this configuration, a base station (BS) simultaneously serves multiple users through a communication beam while utilizing a sensing beam to detect the presence of an RFID tag. A joint beamforming design problem is formulated to maximize the sum-rate for the users while ensuring the minimum quality of service (QoS) for the tag detection and the minimum QoS of all communication users. To tackle the non-convex nature of objective function the Lagrangian dual transform technique is employed. Due to the coupling of variables, an alternating optimization (AO) based algorithm is proposed with guaranteed convergence. Through numerical simulations, we validate the effectiveness of our proposed algorithm. Additionally, we assess the impact of several key parameters on system performance, including the number of transmitting antennas at the BS, the available transmit power at the BS, the minimum QoS for the communication users, and the number of communication users.

Index Terms—Backscatter communication, integrated sensing and communication, sum-rate maximization, lagrangian dual transform.

I. INTRODUCTION

THE need for 6G technology is increasingly pressing in light of the growing demands for faster data rates, enhanced connectivity, and greater energy efficiency, especially as the number of connected devices continues to rise. Backscatter communication (BackCom) plays a crucial role in addressing these challenges by allowing devices to transmit data by reflecting existing radio signals rather than generating their own. This method significantly reduces energy consumption [1], making it particularly beneficial for low-power devices and Internet of Things (IoT) applications. Backscatter technology contributes to the sustainability goals of 6G by minimizing energy use, and enabling the development of greener infrastructure. This synergy not only ensures efficient resource utilization but also facilitates advanced applications such as smart cities, environmental monitoring, and remote sensing [2], [3].

Another energy-efficient technology, integrated sensing and communication (ISAC), merges the capabilities of wireless communication and environmental sensing into a unified system, playing a crucial role in the development of future 5G and 6G networks. It offers several important benefits, including

better use of available spectrum, lower hardware costs, and reduced electromagnetic pollution. Unlike traditional networks that focus only on communication, ISAC allows devices to both communicate and sense their environment at the same time within the same frequency block [4]. This capability enables ISAC devices to gather useful information from radio frequency (RF) signals and their reflections. As a result, they can provide new services such as precise location tracking, gesture recognition, activity detection, and object tracking [5].

In the existing literature, numerous authors have extensively examined the significance of the BackCom and the ISAC [6]–[13]. In [6], the authors presented a backscatter communication network that maximizes energy efficiency by jointly optimizing the scheduling of backscatter devices and the transmission power of the carrier emitter. In [7], the authors propose an energy-efficient beamforming strategy for an ISAC system where the transmitted waveform is optimized to facilitate joint multi-user communication and target estimation.

A better efficient communication framework can be achieved by merging the real-time sensing functions of ISAC with the ultra-low-power data transmission of BackCom. This integration could lead to improved performance in applications such as smart environments like smart warehouses [14], where devices need to both sense their surroundings and communicate data with minimal energy consumption. In integrated sensing and backscatter communications (ISABC), the traditional sensing in ISAC systems is replaced by a passive backscatter tag. This tag functions as the sensing target, providing the base station (BS) with essential sensing information while also transmitting additional data to the user. A key concern in this setup is the potential interference the backscatter tag may introduce to the communication users, as the tag interacts with both the base station and the users.

Recently, a pertinent study [15] introduced an integrated sensing and backscatter communication system where a transmit beamforming is utilized by the BS to communicate with a user while simultaneously broadcasting sensing signals for RFID tag detection. The communication performance for both the user and the backscattering tag, along with the sensing performance at the BS, was analyzed by the authors, under various power allocations between sensing and communication. However, this work overlooked the detection requirements for RFID tags, specifically the sensitivities of both the tag and the reader, which are crucial in practical applications. Additionally, the study did not implement transmit beamforming for the sensing signals, which is essential for extending the RFID

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detection range. In [16], the authors previously developed a comparable system that jointly designs sensing and communication beams while accounting for both tag detection and communication constraints, with the objective of minimizing the total transmit power. However, this paper focuses solely on minimizing power at the BS, considering only a single user.

Practical systems must manage power efficiently, especially when multiple users compete for resources, and interference from backscatter signals can degrade performance. This motivates us to design a system that maximizes communication rates for multiple users while considering the detection requirements of RFID tags, and power constraints taking into account the effects of interference from the backscatter tag.

The major contributions of this work are summarized below:

- 1) ISABC system with multiuser transmission enabled by a tag, in which a DFBS source manages to serve a multiuser downlink network while simultaneously sensing the modulated information from the tag.
- 2) We formulate an optimization problem to maximize the downlink sum-rate, subject to quality of services (QoS) constraints at the tag, users, and the BS.
- 3) To tackle the non-convex nature of objective function the Lagrangian dual transform technique is employed. Due to the coupling of variables, an alternating optimization (AO) based algorithm is proposed with guaranteed convergence.

Notations: Vectors and matrices are represented by bold-face lowercase and uppercase letters. The notation $\mathbb{C}^{x \times y}$ denotes the space of $x \times y$ complex-valued matrices. For a complex-valued vector $\mathbf{x}$, $\|\mathbf{x}\|$ denotes its Euclidean norm, $|x|$ denotes absolute value. The complex normal distribution with mean $\mathbf{x}$ and variance σ^2 is denoted by $\mathcal{CN}(\mathbf{x}, \sigma^2)$. For any general matrix $\mathbf{M}$, $\mathbf{M}^H$ denotes its conjugate transpose. The expectation operator is denoted by $\mathbb{E}(\cdot)$ and $\text{Re}\{\cdot\}$ denotes the real part of a complex number.

II. SYSTEM FRAMEWORK

In this work, a backscatter ISAC system is considered, where a BS equipped with M_t transmit antennas and M_r receive antennas simultaneously senses a passive RFID tag and communicates with N single-antenna users ($\mathcal{N} = \{1 \dots N\}$), as illustrated in Fig. 1. The BS transmits a joint communication and sensing signal to serve the users while simultaneously reading the tag. The tag reflects the incident signal, modulates it with its data, and scatters it back to the BS for detection and data retrieval. It is assumed that the BS can differentiate between the received and transmitted signals.

A. Signal model

The transmit signal at the BS is formulated as the combination of communication and sensing signals, each associated with its respective beamforming vector. The ISAC signal transmitted by the BS is expressed as follows

$$\mathbf{x} = \mathbf{v}s^t + \sum_{i \in \mathcal{N}} \mathbf{f}_i s_i^u, \quad (1)$$

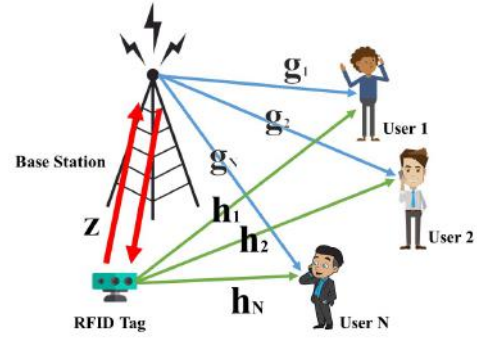


Fig. 1. Backscatter ISAC system model.

where $s_i^u \in \mathbb{C}$ is the communication data for the i^{th} user and $s^t \in \mathbb{C}$ is the RFID sensing signal. The signals are assumed to possess unit average energy. $\mathbf{f}_i \in \mathbb{C}^{M_t}$, $\mathbf{v} \in \mathbb{C}^{M_t}$ are the beamforming vectors for communication and sensing respectively.

B. Backscatter Model

The RFID tag processes the received signal and sent back to BS by modulating its signal [17]. We denote the channel between the BS and the tag as $\mathbf{z} \in \mathbb{C}^{M_t}$. The received signal at the tag can be expressed as:

$$\begin{aligned} y_t &= \mathbf{z}^H \mathbf{x} + n_t, \\ &= \mathbf{z}^H (\mathbf{v}s_t + \sum_{i \in \mathcal{N}} \mathbf{f}_i s_i^u) + n_t, \end{aligned} \quad (2)$$

where $n_t \in \mathcal{N}(0, \sigma_t^2)$ is the noise at the tag. The SINR to decode the tag's data sent by BS at tag is written as

$$\Gamma_t = \frac{|\mathbf{z}^H \mathbf{v}|^2}{\sum_{i \in \mathcal{N}} |\mathbf{z}^H \mathbf{f}_i|^2 + \sigma_t^2}. \quad (3)$$

The tag reflects the signal containing the stored data by modulating the incoming signal. Formally, the backscatter-modulated signal can be expressed as

$$r = d\sqrt{\eta}(\mathbf{z}^H (\mathbf{v}s_t + \sum_{i \in \mathcal{N}} \mathbf{f}_i s_i^u) + n_t), \quad (4)$$

where d represents the encoded data of the tag, with $E[|d|^2] = 1$, and η is the backscatter modulation efficiency after modulation. The received signal from the tag to the BS can be written as

$$y_r = \mathbf{w}^H \mathbf{z}r + \mathbf{w}^H n_r, \quad (5)$$

where $\mathbf{w} \in \mathbb{C}^{M_r}$ is the combining vector used by the BS which is designed using the matched filter criterion $\mathbf{w} = \mathbf{z}/\|\mathbf{z}\|$ and $n_r \in \mathcal{N}(0, \sigma_r^2)$ is the noise at the BS. From (4) and (5), y_r is given as

$$\begin{aligned} y_r &= \sqrt{\eta}d(\mathbf{w}^H \mathbf{z} \mathbf{z}^H \mathbf{v}s_t \\ &\quad + \sum_{i \in \mathcal{N}} \mathbf{w}^H \mathbf{z} \mathbf{z}^H \mathbf{f}_i s_i^u + \mathbf{w}^H \mathbf{z} n_t) + \mathbf{w}^H n_r. \end{aligned} \quad (6)$$

The SINR to decode the modulated signal sent by the tag at the BS is given by

$$\Gamma_r = \frac{\eta |\mathbf{w}^H \mathbf{z} \mathbf{z}^H \mathbf{v}|^2}{\eta \left(\sum_{i \in \mathcal{N}} |\mathbf{w}^H \mathbf{z} \mathbf{z}^H \mathbf{f}_i|^2 + |\mathbf{w}^H \mathbf{z}|^2 \sigma_t^2 \right) + \|\mathbf{w}^H\|^2 \sigma_r^2}. \quad (7)$$

Note that, for successful detection of the tag, it is crucial for both the SINRs at the tag and the BS to satisfy their respective sensitivity QoS constraints.

C. Communication model

The communication user receives transmitted signals from BS and backscattered signals from RFID tags. The signals received by the j^{th} user is written as

$$y_j^u = \mathbf{g}_j^H (\mathbf{v} s_t + \sum_{i \in \mathcal{N}} \mathbf{f}_i^u s_i^u) + h_j y_t d \sqrt{\eta} + n_j^u, \quad (8)$$

where $y_j^u \in \mathbb{C}$ is the received signal at j^{th} user, $\mathbf{g}_j \in \mathbb{C}^{M_t}$ is the channel between j^{th} user and BS, h_j is the channel between j^{th} user and tag, and $n_j^u \sim \mathcal{CN}(0, \sigma_u^2)$ represents the receiver noise at the j^{th} user. From (8), the received SINR for j^{th} user can be defined in equation (9) is shown at the top of the next page. The corresponding user rate is given as,

$$R_j^u = \log(1 + \Gamma_j^u). \quad (10)$$

III. PROBLEM FORMULATION

This work aims to design communication and sensing beamformers that maximize the sum-rate for communication users while meeting QoS constraints for the tag, the base station, and the users.

$$(P1) \max_{\mathbf{v}, \mathbf{f}_j} \sum_{j \in \mathcal{N}} \log_2(1 + \Gamma_j^u) \quad (11a)$$

$$\text{s.t. } (C.1) : \|\mathbf{v}\|^2 + \sum_{j \in \mathcal{N}} \|\mathbf{f}_j\|^2 \leq p_{\max}, \quad (11b)$$

$$(C.2) : \Gamma_j^u \geq \gamma_j, \forall j \in \mathcal{N}, \quad (11c)$$

$$(C.3) : \Gamma_t \geq \gamma_t, \quad (11d)$$

$$(C.4) : \Gamma_r \geq \gamma_r. \quad (11e)$$

In this problem, constraint (C.1) limits the transmit power at the BS not to exceed $p_{\max}$. Constraints (C.2), (C.3) and (C.4) ensure the minimum QoS requirement for each communication user, tag, and BS respectively, where γ_j and γ_t, γ_r denotes the corresponding minimum acceptable SNRs. The optimization problem (P1) presents considerable challenges due to the structure of its objective function, which includes the summation of multiple logarithmic terms. Additionally, the fractional nature of the SINR constraints and the coupling of variables renders the problem non-convex, further complicating the solution process.

IV. PROPOSED SOLUTION

To enhance the tractability of the problem (P1), We start by applying the Lagrangian dual transform [18] to extract the SINR ratio from the logarithmic function, introducing an auxiliary variable $\alpha = [\alpha_1, \alpha_2, \dots, \alpha_M]^T$. This reformulates the objective function into an equivalent form as follows:

$$\sum_{j=1}^N [\log_2(1 + \alpha_j) - \alpha_j + \tau(\alpha_j, \Gamma_j^u)], \alpha_j \geq 0, \quad (12)$$

where $\tau(\alpha_j, \Gamma_j^u) = (1 + \alpha_j) \Gamma_j^u / (1 + \Gamma_j^u)$. Thereby, based on the quadratic transform theory proposed in [18], $\tau(\alpha_j, \Gamma_j^u)$ is transformed as

$$\tau(\alpha_j, \Gamma_j^u) = 2\sqrt{(1 + \alpha_j) \text{Re}(\beta_j^* A_j)} - \beta_j^2 B_j, \quad (13)$$

where $\beta_j \in \beta = [\beta_1, \beta_2, \dots, \beta_M]^T$ is an auxiliary variable, and the definitions of A_j and B_j are given by $A_j = \mathbf{g}_j^H \mathbf{f}_j$ and $B_j = |\mathbf{g}_j^H \mathbf{v}|^2 + \sum_{i \in \mathcal{K}} |\mathbf{g}_j^H \mathbf{f}_i|^2 + h_{t,j}^2 \eta (|\mathbf{z}^H \mathbf{v}|^2 + \sum_{i \in \mathcal{N}} |\mathbf{z}^H \mathbf{f}_i|^2 \sigma_t^2) + \sigma_j^2$. Thus, the problem (P1) is transformed as

$$(P2) \max_{\mathbf{v}, \mathbf{f}_j, \alpha_j, \beta_j} \sum_{j=1}^N \left\{ \log_2(1 + \alpha_j) - \alpha_j + 2\sqrt{(1 + \alpha_j) \text{Re}(\beta_j^* A_j)} - |\beta_j|^2 B_j \right\} \quad (14a)$$

$$\text{s.t. } (C.1) : \|\mathbf{v}\|^2 + \sum_{j \in \mathcal{N}} \|\mathbf{f}_j\|^2 \leq p_{\max} \quad (14b)$$

$$(C.2) : \Gamma_j^u \geq \gamma_j, \forall j \in \mathcal{N} \quad (14c)$$

$$(C.3) : \Gamma_t \geq \gamma_t \quad (14d)$$

$$(C.4) : \Gamma_r \geq \gamma_r \quad (14e)$$

$$(C.5) : \alpha_j \geq 0, \forall j \in \mathcal{N} \quad (14f)$$

The problem (P2) poses a significant challenge due to the coupling of variables, primarily due to the strong inter dependencies between the variables $\mathbf{v}$ and $\mathbf{f}_j$ in both the constraints and the objective function. As a result, obtaining globally optimal solutions using conventional mathematical optimization methods within polynomial time becomes intractable. To tackle this issue, one can implement an alternating optimization scheme [19], which will decompose (P2) into more tractable sub-problems, thereby streamlining the search for the optimal sum-rate. The AO method is an iterative process that enables the sequential updating of the variables $\alpha_j, \beta_j, \mathbf{v}$ and $\mathbf{f}_j$ across two main steps. The detailed derivation is as follows:

Step 1: Optimize α_j and β_j , at fixed $\mathbf{v}$ and $\mathbf{f}_j$. The optimal values of α_j and β_j can be determined by setting the partial derivatives of objective function with respect to α and β to zero. This yields the optimal expressions as

$$\alpha_{\text{opt},j} = \Gamma_j, \quad \beta_{\text{opt},j} = \sqrt{(1 + \alpha_{\text{opt},j})} \frac{A_j}{B_j}. \quad (15)$$

Step 2: Optimize $\mathbf{v}$ and $\mathbf{f}_j$ at sub-optimal α and β . The problem (P2) is reformulated as:

$$(P3) \min_{\mathbf{f}_j, \mathbf{v}} \sum_{j=1}^M (|\beta_j|^2 B_j - 2(1 + \alpha_j) \text{Re}(\beta_j^* A_j)), \quad (16)$$

$$\text{s.t. } (C.1), (C.2), (C.3) \text{ and } (C.4). \quad (17)$$

Due to the fractional nature of the SINR constraints in (C.2), (C.3) and (C.4), the problem (P3) is non-convex. However, these constraints can be transformed into second-order cone constraints, which are convex. For example, the SINR constraint for the tag at the BS can be reformulated as follows:

$$\frac{1}{\gamma_t} |\mathbf{z}^H \mathbf{v}|^2 \geq \sum_{i \in \mathcal{N}} |\mathbf{z}^H \mathbf{f}_i|^2 + \sigma_t^2. \quad (18)$$

$$\Gamma_j^u = \frac{|\mathbf{g}_j^H \mathbf{f}_j|^2}{|\mathbf{g}_j^H \mathbf{v}|^2 + \sum_{i \in \mathcal{N}, i \neq j} |\mathbf{g}_j^H \mathbf{f}_i|^2 + h_j \eta (|\mathbf{z}^H \mathbf{v}|^2 + \sum_{i \in \mathcal{N}} |\mathbf{z}^H \mathbf{f}_i|^2 + \sigma_t^2) + \sigma_j^2}. \quad (9)$$

To simplify, utilizing the property that arbitrary phase rotation does not change the absolute value, i.e., $|\mathbf{z}^H \mathbf{v}| = |\mathbf{z}^H \mathbf{v} e^{j\theta}|$ by selecting a phase rotation $e^{j\theta}$ to make $|\mathbf{z}^H \mathbf{v}|$ real and positive, the left hand side (LHS) of (18) is transformed as

$$|\mathbf{z}^H \mathbf{v}| = \text{Re}\{\mathbf{z}^H \mathbf{v}\} \quad (19)$$

Then, by applying square root on both sides of (18), the SINR constraint can be cast in second-order cone form as:

$$\sqrt{\frac{1}{\gamma_t}} \text{Re}\{\mathbf{z}^H \mathbf{v}\} \geq \left\| \begin{bmatrix} \lfloor \mathbf{z}^H \mathbf{f}_i \rfloor_{i \in \mathcal{N}} \\ \sigma_t \end{bmatrix} \right\| \quad (20)$$

Similarly, the constraint (C.4) is written as

$$\sqrt{\frac{\eta}{\gamma_r}} |\mathbf{w}^H \mathbf{z}| \text{Re}\{\mathbf{z}^H \mathbf{v}\} \geq \left\| \begin{bmatrix} \lfloor \sqrt{\eta} \mathbf{w}^H \mathbf{z} \mathbf{z}^H \mathbf{f}_i \rfloor_{i \in \mathcal{N}} \\ \sqrt{\eta} \mathbf{w}^H \mathbf{z} \sigma_t \end{bmatrix} \right\|. \quad (21)$$

The constraint (C.2) can be written as

$$\sqrt{\frac{1}{\delta_j^u}} \text{Re}\{\mathbf{g}_j^H \mathbf{f}_j\} \geq \left\| \begin{bmatrix} \mathbf{g}_j^H \mathbf{v} \\ \lfloor \mathbf{g}_j^H \mathbf{f}_i \rfloor_{i \in \mathcal{N}, i \neq j} \\ \sqrt{\eta} h_{tj} \mathbf{z}^H \mathbf{v} \\ \lfloor \sqrt{\eta} h_{tj} \mathbf{z}^H \mathbf{f}_i \rfloor_{i \in \mathcal{N}} \\ \sqrt{\eta} h_{tj} \sigma_t \end{bmatrix} \right\|. \quad (22)$$

Since the objective function of problem (P3) no longer contains logarithmic terms or fractions. Additionally, the fractional nature of the SINR constraints (C.2), (C.3) and (C.4) has been transformed into second-order cone constraints, resulting in the entire problem becoming convex. Consequently, the final optimization problem can be expressed as follows:

$$(P4) \quad \min_{\mathbf{f}_j, \mathbf{v}} \sum_{j=1}^M (|\beta_j|^2 B_j - 2(1 + \alpha_j) \text{Re}(\beta_j^* A_j)), \quad (23)$$

$$\text{s.t. (C.1), (20), (21) and (22).} \quad (24)$$

Based on the aforementioned discussion, we present an iterative algorithm based on AO, outlined in **Algorithm 1**. This algorithm computes sub-optimal values for α and β_j using (15), while the variables $\mathbf{f}_j$ and $\mathbf{v}$ are optimized by solving the problem (P4) via CVX during each iteration. The process repeats until the solution converges, providing an effective approximation to the optimal solution for the problem (P1). The algorithm halts when the maximum number of iterations $i_{\max}$ is reached. As the objective function is both non-increasing and bounded below with each iteration, the algorithm is guaranteed to converge to a stationary point for problem (P1), following the principles outlined in [20].

Algorithm 1 Proposed algorithm

- 1: Initialize $i = 0$ and $i_{\max}$.
 - 2: Initialize $\mathbf{f}_j^{(0)}$ and $\mathbf{v}^{(0)}$ randomly
 - 3: **while** $i < i_{\max}$ **do**
 - 4: Update $i = i + 1$.
 - 5: Update $\alpha_j^{(i)}$ and $\beta_j^{(i)}$ by using (15) for $\mathbf{f}_j^{(i-1)}$ and $\mathbf{v}^{(i-1)}$.
 - 6: Update $\mathbf{f}_j^{(i)}$ and $\mathbf{v}^{(i)}$ by solving problem (P4) for $\alpha_j^{(i)}$ and $\beta_j^{(i)}$ using CVX.
 - 7: **end while**
-

V. RESULTS AND DISCUSSIONS

In this section, we begin by outlining the simulation setup and evaluating the system's performance.

A. Simulation Setup

We consider a scenario where the BS is positioned at the origin in cartesian coordinates. The transmit and receive antennas at the BS are arranged as uniform linear arrays along the y-axis, oriented towards the positive x-axis. The system operates at a frequency of 2.4 GHz, with antenna spacing set to half the wavelength. The total transmit power of the BS is set to $P = 30$ dBm. For the channel model, we assume a line-of-sight (LOS) scenario and the variance of the received noise is given by $\sigma_t^2 = \sigma_r^2 = \sigma_u^2 = 10 \log_{10}(kTB) + N_f$ dBm where k is Boltzmann's constant, $T = 270$ K is the temperature, $B = 10$ MHz is the bandwidth, and $N_f = 7$ dB is the noise figure [16]. The sensitivity values for the tag and reader are set to -25.5 dBm and -94 dBm, respectively. The backscatter modulation efficiency of the tag is assumed to be $\eta = 0.16$ [16].

B. Simulation Results

In Fig. 2, the system's convergence behavior is evaluated for various numbers of transmit antennas. The results demonstrate that the proposed algorithm converges within 6-9 iterations across all configurations. As the number of M_t increases, the average sum-rate converges to higher values due to the combined effects of diversity gain and improved beamforming. We observe that with an increase in transmit antennas from 1 to 8, the average sum-rate increases by 236 %.

In Fig. 3, the average sum-rate is plotted against varying BS power levels. As the power increases, the average sum-rate also rises, as depicted in the graph. This positive correlation demonstrates that higher transmit power enhances the signal strength, leading to better communication performance and increased throughput. Furthermore, when the number of antennas is increased from 4 to 8, a similar trend is observed, but with a notable increase in the overall data rate. The additional antennas allow for more effective signal transmission and reception, reducing interference and enhancing the capacity

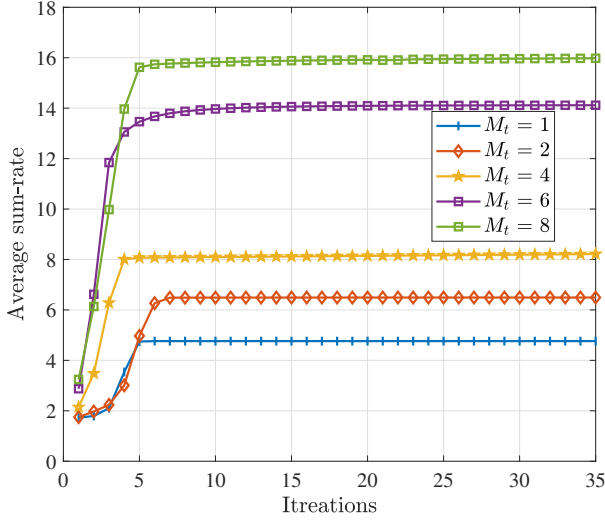


Fig. 2. Convergence of proposed algorithms.

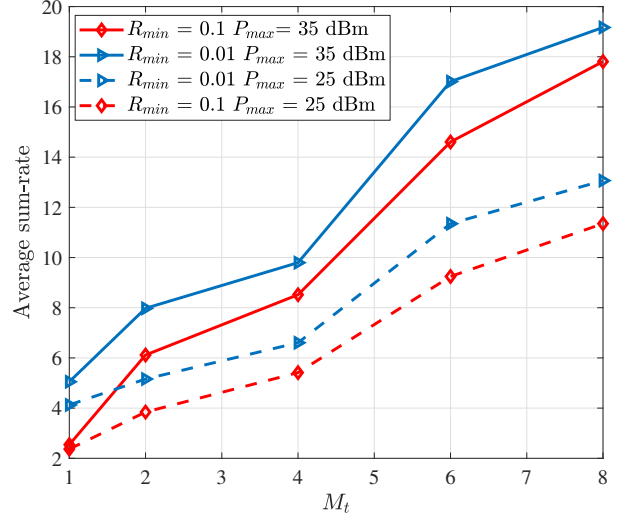


Fig. 4. Average sum-rate vs number of transmitting antenna.

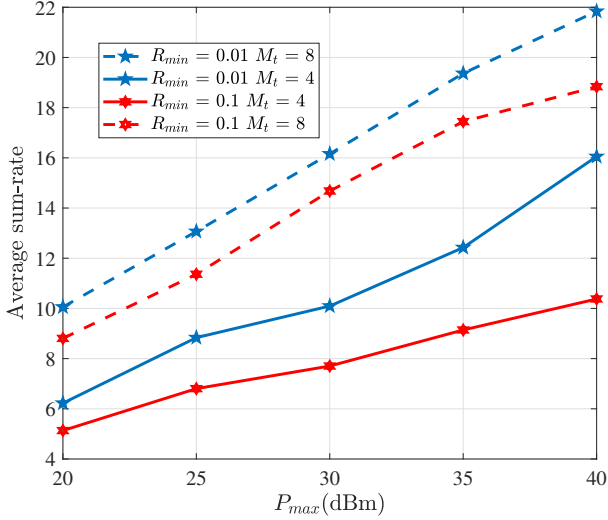


Fig. 3. Average sum-rate vs available transmit power at BS

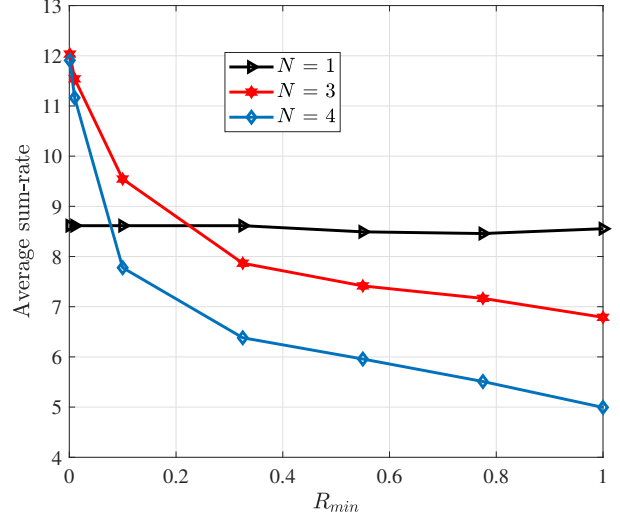


Fig. 5. Average sum-rate vs minimum user rate.

of the system. At $M_t = 4$, when power is increased from 20 dBm to 40 dBm, the system with a minimum required rate of $R_{min} = 0.01$ experiences a 167% increase, while the system with $R_{min} = 0.1$ sees only a 105% increase. This discrepancy arises because the system allocates more power to effectively meet each user's minimum rate.

Fig. 4 illustrates the dependency of the average sum-rate on the number of transmitting antennas for different power and threshold rate levels at users. The average sum-rate rises with an increase in the number of antennas due to the combined effects of diversity gain and improved beamforming. Additionally, when the BS power is increased from 25 dBm to 35 dBm, the sum-rate further improves, highlighting the combined effect of higher power and additional antennas on system

performance. At $R_{min} = 0.1$ and an increase in maximum power from 25 dBm and 35 dBm with a single antenna, the rates at both power levels are nearly identical. However, as the number of antennas increases, the gap between the two rates widens significantly. Specifically, increasing the antennas from 1 to 8 results in a 380% rate increase at 25 dBm and a 600% rate increase at 35 dBm.

Fig. 5 depicts the relation between the average sum-rate and minimum user rate (R_{min}) for the number of users. As the R_{min} requirement for users increases, the overall average sum-rate decreases. This behavior is due to the random distribution of users in the model, where the rate is influenced by the channel conditions each user experiences. Users with better channels and less interference receive higher data rates.

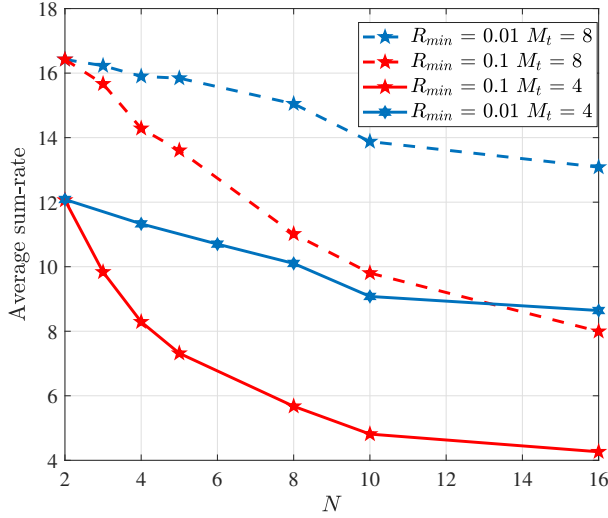


Fig. 6. Average sum-rate vs number of users.

When the minimum rate requirement increases from 0.01 to 0.1, there is a decrease in the average sum-rate by 55.2%, 41.2%, and 0.6% for $N = 4$, $N = 3$, and $N = 1$ users, respectively. This reduction occurs because the system must allocate sufficient power to meet each user's minimum rate.

In Fig. 6, the average sum-rate is plotted against the number of users. As illustrated, the average sum-rate decreases as the number of users increases, primarily due to interference among them. This interference negatively impacts the overall signal quality, leading to lower data rates for each user. Furthermore, It is observed that as the number of users increases, the user rate decreases more slowly with $R_{\min} = 0.01$ compared to $R_{\min} = 0.1$. In the scenario with $M_t = 4$, both rates initially start at similar levels. However, with $R_{\min} = 0.01$, the rate declines by only 28.5% from the starting point, while with $R_{\min} = 0.1$, the rate decreases by 64.5%. This occurs because allocating additional power to meet these minimum rate requirements restricts the amount of power available for enhancing the overall sum-rate.

VI. CONCLUSION

This work investigates the beamforming design for a multi-user ISAC system incorporating a backscattering RFID tag. Specifically, a beamforming optimization problem is formulated to maximize the average sum-rate while satisfying tag detection and power constraints. To tackle the non-convex nature of the problem, we employed the Lagrangian dual transform technique and AO techniques. Through numerical simulations, we validate the effectiveness of our proposed algorithm and examine the influence of several critical parameters on system performance. These parameters include the number of transmitting antennas, the base station's available transmit power, the minimum rate requirement for users, and the total number of users.

REFERENCES

- [1] X. Lu, D. Niyato, H. Jiang, D. I. Kim, Y. Xiao, and Z. Han, "Ambient backscatter assisted wireless powered communications," *IEEE Wirel. Commun.*, vol. 25, no. 2, pp. 170–177, Apr. 2018.
- [2] T. Jiang, Y. Zhang, W. Ma, M. Peng, Y. Peng, M. Feng, and G. Liu, "Backscatter communication meets practical battery-free internet of things: A survey and outlook," *IEEE Commun. Surv. Tutor.*, vol. 25, no. 3, pp. 2021–2051, May 2023.
- [3] S. Mondal, D. Bepari, A. Chandra, K. Singh, C.-P. Li, and Z. Ding, "A comprehensive survey on noma-based backscatter communication for iot applications," *IEEE Internet of Things Journal*, pp. 1–1, 2025.
- [4] J. Wang, N. Varshney, C. Gentile, S. Blandino, J. Chuang, and N. Golmie, "Integrated sensing and communication: Enabling techniques, applications, tools and data sets, standardization, and future directions," *IEEE Internet Things J.*, vol. 9, no. 23, pp. 23 416–23 440, Dec 2022.
- [5] F. Liu, Y. Cui, C. Masouros, J. Xu, T. X. Han, Y. C. Eldar, and S. Buzzi, "Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1728–1767, Jun 2022.
- [6] G. Yang, R. Dai, and Y.-C. Liang, "Energy-efficient uav backscatter communication with joint trajectory design and resource optimization," *IEEE Trans. Wirel. Commun.*, vol. 20, no. 2, pp. 926–941, Feb 2021.
- [7] J. Zou, S. Sun, C. Masouros, Y. Cui, Y.-F. Liu, and D. W. K. Ng, "Energy-efficient beamforming design for integrated sensing and communications systems," *IEEE Trans. Wirel. Commun.*, vol. 72, no. 6, pp. 3766–3782, Jun 2024.
- [8] A. Raviteja, K. Singh, K. Agrawal, Z. Ding, and C.-P. Li, "Fd-noma enabled multiuser transmission with backscatter communication," *IEEE Wirel. Commun.*, vol. 12, no. 4, pp. 723–727, Apr. 2023.
- [9] Z. Wang, Y. Liu, X. Mu, Z. Ding, and O. A. Dobre, "Noma empowered integrated sensing and communication," *IEEE Wirel. Commun. Lett.*, vol. 26, no. 3, pp. 677–681, Mar 2022.
- [10] Z. He, W. Xu, H. Shen, D. W. K. Ng, Y. C. Eldar, and X. You, "Full-duplex communication for ISAC: Joint beamforming and power optimization," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 9, pp. 2920–2936, Sep. 2023.
- [11] I. Mbaye, S. Al-Rubaye, C. Conrad, and G. Inalhan, "Integrated sensing and new radio communications for air vehicle positioning," *Vehicles*, vol. 6, no. 3, pp. 1665–1689, Jul. 2024. [Online]. Available: <https://www.mdpi.com/2624-8921/6/3/80>
- [12] F. Nassar, K. Singh, S. Prakriya, R. Allu, C. Pan, and C.-P. Li, "Robust beamformer design for backscatter-enabled ris-assisted noma isac," in *Proc. IEEE Int. Conf. Commun. Workshops*, pp. 1–2, Jun 2024, pp. 608–613.
- [13] P. Saikia, A. Jee, K. Singh, T. A. Tsiftsis, and A.-A. A. Boulogeorgos, "Hybrid-ris empowered uav-aided isac systems," in *Proc. IEEE 100th Veh. Technol. Conf. (VTC-Fall)*, Oct 2024, pp. 1–5.
- [14] K. Zhao, M. Zhu, B. Xiao, X. Yang, C. Gong, and J. Wu, "Joint RFID and UWB technologies in intelligent warehousing management system," *IEEE Internet Things J.*, vol. 7, no. 12, pp. 11 640–11 655, Dec. 2020.
- [15] D. Galappaththige, C. Tellambura, and A. Maaref, "Integrated sensing and backscatter communication," *IEEE Wirel. Commun. Lett.*, vol. 12, no. 12, pp. 2043–2047, Dec 2023.
- [16] H. Luo, U. Demirhan, and A. Alkhateeb, "Isac with backscattering rfid tags: Joint beamforming design," in *ICC 2024 - IEEE Int. Conf. Commun.*, Jun 2024, pp. 921–925.
- [17] A. Bletsas, P. N. Alevizos, and G. Vougioukas, "The art of signal processing in backscatter radio for μ w (or less) internet of things: Intelligent signal processing and backscatter radio enabling batteryless connectivity," *IEEE Signal Process. Mag.*, vol. 35, no. 5, pp. 28–40, Sep. 2018.
- [18] K. Shen and W. Yu, "Fractional programming for communication systems—part i: Power control and beamforming," *IEEE Trans. Signal Process.*, vol. 66, no. 10, pp. 2616–2630, May 2018.
- [19] Z. Sun, S. Xu, Q. Xue, S. Han, and C. Li, "Weighted sum rate maximization for RIS backscatter aided NOMA networks," *IEEE Trans. Commun.*, pp. 1–1, Jul. 2024.
- [20] S. K. Joshi, P. C. Weeraddana, M. Codreanu, and M. Latva-aho, "Weighted sum-rate maximization for MISO downlink cellular networks via branch and bound," *IEEE Trans. Signal Process.*, vol. 60, no. 4, pp. 2090–2095, Apr. 2012.



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K, Rojith; Allu, Raviteja; Singh, Keshav; Al-Rubaye, Saba; Li, Chih-Peng

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