IRS-Assisted Integrated Localization and Communication for Multiuser mmWave Massive MIMO Systems

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***Abstract*—This paper introduces an intelligent reflecting surface (IRS)-aided integrated sensing and communications (ISAC) framework for joint signal demodulation and localization in multiuser millimeter-wave (mmWave) massive multiple-input multiple-output (MIMO) systems. A time block is divided into uplink estimation stage and downlink transmission stage. In the uplink estimation stage, a joint active beamforming at the BS and passive beamforming at the IRSs are designed based on estimated angle of arrival (AoA) information. In the downlink transmission stage, a joint signal demodulation and location sensing algorithm at the users is proposed by exploiting the statistical properties of the received signals. Numerical results demonstrate that the proposed ISAC framework can achieve centimeter-level localization accuracy while maintaining communication performance compared to communication-only systems with perfect channel state information (CSI).**

***Index Terms*—Intelligent reflecting surface (IRS), integrated sensing and communication (ISAC), beamforming, localization.**

I. Introduction

The next-generation mobile communication systems are poised to support a wide range of advanced applications and services, including machine-type communication, autonomous driving, and augmented reality [1]. These emerging services and applications necessitate high-data rate transmission and high-accurate sensing, imposing stringent demands on signal frequencies and rendering scarce spectrum even more valuable. Recently, advancements in millimeter-wave (mmWave) and massive multiple-input multiple-output (MIMO) technologies have paved the way for future wireless systems to achieve high-resolutions in both time and angular domains. This opens up possibilities for achieving high-precision sensing by exploiting communication signals. Consequently, the research on integrated sensing and communication (ISAC) has rapidly gained attention [2]-[3].

In parallel with ISAC technology, there has been significant research interest from both academia and industry in intelligent reflecting surfaces (IRSs). IRSs can leverage the scattered signal in wireless communication environments by utilizing the reflecting elements that have the ability to independently adjust the phase or amplitude of the incident signal [4]. In particular, IRSs provide a virtual line-of-sight (V-LoS) path between the base station (BS) and the users enhancing ISAC system performance [5]-[8]. Specifically, in the work [5], an investigation was conducted on an IRS-assisted ISAC system with a joint active and passive beamforming scheme. The findings revealed that the integration of IRS and ISAC can lead to substantial improvements compared to the systems without IRS. Another work [6] proposed a beamforming scheme for a dual-functional MIMO radar-communication system, where the BS enabled simultaneous radar sensing and multi-user communications. Simulation results showed that the communication and sensing performance was comparable to the communication-only and sensing-only systems that were independently designed. To investigate the performance trade-offs between communication and sensing in ISAC systems, work [7] utilized the Pareto boundary of the achievable Cramer-Rao bounded rate (C-R) region as a metric and provided valuable insights into uncovering the fundamental limits of MIMO ISAC systems.

However, previous research assumes perfect channel state information (CSI). Moreover, the adopted performance metrics are limited to either the Cramer-Rao bound (CRB) or beampattern gain. These metrics are unable to directly capture crucial information regarding the target, such as velocity, direction, acceleration, and location. In spite of recent works [8] that consider user location accuracy as a specific performance metric, they overlook the significant impact of non-line-of-sight (NLoS) paths, multiuser interference as well as data transmission. To make it more practical, in this work, imperfect CSI, multipath and multiuser interference are taken into consideration. Furthermore, concurrent localization and signal demodulation are incorporated. The main contributions are summarized as follows:

1) An integrated sensing and communication framework is proposed for mmWave massive MIMO systems.
2) We propose a joint active beamforming at the BS and passive beamforming at the IRSs scheme based on estimated AoA information.
3) We present a joint signal demodulation and location sensing algorithm at the users by exploiting the statisti-

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cal properties of the received signals.

The rest of this paper is outlined as follows. In Section II, we introduce the IRS-assisted ISAC system. Then we propose the beamforming design scheme and the integrated signal demodulation and user localization algorithm in Sections III and IV, respectively. Numerical results and discussions are provided in Section V, and Section VI concludes the paper.

II. System Model

We investigate an IRS-assisted ISAC multiuser mmWave massive MIMO system, as depicted in Fig. 1, comprising one BS and K users. The BS is equipped with a uniform linear array (ULA) of N_B elements along the y-axis, and each user has an $N_U = N_{ux} \times N_{uy}$ uniform rectangular array (URA) lying on the x-y plane. The direct link between the BS and users is obstructed, similar to the scenario in [8]. To address this issue, a semi-passive IRS is deployed to establish VLoS reflection paths, facilitating user localization and communication. The semi-passive IRS consists of two sub-arrays, each utilizing a URA of $M = M_y \times M_z$ elements on the y-z plane. The channels between the users and the IRS, as well as the channels between the IRS and the BS, are modelled as quasi-static block-fading channels [5]. Specifically, the channels keep unchanged in one time block, but independently fade over time blocks. As shown in Fig. 2, a time block is partitioned into two stages, one for uplink estimation, the other for downlink transmission. In the following, we introduce the transmission protocol for integrated location and communication in detail.

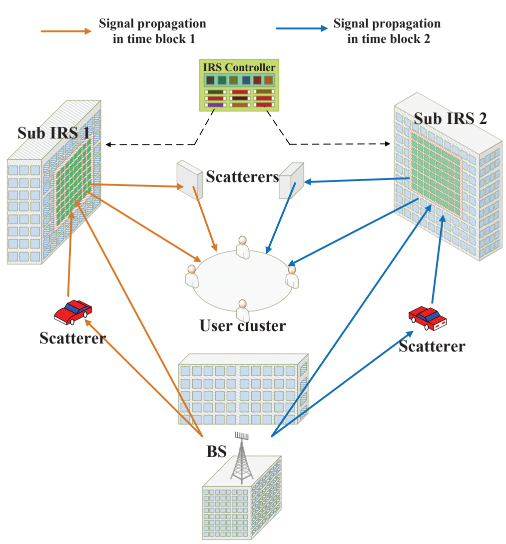

Fig. 1: System model: An IRS-assisted ISAC system.

A. Uplink Estimation Stage

In the uplink stage, the two sub-IRSs are activated. The K users transmit the orthogonal pilot sequence of length $\tau_{0,p}$ time slots simultaneously over uplink channels for AoA estimation. Let the pilot sequence of the k-th user be $\mathbf{s}_{\mathrm{u},k}^{\mathrm{p}} = [s_{\mathrm{u},k}(1), \cdots, s_{\mathrm{u},k}(\tau_{0,\mathrm{p}})]$, therefore, the received signal at the j-th sub-IRSs can be expressed as

$$\mathbf{y}_{\mathrm{u},j}(t) = \sum_{k=1}^{K} \sqrt{P_{\mathrm{u}}} \mathbf{H}_{\mathrm{U2I},j,k} \mathbf{w}_{\mathrm{u},k} s_{\mathrm{u},k}(t) + \mathbf{n}_{\mathrm{u}}(t), j = 1, 2, \tag{1}$$

where P_{u} denotes the transmit power at users, and $\mathbf{w}_{\mathrm{u},k} \in \mathbb{C}^{N_U \times 1}$, satisfying $\|\mathbf{w}_{\mathrm{u},k}\|^2 = 1$, is the transmit beamforming vector, which is randomly constructed due to unknown CSI.

$$\mathbf{H}_{\mathrm{U2I},j,k} = \sum_{l=1}^{L_{\mathrm{U2I},j,k}} \alpha_{\mathrm{U2I},j,k}^{l} \mathbf{a}_{\mathrm{I}}\left(u_{\mathrm{r,I},j,k}^{l}, v_{\mathrm{r,I},j,k}^{l}\right) \mathbf{a}_{\mathrm{U}}^{\mathrm{H}}\left(u_{\mathrm{t,U},j,k}^{l}, v_{\mathrm{t,U},j,k}^{l}\right), \tag{2}$$

denotes the the mmWave channel from the k-th user to the j-th sub-IRS, where $L_{\mathrm{U2I},j,k}$ is the number of paths between the k-th user and the j-th sub-IRS and $\alpha_{\mathrm{U2I},j,k}^{l}$ represents the complex gain for the l-th path, consisting of path loss. $\mathbf{a}_{\mathrm{I}}\left(u_{\mathrm{r,I},j,k}^{l}, v_{\mathrm{r,I},j,k}^{l}\right)$ and $\mathbf{a}_{\mathrm{U}}^{\mathrm{H}}\left(u_{\mathrm{t,U},j,k}^{l}, v_{\mathrm{t,U},j,k}^{l}\right)$ are the array response vectors at the k-th user and the sub-IRS, where the superscript "H" represents the Hermitian transpose. The effective angle of arrivals (AoAs) at the j-th sub-IRS and angles of departure (AoDs) from the k-th user are respectively denoted as $\{u_{\mathrm{r,I},j,k}^{l}, v_{\mathrm{r,I},j,k}^{l}\}$ and $\{u_{\mathrm{t,U},j,k}^{l}, v_{\mathrm{t,U},j,k}^{l}\}$. $\mathbf{n}_{\mathrm{u}} \in \mathbb{C}^{M \times 1}$ is the additive white Gaussian noise (AWGN), whose elements follow the complex Gaussian distribution with zero mean and variance σ_{u}^2, i.e., $\mathcal{CN}\left(0, \sigma_{\mathrm{u}}^2\right)$.

Based on the received pilot sequences, the IRS can estimate the AoAs by some means. In this paper, we utilize the estimation method that we proposed in [8] to obtain the AoA information.

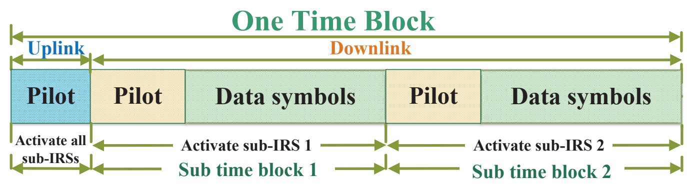

Fig. 2: Transmission protocol.

B. Downlink Transmission Stage

The downlink stage includes two sub-time-blocks, with T_1 and T_2 time slots, respectively. In the j-th sub-time-block, the BS transmits symbols $\mathbf{s}_{\mathrm{d},j,k} = [\mathbf{s}_{\mathrm{d},j,k}^{\mathrm{p}}, \mathbf{s}_{\mathrm{d},j,k}^{\mathrm{q}}]$ to the k-th user, including orthogonal pilot symbols using τ_1 time slots, i.e., $\mathbf{s}_{\mathrm{d},j,k}^{\mathrm{p}} = [s_{\mathrm{d},j,k}(1), \cdots, s_{\mathrm{d},j,k}(\tau_1)]$, and data symbols, i.e., $\mathbf{s}_{\mathrm{d},j,k}^{\mathrm{q}} = [s_{\mathrm{d},j,k}(\tau_1+1), \cdots, s_{\mathrm{d},j,k}(T_j)]$. The j-th sub-IRS operates in reflecting mode, while the other is switched off. Without loss of generality, we focus on the j-th sub-time-block, and the received signal at the k-th user is given by

$$\mathbf{y}_{\mathrm{d},j,k}(t) = \mathbf{H}_{\mathrm{I2U},j,k} \boldsymbol{\Theta}_j \mathbf{H}_{\mathrm{B2I},j} \sum_{i=1}^{K} \mathbf{w}_{\mathrm{d},j,i} s_{\mathrm{d},j,i}(t) + \mathbf{n}_{\mathrm{d}}(t), \tag{3}$$

where $\mathbf{w}_{\mathrm{d},j,i}$ is the beamforming vector at the BS with power constraint $\sum_{k=1}^{K} \|\mathbf{w}_{\mathrm{d},j,i}\|^2 \leq P$, which is designed based on AoA information obtained at the uplink estimation stage.

$$\mathbf{H}_{\mathrm{I2U},j,k}=\sum_{l=1}^{L_{\mathrm{I2U},j,k}} \alpha_{\mathrm{I2U},j,k}^{l}\mathbf{a}_{\mathrm{U}}\left(u_{\mathrm{r,U},j,k}^{l}, v_{\mathrm{r,U},j,k}^{l}\right)\mathbf{a}_{\mathrm{I}}^{\mathrm{H}}\left(u_{\mathrm{t,I},j,k}^{l}, v_{\mathrm{t,I},j,k}^{l}\right), \tag{4}$$

and

$$\mathbf{H}_{\mathrm{B2I},j} = \sum_{l=1}^{L_{\mathrm{B2I},j}} \alpha_{\mathrm{B2I},j}^{l}\mathbf{a}_{\mathrm{I}}\left(u_{\mathrm{r,I},j}^{l}, v_{\mathrm{r,I},j}^{l}\right)\mathbf{a}_{\mathrm{B}}^{\mathrm{H}}\left(u_{\mathrm{t,B},j}^{l}\right), \tag{5}$$

denote the mmWave channels from the j-th sub-IRS to the k-th user and from the BS to the j-th sub-IRS, respectively, where $L_{\mathrm{B2I},j}$ and $L_{\mathrm{I2U},j,k}$ are the number of paths, and $\alpha_{\mathrm{B2I},j}^{l}$ and $\alpha_{\mathrm{I2U},j,k}^{l}$ represents the complex gain. $\mathbf{a}_{\mathrm{B}}^{\mathrm{H}}\left(u_{\mathrm{t,B},j}^{l}\right)$, $\mathbf{a}_{\mathrm{U}}\left(u_{\mathrm{r,U},j,k}^{l}, v_{\mathrm{r,U},j,k}^{l}\right)$ and $\mathbf{a}_{\mathrm{I}}^{\mathrm{H}}\left(u_{\mathrm{t,I},j,k}^{l}, v_{\mathrm{t,I},j,k}^{l}\right)$ are the array response vector at the BS, the user, and the IRS, respectively, which are given as $\mathbf{a}_{\mathrm{B}}(u) = \left[1, \cdots, e^{j(n-1)u}, \cdots, e^{j(N_B-1)u}\right]^T$, and $\mathbf{a}(u,v)=\mathbf{a}(u)\otimes\mathbf{a}(v)$. The phase shift matrix of the j-th sub-IRS is defined as $\mathbf{\Theta}_j = \mathrm{diag}\left(\boldsymbol{\theta}_j\right)$, with the phase shift beam being $\boldsymbol{\theta}_j = \left[e^{\mathrm{j}\theta_{1,j}}, \cdots, e^{\mathrm{j}\theta_{M,j}}\right]^T \in \mathbb{C}^{M\times 1}$, where $\theta_{m,j} \in [0, 2\pi], \forall m = [1, \cdots, M]$ denotes the phase shift of the m-th element of the j-th sub-IRS, which is also designed based on the estimated AoA information. $\mathbf{n}_{\mathrm{d}}$ denotes the noise, whose elements follow the complex Gaussian distribution with $\mathcal{CN}\left(0, \sigma_{\mathrm{d}}^2\right)$.

With the received signals during the two sub-time-blocks, the users conduct location sensing and signal demodulation. In what follows, we first design the beamforming scheme at the BS and IRSs, and then provide joint location sensing and signal demodulation algorithm at the users.

III. Beamforming Design Scheme

In this section, we introduce the beamforming design scheme to reduce inter-user interference and enhance both communication and localization performance by exploiting the AoA information, i.e., $\{u_{\mathrm{r,I},j,k}^{l}, v_{\mathrm{r,I},j,k}^{l}\}$, estimated in the uplink estimation stage[1].

Inspired by radar communication systems that design the beamforming scheme without prior knowledge about the target location by maximizing transmit beampattern or minimizing the cross-correlation at various directions [12]-[13], we propose a beamforming design scheme that utilizes partial angle information. Moreover, since the LoS and NLoS paths between the sub-IRSs and the users cannot be distinguished, it is important to take beampattern among all the effective AoAs into consideration for fairness. Therefore, we aim at minimizing the maximum weighted auto-correlation and cross-correlation beampattern gain among all the users for fairness. Without loss of generality, we focus on the j-th sub-time-block, and the optimization problem is formulated as

$$\min_{\mathbf{\Theta}_j, \mathbf{w}_{\mathrm{d},j,k}} \max_{k} \quad \eta f_{1,j,k} + \sum_{i=2}^{4} f_{i,j,k}, \tag{6a}$$

$$\text{s.t.} \quad \sum_{k=1}^{K} \left\|\mathbf{w}_{\mathrm{d},j,k}\right\|^2 \leq P, \tag{6b}$$

$$\left|\mathbf{\Theta}_j\right| = \mathbf{I}, \tag{6c}$$

where η denotes the weighting factor, and the desired transmit beampattern gain for the k-th user at directions $\{\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\}$ is denoted as

$$f_{1,j,k} = \sum_{L_{\mathrm{I2U},j,k}}^{L} \left|\mathbf{a}_{\mathrm{I}}^{\mathrm{H}}\left(\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\right)\mathbf{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\mathbf{w}_{d,j,k}\right|^2. \tag{7}$$

Besides,

$$\begin{aligned} f_{2,j,k} = &\tfrac{2}{L_{\mathrm{I2U},j,k}{}^2 - L_{\mathrm{I2U},j,k}} \textstyle\sum_{l=1}^{L_{\mathrm{I2U},j,k}-1} \sum_{p=l+1}^{L_{\mathrm{I2U},j,k}} \\ &\left|\mathbf{a}_I^H\left(\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\right)\mathbf{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\mathbf{w}_{\mathrm{d},j,k}\right. \\ &\left.\mathbf{w}_{\mathrm{d},j,k}^H\mathbf{H}_{\mathrm{B2I},j}^H\mathbf{\Theta}_j^H\mathbf{a}_I\left(\hat{u}_{\mathrm{t,I},j,k}^{p}, \hat{v}_{\mathrm{t,I},j,k}^{p}\right)\right|^2, \end{aligned} \tag{8}$$

denotes the cross-correlation for the k-th user between the directions $\{\hat{u}_{\mathrm{t,I},j,k}^{p}, \hat{v}_{\mathrm{t,I},j,k}^{p}\}$ and $\{\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\}$.

$$\begin{aligned} f_{3,j,k} = &\tfrac{2}{L_{\mathrm{I2U},j,k}{}^2 - L_{\mathrm{I2U},j,k}} \textstyle\sum_{l=1}^{L_{\mathrm{I2U},j,k}-1} \sum_{p=l+1}^{L_{\mathrm{I2U},j,k}} \\ &\left|\mathbf{a}_I^H\left(\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\right)\mathbf{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\textstyle\sum_{i\neq k}^{K}\mathbf{w}_{\mathrm{d},j,i}\right. \\ &\left.\mathbf{w}_{\mathrm{d},j,i}^H\mathbf{H}_{\mathrm{B2I},j}^H\mathbf{\Theta}_j^H\mathbf{a}_I\left(\hat{u}_{\mathrm{t,I},j,k}^{p}, \hat{v}_{\mathrm{t,I},j,k}^{p}\right)\right|^2, \end{aligned} \tag{9}$$

signifies the cross-correlation, corresponding to the inter-user-interference between the directions $\{\hat{u}_{\mathrm{t,I},j,k}^{p}, \hat{v}_{\mathrm{t,I},j,k}^{p}\}$ and $\{\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\}$, and

$$\begin{aligned} f_{4,j,k} = &\tfrac{1}{L_{\mathrm{I2U},j,k}} \textstyle\sum_{L_{\mathrm{I2U},j,k}}^{L} \left|\mathbf{a}_{\mathrm{I}}^{\mathrm{H}}\left(\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\right)\mathbf{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\right. \\ &\left.\textstyle\sum_{i\neq k}^{K}\mathbf{w}_{d,j,i}\mathbf{w}_{d,j,i}^H\mathbf{H}_{\mathrm{B2I},j}^H\mathbf{\Theta}_j^H\mathbf{a}_{\mathrm{I}}\left(\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\right)\right|^2, \end{aligned} \tag{10}$$

denotes the beampattern gain, corresponding to the inter-user-interference at directions $\{\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\}$.

The above optimization problem is highly nonconvex with coupled variables, hence the optimal solution is difficult to obtain. However, by using alternating optimization methods [4], the active beamforming at the BS and the passive beamforming at the j-th sub-IRS can be properly optimized as follows:

1) Optimize $\mathbf{w}_{\mathrm{d},j,k}$ with given $\mathbf{\Theta}_j$: With given $\mathbf{\Theta}_j$, the above problem can be rewritten as

$$\text{(P1-2):} \quad \min_{\mathbf{W}_{\mathrm{d},j,k}} \max_{k} \quad \eta f_{1,j,k}^{\mathrm{w}} + \sum_{i=2}^{4} f_{i,j,k}^{\mathrm{w}}, \tag{11a}$$

$$\text{s.t.} \quad \mathrm{rank}(\mathbf{W}_{\mathrm{d},j,k}) = 1, \tag{11b}$$

$$(6b), \tag{11c}$$

where $\mathbf{W}_{\mathrm{d},j,k} = \mathbf{w}_{\mathrm{d},j,k}\mathbf{w}_{\mathrm{d},j,k}^H$, and

$$\begin{aligned} f_{1,j,k}^{\mathrm{w}} = &\textstyle\sum_{L_{\mathrm{I2U},j,k}}^{L} \mathbf{a}_{\mathrm{I}}^{\mathrm{H}}\left(\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\right)\mathbf{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\mathbf{W}_{d,j,k} \\ &\mathbf{H}_{\mathrm{B2I},j}\mathbf{\Theta}_j\mathbf{a}_{\mathrm{I}}\left(\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\right), \end{aligned} \tag{12}$$

$$\begin{aligned} f_{2,j,k}^{\mathrm{w}} = &\tfrac{2}{L_{\mathrm{I2U},j,k}{}^2 - L_{\mathrm{I2U},j,k}} \textstyle\sum_{l=1}^{L_{\mathrm{I2U},j,k}-1} \sum_{p=l+1}^{L_{\mathrm{I2U},j,k}} \\ &\left|\mathbf{a}_I^H\left(\hat{u}_{\mathrm{t,I},j,k}^{l}, \hat{v}_{\mathrm{t,I},j,k}^{l}\right)\mathbf{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\mathbf{W}_{\mathrm{d},j,k}\right. \\ &\left.\mathbf{H}_{\mathrm{B2I},j}^H\mathbf{\Theta}_j^H\mathbf{a}_I\left(\hat{u}_{\mathrm{t,I},j,k}^{p}, \hat{v}_{\mathrm{t,I},j,k}^{p}\right)\right|^2, \end{aligned} \tag{13}$$

[1]According to the reciprocity of the channels, i.e. $\mathbf{H}_{\mathrm{U2I},j,k} = \mathbf{H}_{\mathrm{I2U},j,k}^T$, the geometric relationship between the AoAs at the sub-IRSs in uplink estimation stage and the AoDs at the sub-IRSs in downlink transmission stage is given as follows $u_{\mathrm{r,I},j,k}^{p} = -u_{\mathrm{t,I},j,k}^{p}$ and $v_{\mathrm{r,I},j,k}^{p} = -v_{\mathrm{t,I},j,k}^{p}$.

$$f_{3,j,k}^{\mathrm{w}}=\frac{2}{{L_{\mathrm{I2U},j,k}}^2-L_{\mathrm{I2U},j,k}}\sum_{l=1}^{L_{\mathrm{I2U},j,k}-1}\sum_{p=l+1}^{L_{\mathrm{I2U},j,k}} \left|\mathbf{a}_I^H\left(\hat{u}_{\mathrm{t,I},j,k}^l,\hat{v}_{\mathrm{t,I},j,k}^l\right)\mathbf{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\sum_{i\neq k}^{K}\mathbf{W}_{\mathrm{d},j,i} \mathbf{H}_{\mathrm{B2I},j}^H\mathbf{\Theta}_j^H\mathbf{a}_I\left(\hat{u}_{\mathrm{t,I},j,k}^p,\hat{v}_{\mathrm{t,I},j,k}^p\right)\right|^2, \tag{14}$$

and

$$f_{4,j,k}^{\mathrm{w}}=\frac{1}{L_{\mathrm{I2U},j,k}}\sum_{L_{\mathrm{I2U},j,k}}^{L} \left|\mathbf{a}_{\mathrm{I}}^{\mathrm{H}}\left(\hat{u}_{\mathrm{t,I},j,k}^l,\hat{v}_{\mathrm{t,I},j,k}^l\right)\mathbf{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\sum_{i\neq k}^{K}\mathbf{W}_{d,j,i} \mathbf{H}_{\mathrm{B2I},j}^H\mathbf{\Theta}_j^H\mathbf{a}_{\mathrm{I}}\left(\hat{u}_{\mathrm{t,I},j,k}^l,\hat{v}_{\mathrm{t,I},j,k}^l\right)\right|^2. \tag{15}$$

The optimization problem (P2-1) is still non-convex because of the rank-one constraints. However, by using the semi-definite relaxation (SDR) method, the above problem can be converted to semi-definite quadratic programming (SQP), which can be solved by existing toolboxes such as CVX, as that in [12].

2) Optimize $\mathbf{\Theta}_j$ with given $\mathbf{w}_{\mathrm{d},j,k}$: Similarly, with given $\mathbf{w}_{\mathrm{d},j,k}$, the above problem can be rewritten as

$$\text{(P1-3):}\quad \min_{\mathbf{V}_j}\max_{k}\quad \eta f_{1,j,k}^{\mathrm{v}}+\sum_{i=2}^{4}f_{i,j,k}^{\mathrm{v}}, \tag{16a}$$

$$\text{s.t.}\quad \mathrm{rank}(\mathbf{V}_j)=1, \tag{16b}$$

$$(6c), \tag{16c}$$

where $\mathbf{V}_j=\mathbf{\Theta}_j\mathbf{\Theta}_j^H$, and

$$f_{1,j,k}^{\mathrm{v}}=\sum_{L_{\mathrm{I2U},j,k}}^{L}\mathbf{w}_{d,j,k}^T\mathbf{H}_{\mathrm{B2I},j}^T\mathrm{diag}\left(\mathbf{a}_{\mathrm{I}}^*\left(\hat{u}_{\mathrm{t,I},j,k}^l,\hat{v}_{\mathrm{t,I},j,k}^l\right)\right)\mathbf{V}_j \mathrm{diag}\left(\mathbf{a}_{\mathrm{I}}^{\mathrm{T}}\left(\hat{u}_{\mathrm{t,I},j,k}^l,\hat{v}_{\mathrm{t,I},j,k}^l\right)\right)\mathbf{H}_{\mathrm{B2I},j}^*\mathbf{w}_{d,j,k}^*, \tag{17}$$

$$f_{2,j,k}^{\mathrm{v}}=\frac{2}{{L_{\mathrm{I2U},j,k}}^2-L_{\mathrm{I2U},j,k}}\sum_{l=1}^{L_{\mathrm{I2U},j,k}-1}\sum_{p=l+1}^{L_{\mathrm{I2U},j,k}} \left|\mathbf{w}_{d,j,k}^T\mathbf{H}_{\mathrm{B2I},j}^T\mathrm{diag}\left(\mathbf{a}_{\mathrm{I}}^*\left(\hat{u}_{\mathrm{t,I},j,k}^p,\hat{v}_{\mathrm{t,I},j,k}^p\right)\right)\mathbf{V}_j \mathrm{diag}\left(\mathbf{a}_{\mathrm{I}}^{\mathrm{T}}\left(\hat{u}_{\mathrm{t,I},j,k}^l,\hat{v}_{\mathrm{t,I},j,k}^l\right)\right)\mathbf{H}_{\mathrm{B2I},j}^*\mathbf{w}_{d,j,k}^*\right|^2, \tag{18}$$

$$f_{3,j,k}^{\mathrm{v}}=\frac{2}{{L_{\mathrm{I2U},j,k}}^2-L_{\mathrm{I2U},j,k}}\sum_{l=1}^{L_{\mathrm{I2U},j,k}-1}\sum_{p=l+1}^{L_{\mathrm{I2U},j,k}} \left|\sum_{i\neq k}^{K}\mathbf{w}_{d,j,i}^T\mathbf{H}_{\mathrm{B2I},j}^T\mathrm{diag}\left(\mathbf{a}_{\mathrm{I}}^*\left(\hat{u}_{\mathrm{t,I},j,k}^p,\hat{v}_{\mathrm{t,I},j,k}^p\right)\right)\mathbf{V}_j \mathrm{diag}\left(\mathbf{a}_{\mathrm{I}}^{\mathrm{T}}\left(\hat{u}_{\mathrm{t,I},j,k}^l,\hat{v}_{\mathrm{t,I},j,k}^l\right)\right)\mathbf{H}_{\mathrm{B2I},j}^*\mathbf{w}_{d,j,i}^*\right|^2, \tag{19}$$

and

$$f_{4,j,k}^{\mathrm{v}}=\frac{1}{L_{\mathrm{I2U},j,k}}\sum_{L_{\mathrm{I2U},j,k}}^{L} \left|\sum_{i\neq k}^{K}\mathbf{w}_{d,j,i}^T\mathbf{H}_{\mathrm{B2I},j}^T\mathrm{diag}\left(\mathbf{a}_{\mathrm{I}}^*\left(\hat{u}_{\mathrm{t,I},j,k}^l,\hat{v}_{\mathrm{t,I},j,k}^l\right)\right)\mathbf{V}_j \mathrm{diag}\left(\mathbf{a}_{\mathrm{I}}^{\mathrm{T}}\left(\hat{u}_{\mathrm{t,I},j,k}^l,\hat{v}_{\mathrm{t,I},j,k}^l\right)\right)\mathbf{H}_{\mathrm{B2I},j}^*\mathbf{w}_{d,j,i}^*\right|^2. \tag{20}$$

Similarly, the above problem can be efficiently solved as SQP, and the corresponding rank-one solution can be obtained by the Gaussian Randomization method [4]. Specifically, let $\mathbf{V}_j^*$ denote the non-rank-one solution, and suppose that the eigenvalue decomposition of $\mathbf{V}_j^*$ is $\mathbf{U\Sigma U}^H$. Then, we set $\tilde{\mathbf{v}}=\mathbf{U\Sigma t}$, where $\mathbf{t}\sim\mathcal{CN}(0,\mathbf{I})$. Ultimately, we can construct a feasible solution $[\mathbf{v}^*]_n=\frac{[\tilde{\mathbf{v}}^*]_n}{\left|[\tilde{\mathbf{v}}^*]_n\right|}$

By solving the two optimization problems alternately, the beamforming scheme is guaranteed to converge [12]. Moreover, the complexity is $\mathcal{O}\left\{I\left(KN_B^{3.5}+M^{3.5}\right)\right\}$ where I represents the maximum number of required iterations.

IV. Joint Demodulation and Localization

In this section, simultaneous signal demodulation and localization are achieved by exploiting the statistical properties of the received signals at the users.

We first rewrite the received signals at the k-th user in a more compact form. Define $\mathbf{A}_{0,j,k}^{\mathrm{d}}=[\mathbf{H}_{\mathrm{I2U},j,k}\mathbf{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\mathbf{w}_{\mathrm{d},j,1},\cdots,\mathbf{H}_{\mathrm{I2U},j,k}\mathbf{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\mathbf{w}_{\mathrm{d},j,K}]\in C^{N_U\times K}$, $\mathbf{S}_{\mathrm{d},j}=\left[\mathbf{s}_{\mathrm{d},j,1}^T,\cdots,\mathbf{s}_{\mathrm{d},j,K}^T\right]^T\in\mathbb{C}^{K\times T_j}$, $\mathbf{Y}_{\mathrm{d},j,k}=[\mathbf{y}_{\mathrm{d},j,k}(1),\cdots,\mathbf{y}_{\mathrm{d},j,k}(T_j)]$, and $\mathbf{N}_{\mathrm{d}}=[\mathbf{n}_{\mathrm{d}}(1),\cdots,\mathbf{n}_{\mathrm{d}}(T_j)]\in\mathbb{C}^{N_U\times T_j}$. Then, the received signal at the k-th user during the j-th sub-time-block can be written as

$$\mathbf{Y}_{\mathrm{d},j,k}=\mathbf{A}_{0,j,k}^{\mathrm{d}}\mathbf{S}_{\mathrm{d},j}+\mathbf{N}_{\mathrm{d}},j=1,2, \tag{21}$$

which is a linear mixture with respect to the transmitted signal, and can be decomposed by utilizing the independent component analysis (ICA) technique [9]. In the following subsection, we demodulate the signal in the j-th sub-time-block and estimate the location of the k-th user.

A. Symbol Demodulation

1) Signal Whitening: We first whiten the received signal through the principal component analysis (PCA) method to obtain the uncorrelated signal. The post-whiten signal $\mathbf{Y}_{\mathrm{d1},j,k}$ is given by

$$\mathbf{Y}_{\mathrm{d1},j,k}=\mathbf{V}_j\mathbf{Y}_{\mathrm{d},j,k}, \tag{22}$$

where $\mathbf{V}_j=\mathbf{\Lambda}_{\mathbf{X},j}^{-1}\mathbf{U}_{\mathrm{x},j}\in\mathbb{C}^{K\times M}$ denotes the whitening matrix. $\mathbf{U}_{\mathrm{x},j}$ and $\mathbf{\Lambda}_{\mathbf{X},j}$ is the eigenvector and the eigenvalue that corresponds to the signal space of the auto-correlation matrix at the k-th user, which can be estimated as

$$\hat{\mathbf{R}}_{j,k}=\frac{1}{T_j}\sum_{t=1}^{T_j}\mathbf{y}_{\mathrm{d},j,k}(t)\left[\mathbf{y}_{\mathrm{d},j,k}(t)\right]^H, \tag{23}$$

2) Phase Deviation and Permutation Correction: After obtaining $\mathbf{Y}_{\mathrm{d1},j,k}$, the joint approximative diagonalization of eigen-matrices (JADE) method is applied to exploit the high-order statistical properties of the whitened signal [11]. The extracted signal and the linear mixing matrix are given by

$$\hat{\mathbf{S}}_{\mathrm{d1},j}=\mathbf{G}^H\mathbf{Y}_{\mathrm{d1},j,k},\ \hat{\mathbf{A}}_{1,j,k}^{\mathrm{d}}=\mathbf{Y}_{\mathrm{d1},j,k}[\hat{\mathbf{S}}_{\mathrm{d1},j}]^{\dagger}, \tag{24}$$

where the superscript "†" represents the pseudo-inverse, the unitary matrix $\mathbf{G}$ is obtained by the Givens rotation method and the set $\mathscr{N}$ is obtained by computing the K most significant eigenpairs of the fourth-order cumulants of the whitened signal.

However, the ambiguity caused by the ICA method leads to the difference between the estimated signal and the transmitted signal, as well as between the estimated linear mixing matrix and the original linear mixing matrix. Fortunately, the ambiguity can be eliminated by a semi-blind receiver according to [10]. Therefore, the estimated signal $\hat{\mathbf{S}}_{\mathrm{d2},j,k}$ and the mixing matrix $\hat{\mathbf{A}}_{2,j,k}^{\mathrm{d}}$ is given by

$$\hat{\mathrm{s}}_{\mathrm{d2},j,k}=\mathbf{Q}_j^{-1}\left[\mathbf{P}_j^{-1}\hat{\mathbf{S}}_{\mathrm{d1},j}\right]_{(\mathbf{o}_j,:)},\hat{\mathbf{A}}_{2,j,k}^{\mathrm{d}}=\left[\hat{\mathbf{A}}_{1,j,k}^{\mathrm{d}}\mathbf{P}_j\right]_{(\mathbf{o}_j,:)}\mathbf{Q}_j, \tag{25}$$

where the subscript $(\mathbf{o}_j,:)$ implies that the rows of $\mathbf{P}_j^{-1}\hat{\mathbf{S}}_{\mathrm{d1},j}$ are arranged in the order of elements in $\mathbf{o}_j$. $\mathbf{P}_j$ and $\mathbf{Q}_j$

denote the phase deviation ambiguity matrix and the quadrant ambiguity matrix, respectively, which are given by

$$\mathbf{P}_j^{-1} = diag\Big\{p_{j,1}^{-1}, \cdots, p_{j,K}^{-1}\Big\}, \mathbf{Q}_j = diag\{q_{j,1}, \cdots, q_{j,K}\}, \tag{26}$$

where

$$p_{j,k}^{-1} = \frac{\left| \left(\frac{1}{T_j} \sum\limits_{m=1}^{T_j} \left[\hat{\mathbf{S}}_{\mathrm{d1},j} \right]_{k,m}^4 \right)^{-\frac{1}{4}} e^{j\frac{\pi}{4}} \right|}{\left(\frac{1}{T_j} \sum\limits_{m=1}^{T_j} \left[\hat{\mathbf{S}}_{\mathrm{d1},j} \right]_{k,m}^4 \right)^{-\frac{1}{4}} e^{j\frac{\pi}{4}}}, \tag{27}$$

$[\mathbf{o}_j]_k = \arg\max\limits_{l+1} |\mathbf{r}_{j,k}^{\mathrm{p}}|$, and $q_{j,k} = e^{-j\frac{\pi}{2}\arg\max\limits_{l}\{\Re(\mathbf{r}_{j,k}^{\mathrm{p}})\}}$. $\mathbf{r}_{j,k}^{\mathrm{p}}(l+1) = \frac{1}{\tau_{0,\mathrm{p}}} \sum\limits_{m=1}^{\tau_{0,\mathrm{p}}} \left\{ \left[\hat{\mathbf{S}}_{\mathrm{d1},j}\right]_{k,m} e^{j\varphi_l} \left[\mathbf{s}_{d,j,k}^{p}\right]_m^* \right\}$ is the cross-correlation between the original and the extracted pilot symbols sent to the k-th user, $\varphi_l = \frac{\pi l}{2}, \forall l \in \{0,1,2,3\}$, and $\Re\left(\mathbf{r}_{j,k}^{\mathrm{p}}\right)$ stands for the real part of $\mathbf{r}_{j,k}^{\mathrm{p}}$. Next, the estimated mixing matrix $\hat{\mathbf{A}}_{2,j,k}^{\mathrm{d}}$ is exploited to obtained the users' location.

B. User Location Estimation

It is observed that the k-th column of the mixing matrix $\hat{\mathbf{A}}_{2,j,k}^{\mathrm{d}}$ corresponds to the product of the channel and the beamforming vector from the BS to the k-th user, i.e., $\hat{\mathbf{A}}_{2,j,k}^{\mathrm{d}} = [\mathbf{H}_{\mathrm{I2U},j,k}\boldsymbol{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\mathbf{w}_{\mathrm{d},j,1}, \cdots, \mathbf{H}_{\mathrm{I2U},j,k}\boldsymbol{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\mathbf{w}_{\mathrm{d},j,K}]$. Let $\left[\hat{\mathbf{A}}_{2,j,k}^{\mathrm{d}}\right]_{(:,m)}$ denote the m-th column of $\hat{\mathbf{A}}_{2,j,k}^{\mathrm{d}}$, which satisfies

$$\begin{aligned} \left[\hat{\mathbf{A}}_{2,j,k}^{\mathrm{d}}\right]_{(:,m)} &= \mathbf{H}_{\mathrm{I2U},j,k}\boldsymbol{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\mathbf{w}_{\mathrm{d},j,m} \\ &= \mathbf{B}_{\mathrm{U},j,k}^{\mathrm{d}}\mathbf{e}_{\mathrm{U},j,k,m}^{\mathrm{d}}, \end{aligned} \tag{28}$$

where

$$\mathbf{B}_{\mathrm{U},j,k}^{\mathrm{d}} = \left[\mathbf{a}_{\mathrm{U}}\left(u_{\mathrm{r,U},j,k}^{1}, v_{\mathrm{r,U},j,k}^{1}\right), \cdots, \mathbf{a}_{\mathrm{U}}\left(u_{\mathrm{r,U},j,k}^{L_{\mathrm{I2U},j,k}}, v_{\mathrm{r,U},j,k}^{L_{\mathrm{I2U},j,k}}\right)\right], \tag{29}$$

and

$$\mathbf{e}_{\mathrm{U},j,k,m}^{\mathrm{d}} = [\beta_{\mathrm{t,I},j,k}^{1}, \cdots, \beta_{\mathrm{t,I},j,k,m}^{L_{\mathrm{I2U},j,k,m}}], \tag{30}$$

where $\beta_{\mathrm{t,I},j,k,m}^{l} = \alpha_{\mathrm{I2U},j,k}^{l}\mathbf{a}_{\mathrm{I}}^{\mathrm{H}}\left(u_{\mathrm{t,I},j,k}^{l}, v_{\mathrm{t,I},j,k}^{l}\right)\boldsymbol{\Theta}_j\mathbf{H}_{\mathrm{B2I},j}\mathbf{w}_{\mathrm{d},j,m}$.

Note that the above equation is a classic angle estimation problem, therefore, the effective AoAs, i.e., $\{\hat{u}_{\mathrm{r,U},j,k}^{l}, \hat{v}_{\mathrm{r,U},j,k}^{l}\}, l = 1, \cdots, L_{\mathrm{I2U},j,k}$, can be estimated by applying the multiple signal classification (MUSIC) method.

Then, combining the effective AoAs at the sub-IRSs during the first stage, i.e., $\{\hat{u}_{\mathrm{r,I},j,k}^{p}, \hat{v}_{\mathrm{r,I},j,k}^{p}\}$, the user location can be estimated based on the estimated effective AoAs corresponding to the LoS path, i.e., $\{\hat{u}_{\mathrm{r,I},j,k}^{l_{\mathrm{LoS}}}, \hat{v}_{\mathrm{r,I},j,k}^{l_{\mathrm{LoS}}}\}$, and $\{\hat{u}_{\mathrm{r,U},j,k}^{l_{\mathrm{LoS}}}, \hat{v}_{\mathrm{r,U},j,k}^{l_{\mathrm{LoS}}}\}$, where l_{LoS} is obtained according to the channel reciprocity by

$$l_{\mathrm{LoS}} = \arg\min_{l,p}\left\{\hat{v}_{\mathrm{r,U},j,k}^{l} + \hat{u}_{\mathrm{r,I},j,k}^{p}, l, p = 1, \cdots, L_{\mathrm{I2U},j,k}\right\}. \tag{31}$$

Let $\mathbf{p}_{\mathrm{I},j} = (x_{\mathrm{I},j}, y_{\mathrm{I},j}, z_{\mathrm{I},j})^T$ and $\hat{\mathbf{p}}_{\mathrm{u},k} = (\hat{x}_{\mathrm{u},k}, \hat{y}_{\mathrm{u},k}, \hat{z}_{\mathrm{u},k})^T$ denote the location of the j-th sub-IRS and the k-th user, respectively, the relationship among the location of the j-th sub-IRS, the position of the k-th user, and the LoS (l_{LoS}) path are given as follows

$$\hat{u}_{\mathrm{r,U},j,k}^{l_{\mathrm{LoS}}} = \frac{\hat{x}_{\mathrm{u},k} - x_{\mathrm{I},j}}{\|\hat{\mathbf{p}}_{\mathrm{u},k} - \mathbf{p}_{\mathrm{I},j}\|}, \hat{v}_{\mathrm{r,U},j,k}^{l_{\mathrm{LoS}}} = \frac{\hat{y}_{\mathrm{u},k} - y_{\mathrm{I},j}}{\|\hat{\mathbf{p}}_{\mathrm{u},k} - \mathbf{p}_{\mathrm{I},j}\|}, j = 1, 2. \tag{32}$$

Let $\hat{\mathbf{z}}_k \triangleq (\hat{x}_{\mathrm{u},k}, \hat{y}_{\mathrm{u},k}, \|\hat{\mathbf{p}}_{\mathrm{u},k} - \mathbf{p}_{\mathrm{I},1}\|, \|\hat{\mathbf{p}}_{\mathrm{u},k} - \mathbf{p}_{\mathrm{I},2}\|)^T$, and it can be obtained by

$$\hat{\mathbf{z}}_k = \mathbf{L}_k{}^{-1}\mathbf{f}, \tag{33}$$

where

$$\mathbf{L}_k \triangleq \begin{pmatrix} 1 & 0 & -\hat{u}_{\mathrm{r,U},1,k}^{l_{\mathrm{LoS}}} & 0 \\ 0 & 1 & -\hat{v}_{\mathrm{r,U},1,k}^{l_{\mathrm{LoS}}} & 0 \\ 1 & 0 & 0 & -\hat{u}_{\mathrm{r,U},2,k}^{l_{\mathrm{LoS}}} \\ 0 & 1 & 0 & -\hat{u}_{\mathrm{r,U},2,k}^{l_{\mathrm{LoS}}} \end{pmatrix}, \tag{34}$$

and

$$\mathbf{f} \triangleq (x_{\mathrm{I},1}, y_{\mathrm{I},1}, x_{\mathrm{I},2}, y_{\mathrm{I},2})^T. \tag{35}$$

Besides, $\hat{z}_{\mathrm{u},k}$ can be estimated by

$$\hat{z}_{\mathrm{u},k} = \arg_{\omega_{1,k}} \min_{\omega_{1,k} \in \{z_{\mathrm{I},1} \pm d_{\mathrm{z},1,k}\}, \omega_{2,k} \in \{z_{\mathrm{I},2} \pm d_{\mathrm{z},2,k}\}} |\omega_1 - \omega_2|, \tag{36}$$

where

$$d_{\mathrm{z},j,k} \triangleq \sqrt{\left(\|\hat{\mathbf{p}}_{\mathrm{u},k} - \mathbf{p}_{\mathrm{I},j}\|^2\right)^2 - (\hat{x}_{\mathrm{u},k} - z_{\mathrm{I},j})^2 - (\hat{y}_{\mathrm{u},k} - y_{\mathrm{I},j})^2}. \tag{37}$$

Combining (33) and (36), we obtain the location of the k-th user $\hat{\mathbf{p}}_{\mathrm{u},k}$.

The overall algorithm is summarized in **Algorithm 1**.

Algorithm 1 The joint multiuser demodulation and localization algorithm.

1: **Input** the received signals at the k-th user $\mathbf{Y}_{\mathrm{d},j,k}$ and the effective AoAs at IRSs $\{\hat{u}_{\mathrm{r,I},j,k}^{p}, \hat{v}_{\mathrm{r,I},j,k}^{p}\}$ estimated in [8].
2: Design the beamforming scheme by solving the problem (P1).
3: Estimate the transmit signals $\hat{\mathbf{s}}_{\mathrm{d2},j,k}$ and the mixing matrix $\hat{\mathbf{A}}_{2,j,k}^{\mathrm{d}}$ by exploiting the statistical properties of $\mathbf{Y}_{\mathrm{d},j,k}$ using (22) $\sim$ (25).
4: Estimate all the effective AoAs at the k-th user $\{\hat{u}_{\mathrm{r,U},j,k}^{l}, \hat{v}_{\mathrm{r,U},j,k}^{l}\}$ through (28).
5: Separate the angle information of the LoS path by (31) and perform localization by (33) and (36), respectively.
6: **Output** the estimation of the transmit data $\hat{\mathbf{s}}_{\mathrm{d2},j,k}$ and the location of the k-th user $\hat{\mathbf{p}}_{\mathrm{u},k}$.

V. Simulation Results

In this section, we provide simulation results to demonstrate the effectiveness of the proposed framework. The BS is 10 meters above the horizontal floor, $K = 3$ users are 2 meters, 0 meters, and 2 meters, above the horizontal floor, while the two sub-IRSs are 5 meters and 4 meters above the horizontal floor, respectively, and the distances from the BS to the j-th sub-IRS, to the centre of the user cluster, and from the j-th sub-IRS to the k-th user are respectively set as $d_{\mathrm{B2I},j} = d_{\mathrm{B2U}_{j,k}}$= 50 meters and $d_{\mathrm{I2U},j,k}$= 8 meters [8]. The path loss at the reference distance of 1 m is set as C_0 = 30 dB with exponents set as κ= 2.2 [14]. Without loss of generality, quadrature phase shift keying (QPSK) modulation is considered in the simulation, and unless otherwise specified, the following setup is used: $P = 10$ dBm, $P_U = 30$ dBm, η =-10^3, M = 10×10, $\tau_{0,\mathrm{p}}$ = 5, τ_1= 4, τ_2 = 1000, noise power $\sigma_{\mathrm{u}}^2 = \sigma_{\mathrm{d}}^2$ = -110 dBm, N_B = N_U = 16, $L_{\mathrm{B2I},j} = 10$, $L_{\mathrm{I2U},j,k} = 4$, and the angle separation is assumed to be larger than $4/N_B$, $4/M$, and $4/N_U$ at the BS, sub-IRSs, and users [15].

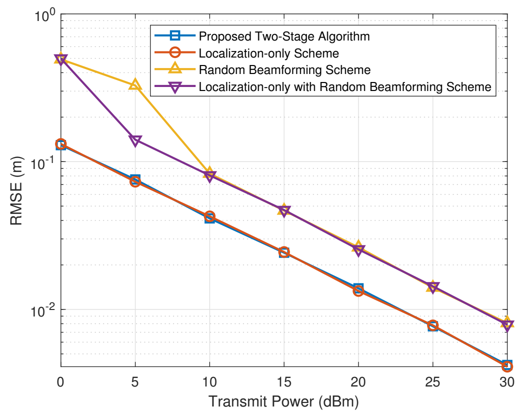

Fig. 3: RMSE of the user location.

Fig. 3 illustrates the localization accuracy of the proposed framework, where the root mean square error (RMSE) of the estimated user location as the performance metric, i.e., $\varepsilon_{\mathrm{R}} = \mathbb{E}\left\{\sqrt{\frac{1}{K}\sum_{k=1}^{K}\left\|\hat{\mathbf{p}}_{\mathrm{u},k} - \mathbf{p}_{\mathrm{u},k}\right\|^2}\right\}$. It can be observed that the localization accuracy improves as the transmit power increases, reaching centimeter-level accuracy. Moreover, the proposed framework achieves performance comparable to the scheme that uses a dedicated orthogonal localization reference signal with a length of $\tau_1 + \tau_2$.

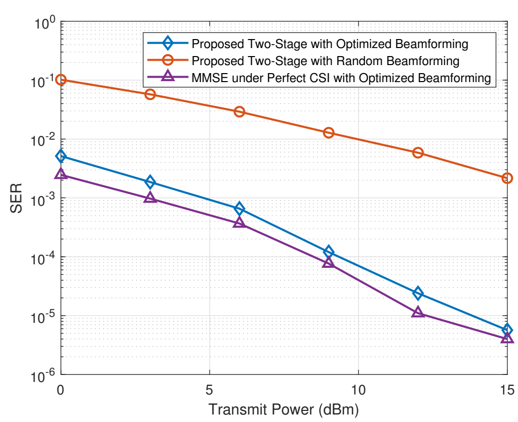

Fig. 4: The communication performance of the proposed algorithm.

Then, we study the demodulation performance of the proposed framework in Fig. 4, where we use the average symbol error rate (SER) as the performance metric. It can be seen that the SER is comparable to that of the MMSE method under perfect CSI, indicating that the proposed algorithm also has good compatibility with signal demodulation. Additionally, the proposed beamforming design scheme outperforms the random beamforming design scheme, demonstrating the effectiveness of the proposed beamforming design scheme.

VI. Conclusion

We proposed a distributed IRS-assisted multiuser ISAC framework including the transmission protocol and beamforming design scheme. Specifically, by exploiting the statistical properties of the received signal, an algorithm was proposed to achieve simultaneous multiuser localization and signal demodulation. Moreover, a radar-inspired beamforming scheme was proposed to enhance the communication and localization performance. Simulation results showed that the proposed algorithm achieved centimeter-level localization accuracy and comparable performance to the MMSE method with perfect CSI.

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