Joint Location and Channel Error Optimization for Beamforming Design for Multi-RIS Assisted MIMO System

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***Abstract*—Reconfigurable intelligent surface (RIS) has been proved to be a promising approach to enhance the performance of wireless communication because of its intelligently reconfiguring the passive reflecting elements. Previous works only consider the beamforming design for a fixed RIS location/deployment and perfect channel state information (CSI). While RIS's location and perfect CSI can be further optimized to enhance the system performance. In this paper, the robust beamforming design is investigated for multi-RIS assisted multiuser millimeter wave system with imperfect CSI, where the weighted sum-rate maximization (WSM) problem is formulated. The considered WSM maximization problem includes channel estimation error, bandwidth as well as RIS placement variables, which results in a complicated nonconvex optimization problem. To handle this problem, we decouple the original problem into a series of subproblems, where the location, bandwidth, channel error, transmit beamforming and passive beamforming are optimized iteratively. Then, we develop an alternating optimization algorithm based on the penalty and gradient projection (GP) methods to alleviate the performance loss caused by the effect of imperfect CSI. Simulations validate that the proposed scheme can bring significant performance gains, especially considering its high spectral efficiency, when designing the location of RIS and imperfect CSI.**

***Index Terms*—Reconfigurable intelligent surface (RIS), imperfect channel state information (CSI), RIS placement optimization, beamforming design, non-convex optimization.**

I. Introduction

RECONFIGURABLE intelligent surface (RIS), as a revolutionary technology, has great potential to improve the performance of beyond 5G and 6G network. Specifically, RIS is made of a newly developed metamaterial, which can establish a favourable transmission environment by collaboratively adjusting amplitude and phase shift to improve the spectral and energy efficiency [1] [2]. More importantly, RIS is a meta-surface equipped with low-cost reflecting elements, and hence they can be easily deployed and integrated into existing wireless communication systems without changing the existing infrastructure and operating standards [3]. Therefore, the design of RISs in enhancing the spectral efficiency (SE) of B5G/6G networks has attracted extensive attention.

In the literature, several design of RISs schemes have been proposed for MIMO systems. The studies in [4] proposed the application of the maximum transmission scheme for RIS-assisted single-cell wireless system, where a joint PBF and ABF optimization problem was formulated. Also, a similar problem was considered for multi-RIS assisted systems to improve robustness against blockages [5]. The authors in [6] investigated an artificial noise-aided secure MIMO communication system by exploiting RIS to enhance the physical layer security. In [7], a RIS-assisted vertical beamforming scheme for cognitive radio networks were proposed by jointly optimizing the beamforming vector, tilt angle as well as the phase shifts. The work of [8] investigated a worst-case robust beamforming design based on quality of service for a multi-user MISO wireless communication, when the CSI was assumed to be imperfect.

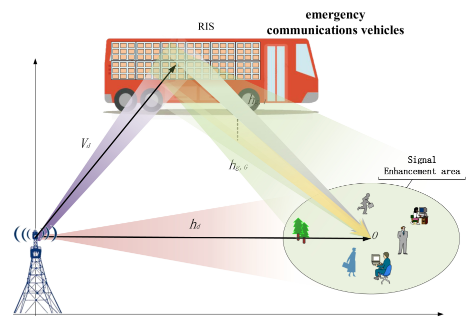

Fig. 1. Illustration of the considered multi-RIS assisted mmWave MIMO communication system.

However, considering fast time-varying fading channels scenarios, the transmitters may only be able to obtain partial or outdated channel state information (CSI). This inevitably results in the signal misalignment in RIS-assisted wireless networks. Since the CSI of reflect beamforming at RIS is obtained through feedback links to multiple users (UEs), knowledge for the CSI of the reflect beamforming at RIS will result in large delay and significant training overhead. Therefore, considering the imperfect CSI of the channels for RIS-assisted communication system could be further investigated.

Motivated by the above observations, the robust beamforming design with imperfect CSI for RIS-assisted wireless communications is still in its infancy and needs to be further discussed in the open literature. In this paper, the robust beamforming framework is proposed for RIS-assisted multiuser wireless communications under imperfect CSI, where CSI error and the placement of RIS can be more flexibly optimized. The effectiveness of the proposed beamformer designs is validated by extensive simulation results, which illustrate that the proposed mechanism and the corresponding algorithm can improve the SE significantly over the conventional system.

II. System Model and Problem Formulation

In this section, we follow the system model of recent state-of-the-art works on IRS-assisted MIMO system [4], [5], [9], in which IRS equipped with reflecting elements is deployed between BS and UEs. The phase shift of the RIS, the optimal placement of RIS and the imperfect channel model are then constructed to optimize the system performance.

A. RIS-assisted Communication Scenario

Consider multi-RIS assisted MIMO system, a multi-antenna BS is deployed to serve K UEs. As shown in Fig. 1, a RIS equipped with G RIS units is deployed to enhance the communication coverage, which are located in the coordinates $\boldsymbol{u} = (u(1), u(2))$ and the altitude $H_{_{RIS}}$. Each RIS unit is arranged in the form of an $M = M_{\mathrm{az}} \times M_{\mathrm{el}}$ rectangular array with M_{az} elements horizontally and M_{el} elements vertically, which are controlled via its smart controller. The BS is deployed at a fixed altitude $H_{_{BS}} = \zeta H_{_{RIS}}$, which is located in the coordinates $\boldsymbol{y}_{_{BS}} = (0, 0)$. $d_{_{BU}} = \sqrt{H_{_{BS}}^2 + \|\boldsymbol{y}_{_{BS}} - \boldsymbol{o}_{_{UE}}\|_2^2}$ denotes the distance from the BS to the k-th UE; $d_{IU} = \sqrt{H_{_{RIS}}^2 + \|\boldsymbol{u} - \boldsymbol{o}_{_{UE_k}}\|_2^2}$ denotes the distance between the BS and the RIS. $d_{BI} = \sqrt{(H_{_{BS}} - H_{_{RIS_g}})^2 + \|\boldsymbol{u} - \boldsymbol{y}_{_{BS}}\|_2^2}$ denotes the distance from the BS to the g-th RIS. The the center horizontal and vertical location of RIS is denoted as $\boldsymbol{u} = (u(1), u(2))$, which is regarded as a reference point. All UEs are placed in the circular coordinate area. The center of the coverage area is denoted by $\boldsymbol{o}_{_0} = [o_{_0}(1), o_{_0}(2)]^T$. Hence, the location of the coverage area can be specified as $\boldsymbol{o}_{_{UE}} = [o_{_a}(1), o_{_b}(2)]^T$, $o_{_a}(1) \in [o_{_0}(1) - r, o_{_0}(1) + r]$, $o_{_b}(1) \in [o_{_0}(2) - r, o_{_0}(2) + r]$, where r denotes the radius of the coverage area.

B. RIS Design with Limited Reflection Elements

We assume that G RIS units serving K UEs and each RIS units has s reflection coefficient, i.e., $M = Gs$. Let $\boldsymbol{\Theta} = [\boldsymbol{\Theta}_1 \ \boldsymbol{\Theta}_2 \ ,..., \ \boldsymbol{\Theta}_G]$ be the reflection coefficient matrix for the RIS, reflecting coefficient matrix of each RIS unit is given by

$$\boldsymbol{\Theta}_g = \mathrm{diag}\{\theta_1, \theta_2, ..., \theta_s\}, \quad g \in \{1, ..., G\} \tag{1}$$

where $\theta_{g,i}$ is i-th reflecting element of g-th RIS unit and the reflecting elements $\{\theta_i\}$ are assumed to be continuously controllable. According to the (1), the setting of the reflecting elements are considered in the following two cases.

1) Ideal RIS: The reflecting elements of RIS are updated with continuous amplitudes and phase shifts in this scenario. Thus, the feasible set of θ_i is formulated as

$$\mathcal{F}_1 = \{\theta_i | |\theta_i|^2 \in [0, 1]\}. \tag{2}$$

2) Non-ideal RIS: The reflecting amplitude of RIS is designed as a fixed value, such as $\varsigma_i = 1$. For this scenario, the continuous and discrete phase shifts design are considered, which can be formulated as

$$\begin{aligned} \text{Continuous}: \mathcal{F}_2 &= \left\{\theta_i | \theta_i = \varsigma_i e^{j\varphi_i}, \varphi_i \in [0, 2\pi), \varsigma_i = 1\right\}, \\ \text{Discrete}: \mathcal{F}_3 &= \left\{\theta_i | \theta_i = \varsigma_i e^{j\varphi_i}, \varphi_i \in \mathcal{D}, \varsigma_i = 1\right\}, \end{aligned} \tag{3}$$

where $\mathcal{D} = \left\{\frac{2\pi n}{2^B}, n = 1, 2, ..., 2^B\right\}$.

III. RIS-assisted Beamforming Design and Problem Formulation

A. Problem Formulation and Transformation

In this section, we investigate the robust beamforming scheme to realize reflected signals toward preferable directions. From a systematic perspective, the SE maximization problem is developed as our design criterion, which can be decomposed into two subproblem: the active/passive beamforming optimization subproblem.

Let $\boldsymbol{s}_k$ be the transmitted symbol and $\boldsymbol{w}_k \in \mathbb{C}$ is the active beamforming vector for the k-th UE. Therefore, the received signal of the k-th UE can be expressed as

$$\hat{y}_k = \left(\boldsymbol{h}_{d,k}^H + \sum_{g=1}^{G} \boldsymbol{h}_{g,k}^H \boldsymbol{\Theta}_g \boldsymbol{V}_g\right) \sum_{k=1}^{K} \boldsymbol{w}_k s_k + n_k, \tag{4}$$

where $\boldsymbol{h}_{d,k}$ is the BS-UE link in the k-th UE, $\boldsymbol{h}_{g,k} \in \mathbb{C}^{M\times 1}$ is the RIS$_g$-UE channel of the k-th UE, $\boldsymbol{V}_g \in \mathbb{C}^{M\times N}$ is the BS-RIS$_g$ channel in the g-th RIS units, $n_k \sim \mathcal{CN}(0, \sigma^2)$ denotes the additive white Gaussian noise (AWGN) at the k-th UE with zero mean and variance σ^2. To make the above expression more tractable, we further define $\boldsymbol{\theta}_g = \mathrm{vec}(\boldsymbol{\Theta}_g)$ and $\boldsymbol{H}_{g,k} = \boldsymbol{V}_g^H \otimes \boldsymbol{h}_{g,k}^H$ and then a decoder f_k is used to decode the desired signal of k-th UE, which can be written as

$$\hat{s}_k = f_k^H \hat{y}_k = f_k^H \left(\boldsymbol{h}_{d,k}^H + \sum_{g=1}^{G} \boldsymbol{h}_{g,k} \boldsymbol{\theta}_g\right) \sum_{k=1}^{K} \boldsymbol{w}_k s_k + f_k^H n_k, \tag{5}$$

Furthermore, it is observed that the residual channel error will substantially impact the overall system performance due to imperfect CSI. Although we consider the simple Rayleigh fading channels for RIS-assisted syatem, it is still difficult to estimate the accurate channel by exploiting the average maximum mean square error (MSE), which is a commonly used scheme for stochastic channels [10], [11].

Therefore, it is important to design robust beamforming scheme. To this end, we introduce the estimation error to model the channel, the received signal at the k-th UE is written as

$$\hat{s}_k = \underbrace{f_k^H \hat{\boldsymbol{h}}_k^H \boldsymbol{w}_k s_k}_{\text{desired signal}} + \underbrace{f_k^H \boldsymbol{h}_{e,k}^H \boldsymbol{w}_k s_k}_{\text{residual error}} + \underbrace{f_k^H \hat{\boldsymbol{h}}_k^H \sum_{k\neq i}^{K-1} \boldsymbol{w}_i s_i}_{\text{multiuser interference}} + \underbrace{f_k^H n_k}_{\text{noise}}, \tag{6}$$

where $\hat{\boldsymbol{h}}_k^H = \boldsymbol{h}_{d,k}^H + \sum_{g=1}^{G} \boldsymbol{H}_{g,k} \boldsymbol{\theta}_g$ denotes the estimated channel of the k-th UE and $\boldsymbol{h}_{e,k}$ is the corresponding residual channel error.

To maximize the spectral efficiency of system, the corresponding signal-to-interference-plus-noise ratio (SINR) of the k-th UE is given by

$$\gamma_k = \frac{\left| f_k^H \left(\boldsymbol{h}_{d,k}^H + \sum_{g=1}^{G} \boldsymbol{H}_{g,k} \boldsymbol{\theta}_g\right) \boldsymbol{w}_k \right|^2}{\sum_{i=1, i\neq k}^{K} \left| f_k^H \left(\boldsymbol{h}_{d,k}^H + \sum_{g=1}^{G} \boldsymbol{H}_{g,k} \boldsymbol{\theta}_g\right) \boldsymbol{w}_i \right|^2 + \left| f_k^H \boldsymbol{h}_{e,k}^H \boldsymbol{w}_k \right|^2 + \sigma^2}. \tag{7}$$

Based on the SINR principle in (7), it is observed that the sum-rate of a UE in a specific cell is coupled with transmit beamforming, the RIS placement, channel estimation error and phase shifts matrices. To make the problem tractable, the weighted sum-rate maximization (WSM) of the proposed RIS assisted mmWave system is adopted as the design criterion, which can be formulated as

$$\mathcal{P}(A1) \max_{\boldsymbol{u},\boldsymbol{w}_k,\boldsymbol{\theta},\boldsymbol{h}_{e,k}} \sum_{k=1}^{K} \omega_k \log_2(1+\gamma_k), \tag{8a}$$

$$s.t. \sum_{k=1}^{K} \left(\boldsymbol{w}_k^H \boldsymbol{w}_k\right) \leq P_{\max}, \tag{8b}$$

$$\theta_{g,m} \in \mathcal{F}_c, \quad c = \{1,2,3\} \tag{8c}$$

$$\|\boldsymbol{h}_{e,k}\|_2 \leq \epsilon, \tag{8d}$$

$$\|f_k\|_2^2 = 1, \tag{8e}$$

where the phase shifts feasible set for $\theta_{g,m}$ is $\mathcal{F}_c$, which can be given by ideal RIS and Non-ideal RIS cases.

It is obvious that the optimization problem $\mathcal{P}(A1)$ in (8) is quite challenging to estimate the RIS-assisted channel due to the following reasons. First, the objective function in (8a) makes $\mathcal{P}(A1)$ essentially a non-convex optimization problem because of the coupling of various optimization variables. Second, computing the objective function of $\mathcal{P}(A1)$ with expectation operations is computationally expensive. Moreover, the presence of the power constraint (8b) and CSI error constraint (8d) further complicate the optimization procedure. In the next section, we develop an innovative scheme to solve these difficult problem.

IV. Solutions of the Optimization Problem

In this section, an alternating optimization strategy is exploited for solving the optimization problem. Nevertheless, considering the the feasible solution involving four variables of problem (8) is nonconvex, which cannot expect to find the feasible solution. To tackle this issues, the sum-of-logarithms-of-ratio problem $\mathcal{P}(A1)$ is equivalently translated into a more tractable form $\mathcal{P}(A2)$ by using the fractional programming (FP) technique [12]. Thus, the problem $\mathcal{P}(A2)$ is decomposed into several subproblem, where each subproblem is alternately solved by while fixing the remaining variables.

Firstly, the closed-form FP scheme is developed in [13]. By introducing an auxiliary variable α_k, the maximization problem (8) w.r.t logarithm function $\log(1+\gamma_k)$ can be given by

$$\max_{\boldsymbol{z},\boldsymbol{\alpha}} \sum_{k=1}^{K} \omega_k \log(1+\alpha_k) - \omega_k\alpha_k + \omega_k(1+\alpha_k)\frac{|A_k(\boldsymbol{z})|^2}{B_k(\boldsymbol{z})} \tag{9a}$$

$$s.t. \quad \alpha_k \geq 0, \quad \forall k = 1, ..., K, \tag{9b}$$

where $\boldsymbol{\alpha} = [\alpha_1, ..., \alpha_K]^T$, $A_k(\boldsymbol{z})$ is nonnegative function, $B_k(\boldsymbol{z})$ is positive function and $B_k(\boldsymbol{z}) > |A_k(\boldsymbol{z})|^2$ for all k. From the objective function of the problem (9), the ratio $\frac{|A_k(\boldsymbol{z})|^2}{B_k(\boldsymbol{z})-|A_k(\boldsymbol{z})|^2}$ can be physically regarded as the SINR term in (8a).

Based on above observations, we introduce closed-form FP scheme by dropping the quadratic transform in (9) to solve the optimization problem (8) as follows.

$$\mathcal{P}(A2) \quad \max_{\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{u},\boldsymbol{\theta},\boldsymbol{w}_k,\boldsymbol{h}_{e,k}} f_{A2}(\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{u},\boldsymbol{\theta},\boldsymbol{w}_k,\boldsymbol{h}_{e,k}), \tag{10a}$$

$$s.t. \ (8b), (8c), (8d), (9b), \tag{10b}$$

where the corresponding objective function is given by

$$\begin{aligned} f_{A2}\left(\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{u},\boldsymbol{\theta},\boldsymbol{w}_k,\boldsymbol{h}_{e,k}\right) &= \sum_{k=1}^{K} \omega_k \left(\log(1+\alpha_k) - \alpha_k\right) \\ &+ \sum_{k=1}^{K} 2\sqrt{\omega_k(1+\alpha_k)} Re\left\{\beta_k^* f_k^H \hat{\boldsymbol{h}}_k^H \boldsymbol{w}_k\right\} \\ &- \sum_{k=1}^{K} |\beta_k|^2 \Big(\sum_{i=1}^{K} \left|f_k^H \hat{\boldsymbol{h}}_k^H \boldsymbol{w}_k\right|^2 + \left|f_k^H \boldsymbol{h}_{e,k}^H \boldsymbol{w}_k\right|^2 + \sigma^2 \|f_k\|_2^2\Big). \end{aligned} \tag{11}$$

Although we have transformed problem (8) into problem (11), it is still not straightforward to solve the problem $\mathcal{P}(A2)$ by simultaneously optimizing all variables. Motivated by this, we decouple it into four subproblems to deal with the RIS placement, bandwidth, channel error and passive beamforming optimization with continuous phase shifts in the following.

A. Location Planning Optimization

We investigate the location planning with fixed the $\boldsymbol{\theta}, \boldsymbol{h}_{e,k}, \boldsymbol{\beta}$ and $\boldsymbol{w}_k$. Therefore, based on the problem $\mathcal{P}(A2)$ in (10), for any given RIS placement, the location planning optimization problem can be formulated as

$$\min_{\boldsymbol{u}} \sum_{k=1}^{K} \frac{\left(H_{RIS}^2 + \|\boldsymbol{u} - \boldsymbol{o}_{UE}\|_2^2\right)\left((\zeta-1)^2 H_{RIS}^2 + \|\boldsymbol{u} - \boldsymbol{y}_{BS}\|_2^2\right)}{\boldsymbol{A}_k + \boldsymbol{B}_k}, \tag{12}$$

where

$$\boldsymbol{A}_k = \sum_{k=1}^{K} 2\sqrt{\omega_k(1+\alpha_k)} Re\left\{\beta_k^* f_k^H \sum_{g=1}^{G} \hat{\boldsymbol{V}}_g^H \otimes \hat{\boldsymbol{h}}_{g,k}^H \boldsymbol{\theta}_g \boldsymbol{w}_k\right\}$$

$$\boldsymbol{B}_k = -|\beta_k|^2 \Big(\sum_{i\neq k}^{K} f_k^H \Big| \sum_{g=1}^{G} \hat{\boldsymbol{V}}_g^H \otimes \hat{\boldsymbol{h}}_{g,k}^H \boldsymbol{\theta}_g \boldsymbol{w}_i \Big|^2\Big).$$

It can be observed that the optimization problem (12) is intrinsically a classical fractional programming problem, which can be solved by checking the first-order derivative. After dropping irrelevant constant terms, the optimal horizontal placement of the RIS is given by

$$\boldsymbol{u} = \xi^*(\delta)\boldsymbol{o}_G \tag{13}$$

with

$$\xi^*(\delta) = \begin{cases} \dfrac{1}{2}, & \delta \geq \dfrac{1}{2} \\ \dfrac{1}{2} - \sqrt{\dfrac{1}{4} - \delta^2} \text{ or } \dfrac{1}{2} + \sqrt{\dfrac{1}{4} - \delta^2}, & \text{otherwise} \end{cases} \tag{14}$$

where $\xi^*(\delta)$ is called the ratio coefficient and $\delta = \frac{(\zeta-1)^2 H_{RIS}^2}{D}$. It is observed from (13) that the optimal horizontal placement of RIS only relies on $\delta = \frac{(\zeta-1)^2 H_{RIS}^2}{D}$.

B. Transmit Beamforming Optimization

We optimize the variables $\boldsymbol{w}_k$ by fixing the remaining variables. Let $\boldsymbol{W} = \{\boldsymbol{w}_1, \boldsymbol{w}_2, ..., \boldsymbol{w}_K\}$, the optimization problem (10) with respect to the $\boldsymbol{W}$ is optimized through the following optimization problem

$$\mathcal{P}(A3) \quad \max_{\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{W}} f_{A3}(\boldsymbol{W}, \boldsymbol{\alpha}, \boldsymbol{\beta}), \tag{15a}$$

$$s.t.\ \mathrm{tr}\left(\boldsymbol{W}^H \boldsymbol{W}\right) \leq P_{\max}, \tag{15b}$$

where $\boldsymbol{\beta} = [\beta_1, ..., \beta_K]^T$ is the auxiliary vector.

It is worth mentioning that the optimization problem (15) is a biconvex optimization problem with respect to $\boldsymbol{w}_k$. Thus, the variable $\boldsymbol{w}_k$ can be optimized by exploiting the Lagrangian multiplier method, which can be is updated as follows

$$\hat{\boldsymbol{w}}_k = \sqrt{\omega_k(1+\alpha_k)}\beta_k f_k \left(\mu \boldsymbol{I}_N + |\beta_i|^2 \left(\sum_{i=1}^{K} \boldsymbol{h}_k \boldsymbol{h}_k^H + \boldsymbol{h}_{e,k} f_k f_k^H \boldsymbol{h}_{e,k}^H\right)\right)^{-1} \boldsymbol{h}_k, \tag{16}$$

where μ is obtained via the bisection search.

C. Passive Beamforming Optimization

After the completion of transmit beamforming, it needs further to solve the passive beamforming optimization problem by adjusting phase shifts pertaining to the RIS. With mathematical manipulations, the optimal solution to the problem (10) with respect to $\boldsymbol{\theta}$ can be rewritten as

$$\mathcal{P}(A4) \quad \max_{\boldsymbol{\theta}} \left\{ f_{A4}(\boldsymbol{\theta}) \triangleq \boldsymbol{\theta}^H \boldsymbol{Q} \boldsymbol{\theta} - 2Re\{\boldsymbol{\theta}^H \boldsymbol{c}\} \right\}, \tag{17a}$$

$$s.t.\ \ \theta_{g,m} \in \mathcal{F}_c, \quad c = \{1, 2, 3\}. \tag{17b}$$

where $\boldsymbol{Q}$ and $\boldsymbol{c}$ are given by

$$\boldsymbol{Q} = \sum_{k=1}^{K} |\beta_k|^2 \sum_{i=1}^{K} \boldsymbol{H}_{g,k} \left(\boldsymbol{w}_i^T \otimes f_k^H\right) \left(\boldsymbol{w}_i^T \otimes f_k^H\right)^H \boldsymbol{H}_{g,k}^H,$$

$$\boldsymbol{c} = \sum_{k=1}^{K} \left(\sqrt{\omega_k(1+\alpha_k)}\beta^* \left(\boldsymbol{w}_k^T \otimes f_k^H\right) \sum_{g=1}^{G} \boldsymbol{H}_{g,k} \right).$$

It follows that the gradient projection (GP) framework is developed to obtain the feasible solution. Specifically, the GP framework is updated in each iteration, which is given by

$$\boldsymbol{\theta}^{(t+1)} = \mathcal{P}_{\mathcal{F}_c} \left(\boldsymbol{\theta}^{(t)} - \eta \nabla f_{A4}(\boldsymbol{\theta}^{(t)}) \right) \tag{18}$$

where η denotes a pre-specified stepsize and $\nabla f_{A4}(\boldsymbol{\theta}) = -2(\boldsymbol{Q}\boldsymbol{\theta}^{(t)} + \boldsymbol{c})$ denotes the gradient of the objective function (17a).

D. Channel Error Optimization

To derive the optimal $\boldsymbol{h}_{e,k}$, the optimization problem (10) is then transformed to

$$\mathcal{P}(A5) \quad \max_{\boldsymbol{h}_{e,k}} f_{A5}(\boldsymbol{h}_{e,k}), \tag{19a}$$

$$s.t. \quad \|\boldsymbol{h}_{e,k}\|_2 \leq \epsilon, \tag{19b}$$

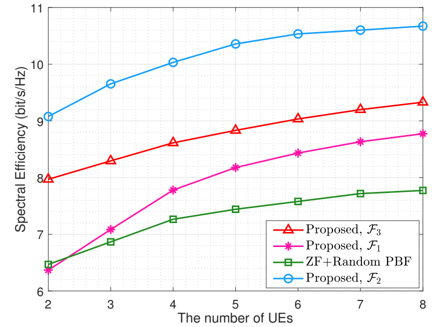

Fig. 2. Spectral efficiency versus the transmit power $P_{\max}$ for multi-RIS assisted system when M = 25, K = 2.

where the objective function with the properties of Kronecker products is

$$f_{A5}\left(\boldsymbol{h}_{e,k}\right) = -\sum_{k=1}^{K} |\beta_k|^2 \left(\sum_{i=1}^{K} \left| \left(\boldsymbol{w}_i^T \otimes f_k^H\right) \boldsymbol{h}_{e,k} \right|^2 + \sigma^2 \right). \tag{20}$$

It is not difficult to observe that above problem (19) with the constraint (19b) is a convex quadratically constrained quadratic program (QCQP); thus the channel error $\boldsymbol{h}_{e,k}$ is updated by exploiting the Karush-Kuhn-Tucker (KKT) condition as follows:

$$\boldsymbol{h}_{e,k} = \begin{cases} \hat{\boldsymbol{h}}_{e,k}, & \epsilon \geq 0 \\ \dfrac{\hat{\boldsymbol{h}}_{e,k}}{\sqrt{\|\hat{\boldsymbol{h}}_{e,k}\|_2}}, & \text{otherwise} \end{cases} \tag{21}$$

where $\hat{\boldsymbol{h}}_{e,k} = \frac{\epsilon}{|\beta_k|^2 \sum_{i=1}^{K} \left(\boldsymbol{w}_i^T \otimes f_k^H\right)}$.

Given $(\boldsymbol{\alpha}^{(0)}, \boldsymbol{\beta}^{(0)}, \boldsymbol{u}^{(0)}, \boldsymbol{\theta}^{(0)}, \boldsymbol{W}^{(0)})$, which is optimal at the t-th iteration, and repeat this process until convergence.

V. Simulation Results

In this section, we provide numerical results to validate the effectiveness of the proposed algorithm for multi-RIS assisted beamforming design with imperfect CSIs. To provide comparisons, the BS equipped with 4 antennas to serve 4 single-antenna UEs. According to [14] and [15], the channel gain is set as $g_v \sim \mathcal{CN}(0, 10^{-0.1PL(r)})$, and r is the distance between BS and UE. The BS with 32 reflect elements is located at the origin. Each RIS unit size is set as $M_{az} = 10$ and $M_{el} = 2$, which is designed to generate the high-quality channel from the BS to UEs. We assume that $G = 2$ RIS units located at (50 m, 30 m). The same path loss factors is considered in the LoS and NLoS links, respectively, i.e., $\alpha = 2$. Unless otherwise stated, the total transmit power is set to $P_{\max} = 30$dBm.

A. Impact of the transmit power

To study an overall observation of the performance of the proposed algorithm, we investigated the spectral efficiency versus the transmit power for $M = 25$ and $K = 4$ in Fig. 2. As illustrated, we investigated the the spectral efficiency achieved by different schemes versus the number of UEs, where three types of phase shifts set are considered in this case. Moreover, the phase shifts set has a great influence on the improvement of

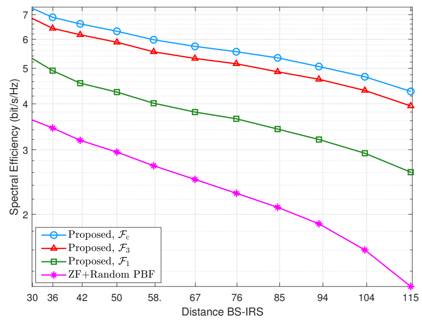

Fig. 3. SE versus the distance between BS and RIS for multi-RIS assisted system when M = 25.

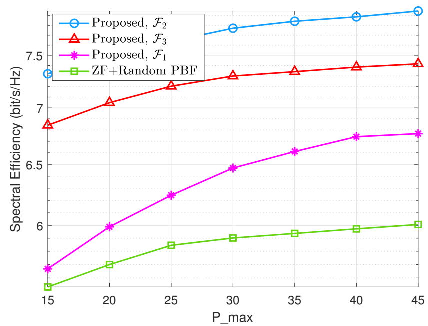

Fig. 4. The SE versus the transmit power $P_{\max}$ for multi-RIS assisted system.

system performance. For achieving the same spectral efficiency, the proposed scheme with phase shifts set $\mathcal{F}_2$ outperforms the phase shifts cases $\mathcal{F}_1$ and $\mathcal{F}_3$, which also verifies the effectiveness of of jointly active/passive beamforming design. This is because more RIS reflecting elements bring more reflection paths by optimizing phase shifts, which improve the performance of system.

B. Effect of RIS Deployment

In this subsection,the effects of RIS deployment position is investigated by moving the RIS from (10 m; 30 m) to (110 m; 30 m). For the sake of presentation, the horizontal coordinate of RIS is denoted by the symbol *x*. Fig. 3 shows the spectral efficiency of different schemes with respect to the horizontal distance of the RIS when the phase shifts set are given by $\{\mathcal{F}_i | i = 1, 2, 3\}$. As expected, increasing horizontal coordinate *x* from 10 m to 110 m leads to the spectral efficiency decreasing, which means long-distance information transmission results in high propagation path loss. According to Fig. 3, different phase shifts sets may lead to different system performance. It is worth noting that the performance of the proposed beamforming algorithm still better than the phase shifters schemes $\mathcal{F}_1$ and $\mathcal{F}_3$ regardless of the RIS deployment.

Fig. 4 displays the SE vs the transmitter power. It can be observed that the SE remains stable when the transmit power obtained by the proposed jointly active/passive beamforming design for M = 25.

VI. Conclusion

In this paper, we proposed a robust beamforming scheme, which strikes a balance between the beamforming gain and the channel error, and the importance of exploiting both the passive beamforming of RIS and flexible deployment in designing multi-RIS assisted wireless communications. We formulated an WSM problem that maximizes the beamforming gain and minimizes the channel estimation error at the same time. The closed-form FP method was employed to make the non-convex WSM problem. Furthermore, to alleviate the effects of the channel estimation error and RIS placement, the joint optimization of transmit/reflect beamforming, channel error and RIS placement algorithm was designed to overcome the channel uncertainty and RIS placement. The simulation results demonstrated that the developed approach is effective compared with conventional benchmark schemes.

References

[1] Z. Chen, J. Tang, X. Y. Zhang, D. K. C. So, S. Jin, and K.-K. Wong, "Hybrid evolutionary-based sparse channel estimation for irs-assisted mmwave MIMO systems," *IEEE Transactions on Wireless Communications*, pp. 1–13, 2021.

[2] W. Tang, M. Z. Chen, X. Chen, J. Y. Dai, Y. Han, M. Di Renzo, Y. Zeng, S. Jin, Q. Cheng, and T. J. Cui, "Wireless communications with reconfigurable intelligent surface: Path loss modeling and experimental measurement," *IEEE Transactions on Wireless Communications*, vol. 20, no. 1, pp. 421–439, 2021.

[3] Z. Chen, J. Tang, X. Y. Zhang, Q. Wu, Y. Wang, D. K. C. So, S. Jin, and K.-K. Wong, "Offset learning based channel estimation for intelligent reflecting surface-assisted indoor communication," *IEEE Journal of Selected Topics in Signal Processing*, vol. 16, no. 1, pp. 41–55, 2022.

[4] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network: Joint active and passive beamforming design," in *2018 IEEE Global Communications Conference (GLOBECOM)*, pp. 1–6, 2018.

[5] P. Wang, J. Fang, X. Yuan, Z. Chen, and H. Li, "Intelligent reflecting surface-assisted millimeter wave communications: Joint active and passive precoding design," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 12, pp. 14960–14973, 2020.

[6] S. Hong, C. Pan, H. Ren, K. Wang, and A. Nallanathan, "Artificial-noise-aided secure MIMO wireless communications via intelligent reflecting surface," *IEEE Transactions on Communications*, vol. 68, no. 12, pp. 7851–7866, 2020.

[7] S. F. Zamanian, S. M. Razavizadeh, and Q. Wu, "Vertical beamforming in intelligent reflecting surface-aided cognitive radio networks," *IEEE Wireless Communications Letters*, pp. 1–1, 2021.

[8] G. Zhou, C. Pan, H. Ren, K. Wang, M. D. Renzo, and A. Nallanathan, "Robust beamforming design for intelligent reflecting surface aided MISO communication systems," *IEEE Wireless Communications Letters*, vol. 9, no. 10, pp. 1658–1662, 2020.

[9] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Transactions on Wireless Communications*, vol. 18, no. 11, pp. 5394–5409, 2019.

[10] T. E. Bogale and L. Vandendorpe, "Robust sum MSE optimization for downlink multiuser MIMO systems with arbitrary power constraint: Generalized duality approach," *IEEE Transactions on Signal Processing*, vol. 60, no. 4, pp. 1862–1875, 2012.

[11] Q. Zhang, C. He, and L. Jiang, "Per-stream MSE based linear transceiver design for MIMO interference channels with CSI error," *IEEE Transactions on Communications*, vol. 63, no. 5, pp. 1676–1689, 2015.

[12] K. Shen and W. Yu, "Fractional programming for communication systems—part II: Uplink scheduling via matching," *IEEE Transactions on Signal Processing*, vol. 66, no. 10, pp. 2631–2644, 2018.

[13] H. Guo, Y.-C. Liang, J. Chen, and E. G. Larsson, "Weighted sum-rate maximization for reconfigurable intelligent surface aided wireless networks," *IEEE Transactions on Wireless Communications*, vol. 19, no. 5, pp. 3064–3076, 2020.

[14] M. R. Akdeniz, Y. Liu, M. K. Samimi, S. Sun, S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter wave channel modeling and cellular capacity evaluation," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1164–1179, 2014.

[15] Y. Cao, T. Lv, and W. Ni, "Intelligent reflecting surface aided multi-user mmwave communications for coverage enhancement," in *2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 1–6, 2020.