Robust Design for RIS-Assisted Anti-Jamming Communications with Imperfect Angular Information: A Game-Theoretic Perspective

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***Abstract*—This paper utilizes a reconfigurable intelligent surface (RIS) to enhance the anti-jamming performance of wireless communications, due to its powerful capability of constructing smart and reconfigurable radio environment. In order to establish the practical interactions between the base station (BS) and the jammer, a Bayesian Stackelberg game is formulated, where the BS is the leader and the jammer acts as the follower. Specifically, with the help of a RIS-assisted transmitter, the BS attempts to reliably convey information to users with maximum utilities, whereas the smart jammer tries to interfere the signal reception of users with desired energy efficiency (EE) threshold. Since the BS and the jammer are not cooperative parties, the practical assumption that neither side can obtain the other's strategies is adopted in the proposed game, and the angular information based imperfect channel state information (CSI) is also considered. After tackling the practical assumption by using Cauchy-Schwarz inequality and the imperfect angular information by using the discretization method, the closed-form solution of both sides can be obtained via the duality optimization theory, which constitutes the unique Stackelberg equilibrium (SE). Numerical results demonstrate the superiority and validity of our proposed robust schemes over the existing approaches.**

***Index Terms*—Anti-jamming, reconfigurable intelligent surface, Stackelberg game, imperfect angular information.**

I. Introduction

WIRELESS communications are increasingly vulnerable to jamming attacks due to the inherent openness and broadcast nature of the wireless channel. To takle this issue, various typical techniques have been proposed to defend against jamming attacks, e.g., frequency hopping [1], power control [2], and spatial beamforming [3]. Nevertheless, due to the emergence of the intelligent jammer which can quickly learn the transmission strategy of legitimate nodes and adaptively adjust the jamming strategy to maximize the damaging effect with the lowest cost [4], the abovementioned fixed anti-jamming schemes are still challenging to cope with the smart jammer. With this focus, game theory has been widely utilized to model and analyze the competitive interactions between the base station (BS) and jammers [5]–[7]. Taking transmission cost into account, a non-zero-sum game was modeled in [6] to address the anti-jamming problem between the BS and jammer. To further analyze the hierarchical behaviors between competitive sides, Stackelberg game was applied to cope with the hierarchical interactions in the anti-jamming communications [4], [8]–[10], and the optimal strategies were found for robust transmissions. In [10], a Bayesian Stackelberg game between the BS and jammer was modeled without instantaneous channel state information (CSI), and the optimal precoding strategies of both the competitive sides and Stackelberg Equilibrium (SE) were achieved. However, the abovementioned methods are still challenging to address the anti-jamming problem in wireless communications, due to the increasing requirment of higher spectrum and energy efficiency. Specifically, frequency hopping consumes additional spectrum resources, and the implementation of spatial beamforming with multiple antennas incurs high power consumption.

To overcome the abovementioned shortcomings, this paper utilizes a reconfigurable intelligent surface (RIS) to enhance the anti-jamming performance from a game-theoretic perspective. RIS is a metasurface comprising of many passive low-cost reflecting units, where each unit can impose a phase shift and/or amplitude to the incident signal, thus reflecting the electromagnetic (EM) wave to the desired direction [11]. Current state-of-the-art for RIS-assisted communication system can be divided into two aspects: RIS as a passive reflector for reconfiguring the EM propagation environment [11] and RIS as an active transceiver for modulating the EM carrier signals [12]. In existing literatures, RIS-based passive reflector has been investigated to increase coverage [11], enhance physical layer security [13], [14], and improve anti-jamming performance [15], [16]. The authors in [14] proposed a RIS-assisted non-orthogonal multiple access (NOMA) scheme to maximize the sum rate via using the artificial jamming in the presence of a passive eavesdropper. In our previous work [16], RIS was used for the first time to enhance secure transmission against simultaneous jamming and eavesdropping attacks in cellular network, where the achievable rate was maximized by joint optimizing the transmit beamforming at the BS and the reflecting beamforming at the RIS. However, RIS-based passive reflector may suffers from the "double fading" effect, namely, the large-scale fading first in the transmitter-RIS link and then again in the RIS-receiver link [17]. Moreover, the jamming signal can be also reflected by RIS-based passive reflector so that the enhancement of desired signal and the suppression of the jamming signal cannot be perfectly balanced. Thus, this paper turns to the second aspect. RIS-assisted transceiver has been utilized to perform continuous modulation [18] and radiation pattern control [12], [19]. Nevertheless, the performance of all the RIS-related works is mainly determined by the accuracy of CSI, which is difficult to be obtained perfectly. With this focus, existing works investigated the robust beamforming design based on the statistical or bounded CSI error model (see [20] and reference therein). However, the CSI estimation error is essentially induced by the user's angle of arrival (AoA) error, thus the robust design with imperfect angular CSI should be investigated in the RIS-aided wireless communication.

Motivated by the above observations, a Bayesian Stackelberg game and a robust beamforming design are proposed to cope with the smart jammer in the RIS-assisted multi-user network. The main contributions of this paper are as follows:

- To our best knowledge, this is the first work to investigate a Bayesian Stackelberg game for anti-jamming communications aided by a RIS-assisted holographic transmitter, and proposes robust beamforming design with angular information based imperfect CSI. To model a practical scenario, the assumption that neither side can obtain the other's strategies is adopted in the proposed game.
- To tackle the imperfect angular information and the practical assumption, we first utilize a discretization method to transform the original angular uncertainty into a worst-case one, and then use the Cauchy-Schwarz inequality to relax the practical assumption. As such, the closed-form beamforming strategies for both the BS and the smart jammer are derived by the duality optimization theory. Besides, the existence and uniqueness of SE for the proposed game are proved. Moreover, the power scaling law of proposed RIS-assisted transmitter is presented.
- Numerical results demonstrate the effectiveness and superiority of our proposed algorithm, in terms of transmit power and outage probability.

II. System Model and Problem Formulation

A. System Model

As shown in Fig. 1, this paper considers a RIS-assisted anti-jamming communication system, where one single-antenna BS serves K single-antenna users through a RIS, in the presence of a smart jammer. The RIS is a uniform planar array (UPA) with $KN_1 \times N_2$ units, while the jammer is equipped with uniform linear arrays (ULA) with M elements. $N_1 \times N_2$ units in the k-th block of the RIS are allocated to k-th user, which can modulate the normalized transmitted data symbol s_k and control the radiation beamforming $\mathbf{v}_k$ for user k [12]. Specifically, BS only uses one antenna to transmit the carrier signal to RIS, and then RIS can directly perform a phase modulation on the carrier signal to generate the normalized data symbol s_k and simultaneously control the k-th radiation beamforming $\mathbf{v}_k$. In addition, one narrow-band power amplifier (PA) is used to control the power of the carrier signal, and the number of PAs is equal to K. Denoting $\mathbf{V}_k = \mathrm{diag}\{\mathbf{v}_k\} = \mathrm{diag}\left\{v_k^1, \cdots, v_k^{N_1\times N_1}\right\}$, where $v_k^{n_1\times n_2} = e^{j\phi_k^{n_1\times n_2}}$ and $\phi_k^{n_1\times n_2} \in [0, 2\pi]$, the transmitted signal at the BS is given by

$$\mathbf{x} = [\sqrt{p_1}\mathbf{V}_1\mathbf{B}_1 s_1; \cdots; \sqrt{p_K}\mathbf{V}_K\mathbf{B}_K s_K] \quad (1)$$

where p_k is the BS's transmit power for k-th user, and $\mathbf{B}_k \in \mathbb{C}^{N_1 N_2 \times 1}$ denotes the channel vector between the BS's antenna and the k-th block of the RIS. The jammer sends the jamming signal $\mathbf{w}_{J,k} s_{J,k} \in \mathbb{C}^{M\times 1}$ to the user k for deteriorating the communication quality, which cannot be obtained by BS. Thus, the received signal at user k is given by

$$y_{U,k} = \sum_{i=1}^{K} \mathbf{G}_{i,k}^H \sqrt{p_i}\mathbf{V}_i\mathbf{B}_i s_i + \sum_{i=1}^{K} \mathbf{h}_{J,k}^H \mathbf{w}_{J,i} s_{J,i} + n_{U,k}, \quad (2)$$

where $\mathbf{G}_{i,k}$ is the channel coefficients from $N = N_1 \times N_2$ RIS units in the i-th block to k-th user, and $\mathbf{h}_{J,k}$ denotes the channel vector between the jammer and k-th user. The symbol $n_{U,k} \sim \mathcal{CN}(0, \sigma_{U,k}^2)$ is the thermal noise for k-th user, and $\mathcal{CN}$ denotes the distribution of a circularly symmetric complex Gaussian random vector. After some mathematical transformations, the received achievable rate at k-th user is

$$\begin{aligned} R_{U,k} &= \log_2\left(1 + \gamma\left(p_k, \mathbf{v}_k, \mathbf{w}_{J,k}\right)\right) \\ &= \log_2\left(1 + \frac{p_k\left|\overline{\mathbf{G}}_{k,k}^H \mathbf{v}_k\right|^2}{\sum\limits_{i\neq k}^{K} p_i\left|\overline{\mathbf{G}}_{i,k}^H \mathbf{v}_i\right|^2 + \sum\limits_{i=1}^{K}\left|\mathbf{h}_{J,k}^H \mathbf{w}_{J,i}\right|^2 + \sigma_{U,k}^2}\right), \end{aligned} \quad (3)$$

where $\overline{\mathbf{G}}_{i,k} = \mathrm{diag}\left\{\mathbf{B}_i^H\right\}\mathbf{G}_{i,k}$. It is worth-mentioning that due to the fact that the distance between BS and RIS is very short, the channel between BS and RIS can be regarded as a constant one as in [18], i.e., $\mathbf{B}_k = \mathbf{1}_N$. As such, we can obtain $\overline{\mathbf{G}}_{i,k} = \mathbf{G}_{i,k}$ and simplify (3) as (9) in [12]. However, in order to analyse the effect of $\mathbf{B}_k$ on the system performance accurately, we adopt the the geometric radar channel to model $\mathbf{B}_k$ in this paper, which has been expressed in [21]. In addition, we consider the practical scenario that both the BS and jammer have incomplete information of (3). Specifically, the accurate jamming channel $\mathbf{h}_{J,k}$ and jammer's strategies $\mathbf{w}_{J,k}$ are unknown to the BS, and the jammer has no knowledge of the accurate channels $\mathbf{G}_{i,k}$, $\mathbf{B}_k$ and BS's strategies p_k, $\mathbf{v}_k$.

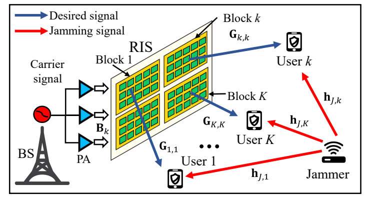


Fig. 1: System model.

B. Channel Model

According to [21], $\mathbf{B}_k$ can be regarded as the near-field channel and expressed as

$$\mathbf{B}_k = \left[\frac{\lambda_w\sqrt{\rho G_{n,k}^D\left(\theta^R, \varphi^R\right) G_{n,k}^R\left(\theta^D, \varphi^D\right)}}{4\pi d_{n,k}} e^{-j\frac{2\pi d_{n,k}}{\lambda_w}}\right]_{n,k}, \quad (4)$$

where λ_w is the wavelength, ρ denotes the power efficiency of the RIS, $d_{n,k}$ is the distance between the n-th RIS unit in the k-th block and the BS's antenna, and $G_{n,k}^D\left(\theta^R, \varphi^R\right)$, $G_{n,k}^R\left(\theta^D, \varphi^D\right)$ are the active and passive antenna gains from the n-th unit and the BS's antenna, respectively. Note that $\mathbf{B}_k$ is a fixed vector and can be precisely measured by the BS, due to the fact that the distance between the RIS and antenna is very short [21]. By taking the array element pattern into account, the geometric 3D channel model can be applied to characterize the far-field channel $\mathbf{G}_{i,k}$ and $\mathbf{h}_{J,k}$ [22], i.e.,

$$\mathbf{G}_{i,k} = g_{ik,0}^B \mathbf{a}_P\left(\theta_{ik,0}^B, \varphi_{ik,0}^B\right) + \sqrt{\frac{1}{L_B}}\sum_{l=1}^{L_B} g_{ik,l}^B \mathbf{a}_P\left(\theta_{ik,l}^B, \varphi_{ik,l}^B\right),$$

$$\mathbf{h}_{J,k} = g_{k,0}^J \mathbf{a}_L\left(\varphi_{k,0}^J\right) + \sqrt{\frac{1}{L_J}}\sum_{l=1}^{L_J} g_{k,l}^J \mathbf{a}_L\left(\varphi_{k,l}^J\right), \forall i, k, \quad (5)$$

where $\theta_{ik,l}^{B}$ is the vertical AoA, $\left\{\varphi_{ik,l}^{B},\varphi_{k,l}^{J}\right\}$ denote the horizontal AoA, $\{L_B, L_J\}$ is total number of multiple paths, and $\left\{g_{ik,l}^{B},g_{k,l}^{J}\right\}$) represent the large-scale fading coefficients. Define $g\in\left\{g_{ik,l}^{B},g_{k,l}^{J}\right\}$, and $g\sim\mathcal{CN}(0,10^{PL/10})$, where $PL=-30.18-26\log 10\,(d)$[dB] and d is the link distance. In addition, $\mathbf{a}_P\left(\theta,\varphi\right)$ and $\mathbf{a}_L\left(\varphi\right)$ are the steering vector of UPA and ULA, respectively.

In this paper, we assume that both $\mathbf{G}_{i,k}$ and $\mathbf{h}_{J,k}$ cannot be accurately obtained by the BS and jammer. Specifically, the involved channel of BS and jammer $\mathbf{G}_{i,k}$, $\mathbf{h}_{J,k}$ belongs to a given continuous AoA-based range, which is given by

$$\begin{aligned}\Delta_{m,k}=&\Big\{\mathbf{G}_{i,k},\mathbf{h}_{J,k}|\,\theta_{ik}^{B}\in\left[\theta_{ik,L}^{B},\theta_{ik,U}^{B}\right],\varphi_{ik}^{B}\in\left[\varphi_{ik,L}^{B},\varphi_{ik,U}^{B}\right],\\ &\theta_{k}^{J}\in\left[\theta_{k,L}^{J},\theta_{k,U}^{J}\right],g_{ik}^{B}\in\left[g_{ik,L}^{B},g_{ik,U}^{B}\right],g_{k}^{J}\in\left[g_{k,L}^{J},g_{k,U}^{J}\right]\Big\},\\ &m\in(B,J),\forall i,k,\end{aligned}\tag{6}$$

where $\theta_{ik,U}^{B}$ and $\theta_{ik,L}^{B}$ denote the upper and lower bounds of BS's vertical AoA, and $\left\{\varphi_{ik,U}^{B},\varphi_{k,U}^{J}\right\}$ and $\left\{\varphi_{ik,U}^{L},\varphi_{k,L}^{J}\right\}$ is the upper and lower bounds of the horizontal AoA, and $\left\{g_{ik,U}^{B},g_{k,U}^{J}\right\}$ and $\left\{g_{ik,L}^{B},g_{k,L}^{J}\right\}$ are the lower and upper bounds of the channel gain amplitude.

C. Stackelberg Game and Problem Formulation

In this subsection, we formulate an anti-jamming Bayesian Stackelberg game, where the BS acts as the leader and the smart jammer is the follower. The BS selects the optimal strategies $\{p_k,\mathbf{v}_k\}$ to serve the users with desired transmit power. Given the minimum achievable rate target $\gamma_{U,k}$, the BS's power minimization problem can be formulated as

$$\begin{aligned}&\min_{\{p_k\}\geq 0,\{\mathbf{v}_k,\Delta_{B,k}\}}\ \sum_{k=1}^{K}p_k\\ &s.t.\ \mathrm{C1}:R_{U,k}\geq\gamma_{U,k},\ \mathrm{C2}:[\mathbf{v}_k\mathbf{v}_k^H]_{n,n}=1,\forall k,n.\end{aligned}\tag{7}$$

For the smart jammer, it chooses the optimal $\{\mathbf{w}_{J,k}\}$ to interfere the signal reception of users with desired EE, which is defined as [10]

$$\Lambda_k=\frac{\gamma\left(p_k,\mathbf{v}_k,\mathbf{0}\right)-\gamma\left(p_k,\mathbf{v}_k,\mathbf{w}_{J,k}\right)}{\left\|\mathbf{w}_{J,k}\right\|^2},\forall k,\tag{8}$$

where $\gamma\left(p_k,\mathbf{v}_k,\mathbf{w}_{J,k}\right)$ is the signal-to-interference-and-noise ratio (SINR) of k-th user which is given in (3). With the EE threshold $\tau_{J,k}$, the jammer's optimization problem is given by

$$\min_{\{\mathbf{w}_{J,k},\Delta_{J,k}\}}\sum_{k=1}^{K}\left\|\mathbf{w}_{J,k}\right\|^2\quad s.t.\ \overline{\mathrm{C}}1:\Lambda_k\geq\tau_{J,k},\forall k.\tag{9}$$

Note that the utility functions of BS and jammer are given by $U_B=1\Big/\sum_{k=1}^{K}p_k$ and $U_J=1\Big/\sum_{k=1}^{K}\left\|\mathbf{w}_{J,k}\right\|^2$.

III. Analysis of the Proposed Stackelberg Game

A. Follower Sub-Game

Denote by $\mathfrak{J}$ the problem (9). Since the jammer can obtain neither the instantaneous CSI $\{\mathbf{G}_{i,k},\mathbf{h}_{J,k},\mathbf{B}_k\}$ nor the BS's strategy $\{p_k,\mathbf{v}_k\}$, $\mathfrak{J}$ cannot be sovled. To ensure $\mathfrak{J}$ is feasible, we first address the unknown $\mathbf{B}_k$. According to [18], when $\mathbf{B}_k$ is a constant vector, i.e., $\mathbf{B}_k=\mathbf{1}_N$, the BS can achieve the best performance. Thus, to guarantee the constraint $\overline{\mathrm{C}}1$ for all the possible $\mathbf{B}_k$, $\mathbf{B}_k=\mathbf{1}_N$ is adopted in the follower sub-game. Then, we introduce a novel discretization method to tackle the imperfect angular CSI $\{\mathbf{G}_{i,k},\mathbf{h}_{J,k}\}$. Specifically, we let $g_k^B=g_{k,U}^B$ and $g_k^J=g_{k,L}^J$ so that the path loss is maximal. Then, any continuous uncertainty Δ_g can be expressed as

$$\Delta_g=\{\mathbf{G}_1,\cdots,\mathbf{G}_S\},\tag{10}$$

where $\mathbf{G}_n$ is one possible channel in Δ_g and S denotes the discrete sample number. Note that the discrete-form uncertainty is a general form due to the fact that S can be taken as infinity. Thus, any imperfect CSI in angular uncertainty set can be expressed as the combination of discrete elements in (10). According to [23], since only angular information based uncertainty region is known, the angle in the set of Δ_g can be uniformly selected, which is given by

$$\theta^{(a)}=\theta_L+(a-1)\,\Delta\theta,\ a=1,\cdots,Q_1,\tag{11}$$

$$\varphi^{(b)}=\varphi_L+(b-1)\,\Delta\varphi,\ b=1,\cdots,Q_2,\tag{12}$$

where $\left\{\theta^{(a)},\varphi^{(b)}\right\}$ are the angular information of $\mathbf{G}^{(a,b)}$, $Q_1\geq N_1$ and $Q_2\geq N_2$ denote the sample number of θ and φ, and $\Delta\theta=(\theta_U-\theta_L)/(Q_1-1)$, $\Delta\varphi=(\varphi_U-\varphi_L)/(Q_2-1)$. The above formulation is also suitable for $\mathbf{h}_{J,k}$. Thus, combining with $\mathbf{B}_k=\mathbf{1}_N$, the equivalent channel $\overline{\mathbf{G}}_{i,k}$ and jamming channel $\mathbf{h}_{J,k}$ with $\Delta_{J,k}$ can be expressed as [23]

$$\widetilde{\mathbf{G}}_{i,k}^{\mathfrak{J}}=\sum_{a=1}^{Q_1}\sum_{b=1}^{Q_2}\mu_{a,b}\mathrm{diag}\left\{\mathbf{B}_i^H\right\}\mathbf{G}_{i,k}^{(a,b)},\ \ \widetilde{\mathbf{h}}_{J,k}^{\mathfrak{J}}=\sum_{c=1}^{Q_3}\eta_c\mathbf{h}_{J,k}^{(c)},\tag{13}$$

where $Q_3\geq M$. Here, $\mu_{a,b}=1/Q_1Q_2$ and $\eta_c=1/Q_3$ are adopted for satisfied robustness [23].

Due to the fact that the jammer does not focus on the inter-user interference induced by the power leakage of the precoding, we can refer to the matched filtering (MF) scheme and directly assume that the jammer's precoding solution is

$$\mathbf{w}_{J,k}=\sqrt{p_{J,k}}\widetilde{\mathbf{h}}_{J,k}^{\mathfrak{J}}\Big/\left\|\widetilde{\mathbf{h}}_{J,k}^{\mathfrak{J}}\right\|,\forall k.\tag{14}$$

where $p_{J,k}$ is the jamming power for k-th user. Then $\mathfrak{J}$ is transformed into a power minimization problems.

By untilizing (13), (14) and denoting $a_k=p_k\left|\widetilde{\mathbf{G}}_{k,k}^{\mathfrak{J},H}\mathbf{v}_k\right|^2$, $b_k=\sum_{i\neq k}^{K}p_i\left|\widetilde{\mathbf{G}}_{i,k}^{\mathfrak{J},H}\mathbf{v}_i\right|^2$, the constraint $\overline{\mathrm{C}}1$ in $\mathfrak{J}$ can be equivalently expressed as $\overline{\mathrm{C}}1^*$, namely

$$\begin{aligned}\overline{\mathrm{C}}1^*:f_{J,k}(p_{J,k})=&\left[a_k-\tau_{J,k}p_{J,k}\left(b_k+\sigma_{U,k}^2\right)\right]\sum_{i=1}^{K}p_{J,i}\left|\widehat{h}_{J,i}^{\mathfrak{J}}\right|^2\\ &-\tau_{J,k}\left(b_k+\sigma_{U,k}^2\right)^2p_{J,k}\geq 0,\end{aligned}\tag{15}$$

where $\widehat{h}_{J,i}^{\mathfrak{J}}=\left(\widetilde{\mathbf{h}}_{J,k}^{\mathfrak{J},H}\widetilde{\mathbf{h}}_{J,i}^{\mathfrak{J}}\right)\Big/\left\|\widetilde{\mathbf{h}}_{J,i}^{\mathfrak{J}}\right\|$. Thus, $\mathfrak{J}$ is simplified to

$$\min_{\{p_{J,k}\}}\sum_{k=1}^{K}p_{J,k}\quad s.t.\ \overline{\mathrm{C}}1^*,\overline{\mathrm{C}}2:p_{J,k}>0,\forall k.\tag{16}$$

Obviously, $\overline{\mathrm{C}}1^*$ is concave due to $\partial_{p_{J,k}}^2f_{J,k}(p_{J,k})=-2\tau_{J,k}\left(b_k+\sigma_{U,k}^2\right)\left|\widehat{h}_{J,i}^{\mathfrak{J}}\right|^2<0$, where $\partial_x{}^2\left(\cdot\right)$ denotes the second-order partial derivative operator with respect to x. Thus, (16) is a convex optimization problem, whose Lagrangian function can be expressed as

$$\mathcal{L}_J=\sum_{k=1}^{K}(1-\varpi_{J,k})\,p_{J,k}-\sum_{k=1}^{K}\lambda_{J,k}f_{J,k}(p_{J,k}),\tag{17}$$

where $\{\lambda_{J,k}\},\{\varpi_{J,k}\}$ are nonnegative Lagrangian multipliers.

Then, the KKT conditions are drived, which are given by

$$\partial_{p_{J,k}}\mathcal{L}_J=1-\varpi_{J,k}-\lambda_{J,k}\partial_{p_{J,k}}f_{J,k}\left(p_{J,k}\right)=0,\tag{18}$$

$$\lambda_{J,k}f_{J,k}(p_{J,k})=0,\varpi_{J,k}p_{J,k}=0,\forall k.\tag{19}$$

Since $p_{J,k}>0$, $\varpi_{J,k}=0$ can be derived from the condition

(19). Substituting $\varpi_{J,k}=0$ into (18), we obtain $\lambda_{J,k}>0$, and thus $f_{J,k}(p_{J,k})=0$. To obtain the stationary SE, inspired by [6], we drop the term $\sum_{i\neq k}^{K} p_{J,i}\left|\widehat{h}_{J,i}^{\mathfrak{J}}\right|^2$ insides $f_{J,k}(p_{J,k})$, and the KKT solution $p_{J,k}^{\star}$ is given by

$$p_{J,k}^{\star}=\frac{a_k}{\tau_{J,k}\left(b_k+\sigma_{U,k}^2\right)}-\frac{\left(b_k+\sigma_{U,k}^2\right)}{\left|\widehat{h}_{J,k}^{\mathfrak{J}}\right|^2},\forall k. \tag{20}$$

However, due to the fact that the jammer has no knowledge of a_k and b_k, the KKT solution is still infeasible. Note that $p_{J,k}^{\star}$ decreases with b_k, which suggests that more jamming power is needed when the inter-user interference induced by $\{p_k,\mathbf{v}_k\}$ is eliminated. In addition, by using the Cauchy-Schwarz inequality, we can obtain the upper bound of a_k, i.e., $a_k^{\max}\leq\widehat{p}_k\left\|\widetilde{\mathbf{G}}_{k,k}^{\mathfrak{J}}\right\|^2\|\mathbf{v}_k\|^2\leq N\widehat{p}_k\left\|\widetilde{\mathbf{G}}_{k,k}^{\mathfrak{J}}\right\|^2$. Here, $\widehat{p}_k$ denotes the estimation of the BS's transmit power, which can be obtained by the rotational invariance techniques [24]. Hence, we derive the feasible power solution, namely

$$p_{J,k}^{\star}=\frac{a_k^{\max}}{\tau_{J,k}\sigma_{U,k}^2}-\frac{\sigma_{U,k}^2}{\left|\widehat{h}_{J,k}^{\mathfrak{J}}\right|^2},\forall k. \tag{21}$$

Although this results in suboptimal solutions, it is impossible to obtain a relaxed and feasible solution with accurate beamforming. Therefore, from a game point of view, a tradeoff should be made between the feasibility and optimality.

B. Leader Sub-Game

Denote by $\mathfrak{B}$ the problem (7). Since the BS has no knowledge of $\{\mathbf{G}_{i,k},\mathbf{h}_{J,k}\}$ and $\mathbf{w}_{J,k}$, $\mathfrak{B}$ also cannot be solved. Similar to the follower sub-game, we use the discretization method to deal with the angular information based imperfect CSI, and thus the worst-case channels with $\Delta_{B,k}$ is given by $\widetilde{\mathbf{G}}_{i,k}^{\mathfrak{B}}$, $\widetilde{\mathbf{h}}_{J,k}^{\mathfrak{B}}$, which is the same as (13). By substituting $\widetilde{\mathbf{G}}_{i,k}^{\mathfrak{B}}$, $\widetilde{\mathbf{h}}_{J,k}^{\mathfrak{B}}$ into (7) and defining $\mathbf{w}_k=\sqrt{p_k}\mathbf{v}_k$, then $\mathfrak{B}$ is recast as

$$\min_{\{p_k\}\geq 0,\{\mathbf{w}_k\}}\ \sum_{k=1}^{K}p_k$$

$$s.t.\ \mathrm{C1}^*:\frac{\left|\widetilde{\mathbf{G}}_{k,k}^{\mathfrak{B},H}\mathbf{w}_k\right|^2}{2^{\gamma_{U,k}}-1}\geq\sum_{i=1,i\neq k}^{K}\left|\widetilde{\mathbf{G}}_{i,k}^{\mathfrak{B},H}\mathbf{w}_i\right|^2+d_k,\forall k, \tag{22}$$

$$\mathrm{C2}^*:[\mathbf{w}_k\mathbf{w}_k^H]_{n,n}=p_k,\forall k,n, \tag{23}$$

where $d_k=\sum_{i=1}^{K}\left|\widetilde{\mathbf{h}}_{J,k}^{\mathfrak{B},H}\mathbf{w}_{J,i}\right|^2+\sigma_{U,k}^2$. However, $\mathfrak{B}$ is still unfeasible due to the unknown d_k. To proceed, we obtain the feasible upper bound of d_k via the Cauchy-Schwarz inequality, i.e., $d_k^{\max}=\sum_{i=1}^{K}\widehat{p}_{J,i}\left\|\widetilde{\mathbf{h}}_{J,k}^{\mathfrak{B}}\right\|^2+\sigma_{U,k}^2$, where $\widehat{p}_{J,k}$ is the estimation of jamming power. Through the substitution of $d_k^{\max}$ into $\mathfrak{B}$ and defination of nonnegative Lagrangian multipliers $\{\beta_{kn}\}$, $\{\lambda_{B,k}\}$, the Lagrangian function for $\mathfrak{B}$ is given by [12]

$$\mathcal{L}_B=\sum_{k=1}^{K}\lambda_{B,k}d_k^{\max}-\sum_{k=1}^{K}p_k\left(\sum_{n=1}^{N}\beta_{kn}-1\right)+\sum_{k=1}^{K}\mathbf{w}_k^H\mathbf{R}_k\mathbf{w}_k, \tag{24}$$

where

$$\mathbf{R}_k=\left(\boldsymbol{\beta}_k+\sum_{i\neq k}^{K}\lambda_{B,i}\widetilde{\mathbf{G}}_{k,i}^{\mathfrak{B}}\widetilde{\mathbf{G}}_{k,i}^{\mathfrak{B},H}-\lambda_{B,k}\frac{\widetilde{\mathbf{G}}_{k,k}^{\mathfrak{B}}\widetilde{\mathbf{G}}_{k,k}^{\mathfrak{B},H}}{2^{\gamma_{U,k}}-1}\right)$$

and $\boldsymbol{\beta}_k=\mathrm{diag}\left(\beta_{k1}\cdots,\beta_{kN}\right)$. Although [12] has proposed an dual method to solve $\mathbf{w}_k$, it may lead high computational complexity and infeasibility due to the usage of CVX tool. Thus, we propose a novel subspace-decomposition based method to obtain $\mathbf{w}_k$. The KKT condition of $\mathbf{w}_k$ is

$$\partial_{\mathbf{w}_k}\mathcal{L}=\mathbf{R}_k\mathbf{w}_k=0. \tag{25}$$

Since $\mathbf{w}_k\neq\mathbf{0}$, we must have $\mathrm{rank}\left(\mathbf{R}_k\right)<N$ and $\mathbf{w}_k\bot\mathbf{R}_k$. Moreover, denoting $\widetilde{\gamma}_{U,k}=1/(2^{\gamma_{U,k}}-1)$, we can obtain that

$$\mathbf{R}_k+\mathbf{R}_n=\boldsymbol{\beta}_k+\boldsymbol{\beta}_n+2\sum_{i\neq k,n}^{K}\lambda_{B,i}\widetilde{\mathbf{G}}_{k,i}^{\mathfrak{B}}\widetilde{\mathbf{G}}_{k,i}^{\mathfrak{B},H} \tag{26}$$

$$+\lambda_{B,k}\left(1-\widetilde{\gamma}_{U,k}\right)\widetilde{\mathbf{G}}_{k,k}^{\mathfrak{B}}\widetilde{\mathbf{G}}_{k,k}^{\mathfrak{B},H}+\lambda_{B,n}\left(1-\widetilde{\gamma}_{U,k}\right)\widetilde{\mathbf{G}}_{n,n}^{\mathfrak{B}}\widetilde{\mathbf{G}}_{n,n}^{\mathfrak{B},H}.$$

Obviously, $\widetilde{\mathbf{G}}_{k,k}^{\mathfrak{B}}\widetilde{\mathbf{G}}_{k,k}^{\mathfrak{B},H}\succeq 0$ and $\{\beta_{kn}\}$, $\{\lambda_{B,k}\}>0$. Thus, for any $\gamma_{U,k}>1$, $\mathbf{R}_k+\mathbf{R}_n\succ 0$, which suggests that $\mathrm{rank}\left(\mathbf{R}_k+\mathbf{R}_n\right)=N$. Denote $\{\mathbf{r}_k\}$ and $\{\mathbf{r}_n\}$ as the eigenvectors set of $\mathbf{R}_k$ and $\mathbf{R}_n$, respectively, and then we can drive from the full-rank property $\mathrm{rank}\left(\mathbf{R}_k+\mathbf{R}_n\right)=N$ that

$$\mathrm{span}\left\{\{\mathbf{r}_k\}\cup\{\mathbf{r}_n\}\right\}=\mathrm{span}\left\{\mathbf{e}_1\cdots,\mathbf{e}_N\right\}, \tag{27}$$

where $\mathbf{I}_N=[\mathbf{e}_1\cdots,\mathbf{e}_N]$. Recall the fact that $\mathbf{w}_k\bot\mathbf{R}_k$, $\mathbf{w}_k\bot\mathrm{span}\left\{\mathbf{r}_k\right\}$ and $\mathbf{w}_k\subseteq\mathrm{span}\left\{\mathbf{r}_n\right\},\forall k\neq n$ can be derived. Since $\mathbf{w}_n\bot\mathrm{span}\left\{\mathbf{r}_n\right\}$, we obtain $\mathbf{w}_k\bot\mathbf{w}_n,\forall k\neq n$. Inspired by [10] and [12], the optimal $\mathbf{w}_k^{\star}$ can be expressed as

$$\mathbf{w}_k^{\star}=\sqrt{p_k}\mathbf{v}_k^{\star}=\sqrt{Np_k}\exp\left\{\arg\left(\frac{\widetilde{\mathbf{H}}_k^{\mathfrak{B}}\left(\widetilde{\mathbf{H}}_k^{\mathfrak{B},H}\widetilde{\mathbf{H}}_k^{\mathfrak{B}}\right)^{-1}_{,k}}{\sqrt{\left(\widetilde{\mathbf{H}}_k^{\mathfrak{B},H}\widetilde{\mathbf{H}}_k^{\mathfrak{B}}\right)^{-1}_{k,k}}}\right)\right\}, \tag{28}$$

where $\widetilde{\mathbf{H}}_k^{\mathfrak{B}}=\left[\widetilde{\mathbf{G}}_{1,k}^{\mathfrak{B}},\cdots,\widetilde{\mathbf{G}}_{K,k}^{\mathfrak{B}}\right]$ and $\left(\mathbf{A}\right)_{,k}$ denotes the elements in the k-th column of $\mathbf{A}$. Note that $\|\mathbf{w}_k\|=\sqrt{Np_k}$ since each phase vector's module is unit, which implies that more power can be used to defend against jamming attacks than the MIMO anti-jamming system. Then $\mathfrak{B}$ is transformed into a power minimization problems.

Inspired by [11], the optimal $\{p_k\}$ is obtained when C1* in $\mathfrak{B}$ is met with equalities, which is given by

$$p_k^{\star}=\frac{2^{\gamma_{U,k}}-1}{\left|\widetilde{\mathbf{G}}_{k,k}^{\mathfrak{B},H}\mathbf{v}_k^{\star}\right|^2}\left(\sum_{i\neq k}^{K}p_i\left|\widetilde{\mathbf{G}}_{i,k}^{\mathfrak{B},H}\mathbf{v}_i^{\star}\right|^2+d_k^{\max}\right),\forall k. \tag{29}$$

According to [25], we can prove that (29) is a standard interference function, which can be solved by the iterative power control scheme in [25], and thus is omitted for simplicity.

C. Existence and Uniqueness of SE for the Proposed Game

In the proposed game, the SE is defined as follows [4].

Theorem 1: If the following conditions (30) are satisfied, the optimal strategies $\left(\left\{\mathbf{w}_{J,k}^{\star}\right\},\{p_k^{\star},\mathbf{v}_k^{\star}\}\right)$ constitutes the SE.

$$U_B\left(p_k^{\star},\mathbf{v}_k^{\star},\mathbf{w}_{J,k}^{\star}\right)\geq U_B\left(p_k,\mathbf{v}_k,\mathbf{w}_{J,k}^{\star}\right),$$
$$U_J\left(p_k^{\star},\mathbf{v}_k^{\star},\mathbf{w}_{J,k}^{\star}\right)\geq U_J\left(p_k^{\star},\mathbf{v}_k^{\star},\mathbf{w}_{J,k}\right). \tag{30}$$

Theorem 2: There exists a unique SE in the proposed anti-jamming Bayesian Stackelberg game.

Proof: According to ***Theorem 1***, the jammer and BS obtain an SE when both sides believe they have achieved the highest utilities. Given the BS's strategy $\{p_k,\mathbf{v}_k\}$, the proposed game simplifies to a non-cooperative game and $\mathfrak{J}$ is convex. Particularly, the strategy space with (14) is a convex and compact subspace of Euclidean space, and thus the jammer's utility function U_J is convex with respect to $\mathbf{w}_{J,k}$ for given $\{p_k, \mathbf{v}_k\}$. According to [10], there exists at least one SE in the follower sub-game, and the unique SE with given $\{p_k, \mathbf{v}_k\}$ can be expressed as $\left(p_k, \mathbf{v}_k, \mathbf{w}^{\star}_{J,k}(\{p_k, \mathbf{v}_k\})\right)$. As such, the SE condition can be rewritten as

$$U_B\big(p_k^{\star},\mathbf{v}_k^{\star},\mathbf{w}^{\star}_{J,k}(\{p_k^{\star},\mathbf{v}_k^{\star}\})\big)\geq U_B\big(p_k,\mathbf{v}_k,\mathbf{w}^{\star}_{J,k}(\{p_k,\mathbf{v}_k\})\big). \quad (31)$$

Then, we turn to the leader sub-game. Clearly, $\mathfrak{B}$ can be transformed into a convex one, and the KKT solution (29) with (28) forms a unique strategy pair with $\left(p_k^{\star}, \mathbf{v}_k^{\star}, \mathbf{w}^{\star}_{J,k}(\{p_k^{\star}, \mathbf{v}_k^{\star}\})\right)$ with that of jammer, which satisfies (29) and thus becomes the SE of the proposed game. ■

D. Power Scaling Law and Differences from MIMO systems

The scaling law of the average received power at users with respect to the number of RIS units is characterized here. For simplicity, we only consider the single-user case $K=1$ with perfect CSI and $\mathbf{B}_k{=}\mathbf{1}_N$. As such, the upper bound of received power at the user is given by $P_u = p\left|\mathbf{G}^H\mathbf{v}\right|^2$, where p is the BS's transmit power, $\mathbf{G}$ is the channel vector between the RIS and the user, and $\mathbf{v}$ is the RIS's phase beamforming. Since there is no multi-user interference, the maximal-ratio transmission (MRT) is the optimal, i.e., $[\mathbf{v}]_n = [\mathbf{G}]_n/|[\mathbf{G}]_n|$.

Theorem 3: Given $\mathbf{G} \sim \mathcal{CN}(0, \varsigma\mathbf{I})$ and $N \to \infty$, we have

$$P_u = \frac{\left(\pi^2 - 7\pi + 16\right)}{4} N^2 \varsigma p, \quad \text{if } [\mathbf{v}]_n = \frac{[\mathbf{G}]_n}{|[\mathbf{G}]_n|}, \forall n. \quad (32)$$

Proof: For the optimal $[\mathbf{v}]_n = [\mathbf{G}]_n/|[\mathbf{G}]_n|$, we have

$$\mathbf{G}^H\mathbf{v}{=}\sum\nolimits_{n=1}^{N}[\mathbf{v}]_n^*[\mathbf{G}]_n = \sum\nolimits_{n=1}^{N}|[\mathbf{G}]_n|. \quad (33)$$

Since $|[\mathbf{G}]_n|$ follows Rayleigh distribution with mean value $\sqrt{\pi\varsigma}/2$ and variance $(4-\pi)\varsigma/2$. By invoking the Lindeberg-Levy central limit theorem, we have $\sum_{n=1}^{N}|[\mathbf{G}]_n| \sim \mathcal{CN}\left(N\sqrt{\pi\varsigma}/2, N(4-\pi)\varsigma/2\right)$. Thus, one obtains that

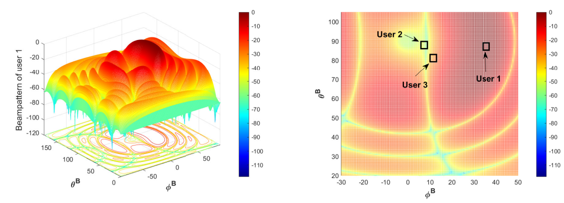
$$P_u = \mathrm{E}\left\{p\left|\mathbf{G}^H\mathbf{v}\right|^2\right\} = \frac{\left(\pi^2 - 7\pi + 16\right)}{4} N^2 \varsigma p. \quad (34)$$

Hence, the proof is completed. ■

According to ***Theorem 3***, the received power increases by a factor of $1/N^2$, which suggests that the BS's transmit power quadratically decreases with the number of RIS units. However, for conventional massive MIMO, the transmit beamforming gain is order N [26]. The fundamental reason behind such a "squared gain" is two-fold. First, RIS can not only achieves the transmit beamforming gain of order N in the RIS-user link as in the conventional massive MIMO, but also captures an inherent aperture gain of order N by collecting more signal power in the BS-IRS link, which, however, cannot be achieved by scaling up the number of transmit antennas in massive MIMO due to the fixed total transmit power [11]. Second, RIS modulates and transmits the signal via reflection and increasing the number of RIS elements, which does not need additional transmit power of the transmitter [12]. The above insightful views confirm that the BS consumes less power in the RIS-assisted anti-jamming system, such that the proposed system has the superior anti-jamming performance than the MIMO system.

IV. Simulation Results

In this section, numerical simulations are provided to validate the proposed algorithm. We consider a total of $K=3$ users, a RIS equipped with $N = N_1 \times N_2$ units for each user, and the antennas number of jammer is $M = KN$. It is assumed that the RIS-aided BS and the jammer are located at $(0,0,10)$ and $(250,0,0)$ in meter (m) in a 3-D plane, respectively. Users are uniformly located in a circle centered at $(150,50,0)$ with radius of 50 m. We set $\sigma^2_{U,k} = -80$ dBm, $L_B = L_J = 5$, $\gamma_{U,k} = 2$ bps/Hz, and $\tau_{J,k} = 0.2$ bps/Hz/Joule. In addition, AoA uncertainty is defined as $\Delta = \theta_U - \theta_L = \varphi_U - \varphi_L$. The seting of $\mathbf{B}_k$ is same as [21]. Here, we set the maximum transmission power of the BS and jammer as 2.4 W, and define the BS's outage probability as $\Pr\left\{\sum_{k=1}^{K} p_k \geq 2.4\ \mathrm{W}\right\}$. We also compare the performance of the proposed robust beamforming (BF) scheme with that of the following schemes: 1) Non-robust scheme: BS optimzes the transmit power and phase shift with the estimated CSI, which is randomly distributed in the given AOA range; 2) MRT robust scheme: BS performs phase beamforming by using MRT; 3) Dual method: the method proposed in [12] is utilized to performs phase beamforming.



(a) 3D vision $\Delta_B = 8°$. (b) Vertical vision $\Delta_B = 8°$.

Fig. 2: 3D Beampattern of $\mathbf{V}_1\mathbf{B}_1$ versus AoA.

Fig. 2 depicts the 3D beampattern of $\mathbf{V}_1\mathbf{B}_1$ versus AoA for different Δ_B. Here, we set $\Delta_J = 8°$ and $N_2 = 12$. It is observed even when the $\Delta_B = 8°$, the received SINR at user 1 is about 0 dB, while the received SINR at region of user 2 and 3 are nulled beyond -30 dB. This phenomenon verifies the effectiveness of our proposed robust design in both combating the jamming attack and eliminating the inter-user interference.

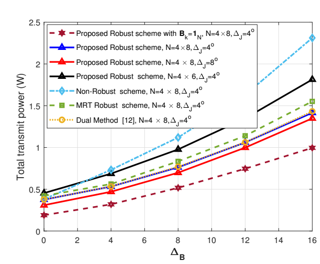


Fig. 3: BS's transmit power versus AoA uncertainty Δ_B.

Fig. 3 shows the BS's transmit power versus the AoA uncertainty Δ_B. As expected, the proposed robust scheme outperforms the non-robust scheme and the MRT scheme, especially for large Δ_B is large. In addition, the power consumption of proposed scheme is almost the same as that of dual method in [12]. The abovementioned results confirm the the superiority and validity of our proposed robust schemes. However, since the rader channel $\mathbf{B}_k$ leads to both the non-uniform power distribution and the power loss on the RIS, the proposed scheme with $\mathbf{B}_k = \mathbf{1}_N$ can achieve superior performance than that with radar channel $\mathbf{B}_k$. Moreover, the transmit power increases with Δ_B, whereas we see the converse with Δ_J. This is because as Δ_J increases, the damage effect induced by the jammer degrades, and thus the BS's power consumption decreases. We can also observe that the use of more RIS units N can improve the performance, which is due to the fact that beam resolution increases with N such that the inter-user interference is decreased.

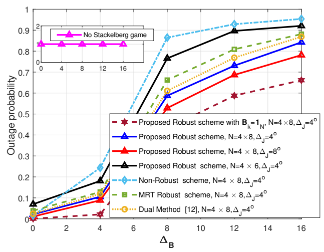


Fig. 4: BS's outage probability versus AoA uncertainty Δ_B.

The BS's outage probability versus AoA uncertainty Δ_B is shown in Fig. 4. We can observe that the outage probability of scheme without Stackelberg game is constant to one, which verifies the validity of proposed Stackelberg anti-jamming game. Besides, since the dual method needs to solve numerical dual variables with uncertainty bound Δ_B, the outage probability of dual method is higher than that of the proposed robust scheme. Finally, in terms of the outage probability, our proposed robust scheme is superior than other schemes even when Δ_B is large, which implies that the robust design is also applicable to mobile users.

V. Conclusions

This paper has proposed a robust BF design with the imperfect angular information for the RIS-assisted Stackelberg anti-jamming game, where the BS is the leader and the jammer acts as the follower to obtain their own maximum utilities. In addition, we adopted the assumption that neither side can obtain the other's strategies. Then, the discretization method and the Cauchy-Schwarz inequality have been utilized to address the imperfect angular information and relax the practical assumption, respectively. Thus, the closed-form solution of both sides can be obtained via the duality optimization theory, which constitutes an unique SE. Numerical results confirmed that the proposed algorithm has the superior performance compared with other exsiting schemes, and revealed the impact of AoA uncertainty on the system performance.

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