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Joint User Scheduling and Phase Shift Design for RIS Assisted Multi-cell MISO Systems

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***Abstract*—This paper investigates the joint user scheduling and phase shift design for reconfigurable intelligent surface (RIS) assisted multi-cell downlink systems. A closed-form ergodic sum spectral efficiency (SE) approximation is utilized as the optimization metric. Based on this approximation, we schedule the users, whose cascaded channels are mostly correlated with each other's, to maximize each user's effective signal. Moreover, the RIS phase shift is designed to be the mean of the scheduled users' cascaded channel phases. With the proposed transmission design, we find the optimal RIS deployment to achieve the highest maximum throughput which depends only on the relative locations of the BSs and RIS. In addition, we consider a more practical discrete RIS phase shift design based on a discrete Fourier transform (DFT) codebook. Simulation results show that the proposed low-complexity scheduling algorithm performs well.**

***Index Terms*—RIS, statistical CSI, user scheduling.**

I. INTRODUCTION

With the commercial deployment of the fifth-generation (5G) mobile communication systems, research on the sixth-generation (6G) of mobile communications has been officially launched around the world. However, the requirements of ultra-high data rate and energy efficiency, global coverage and connectivity, as well as extremely high reliability and low latency, cannot be fully realized with the existing 5G-enabling technologies [1]. In order to meet the diverse requirements of future mobile communication networks, new breakthroughs in basic transmission technologies and resource utilization are needed. Recently, reconfigurable intelligent surfaces (RISs), which are capable of improving the coverage and transmission rate with low power consumption and cost, are widely regarded as one of the enabling technologies for 6G [2–4].

A substantial amount of effort has been devoted to the RIS assisted transmission systems design. In [5–7], assuming perfect channel state information (CSI), the optimal phase shift design of RIS assisted transmission systems was studied. Given that a RIS is a passive structure composed of a large number of reflection units, it is difficult to obtain the instantaneous perfect CSI. To solve this problem, [8, 9] used statistical channel information to design the phase shift or precoding vector. Note that, although the transmission design for RIS assisted systems has been widely considered, the research on the correspoding user scheduling problem involved in RIS assisted communication systems has been scarcely investigated. In [10, 11], the scheduling problem of a single user using statistical CSI for RIS assisted single cell systems was studied, whilst a multi-user gain of loglog$K$ was achieved, where K is the total number of users.

Motivated by the above discussion, this paper advocates using statistical CSI for the cell-edge user scheduling and transmission design in RIS assisted multi-cell systems. Firstly, we schedule the users, whose cascaded channels are mostly correlated with each other's, in order to maximize each user's effective signal. Accordingly, the RIS phase shift is designed to be the mean of the scheduled users' cascaded channel phases, and a joint user scheduling and RIS assisted transmission algorithm is proposed. Then, based on the proposed algorithm, we derive the constraints for the optimal RIS location that can reduce the interference between users. These constraints depend only on the relative locations of the BSs and RIS. Simulation results show that there is little difference between our joint scheduling and transmission algorithm and the optimal algorithms which entail high complexity.

Notation: Vectors are represented as columns and are denoted in lower-case bold-faced characters, whilst matrices are represented in upper-case bold-faced. For a complex value x, $|x|$ denotes the modulus of x. For a complex vector $\mathbf{x}$, $\|\mathbf{x}\|$, $(\mathbf{x})^T$ and $(\mathbf{x})^H$ represent the Euclidean norm, transpose and conjugate transpose of $\mathbf{x}$, respectively. The operator $\angle(\mathbf{x})$ represents the phase of each element of the vector while the range of the phase is normalized to $[-\pi, \pi]$. Moreover, $\mathbb{E}\{\mathbf{x}\}$ represents the expectation of the random vector $\mathbf{x}$; diag $\{a_1, \ldots, a_N\}$ denotes a diagonal matrix with the diagonal elements $a_1, \ldots, a_N$; $\otimes$ denotes the Kronecker product.

II. SYSTEM MODEL

We consider a RIS assisted cellular system consisting of two cells and a single RIS deployed at the cell-edge between two BSs.[1] Each BS deploys a uniform linear array (ULA) with M elements. The RIS deploys a uniform planar array (UPA) containing $N = N_h \times N_v$ reflecting units, where N_h and

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[1] The RIS we considered hereafter is a planar architecture that can only reflect on one side, while the serving cells should be on that same side. Thus, for practical consideration, we only take into account the two cells closest to the RIS and located on the serving side of the RIS.

N_v are the numbers of reflecting units in the horizontal and vertical direction, respectively. Each cell contains K single-antenna users at the cell-edge region, and we further assume that the direct links between these users and the BS do not exist due to blockage or because the received signal is too weak. The BS in each cell can select one user among these cell-edge users, and serve it with the help of the RIS.

Assuming that the scheduled user in cell k is user n_k, its received signal can be expressed as

$$\begin{aligned} y_{k,n_k} = &\sqrt{p\rho_{UE,n_k}\rho_{BS,k}}\mathbf{h}_{k,n_k}^H \mathbf{\Phi}\mathbf{H}_k\mathbf{w}_{n_k}s_k + \\ &\sqrt{p\rho_{UE,n_j}\rho_{BS,j}}\mathbf{h}_{k,n_k}^H\mathbf{\Phi}\mathbf{H}_j\mathbf{w}_{n_j}s_j + z_{n_k}, k=1,2, \end{aligned} \tag{1}$$

where $\rho_{BS,k}$ and ρ_{UE,n_k} denote the large-scale fading coefficients of the link from BS k to the RIS and of the link from the RIS to user n_k in cell k, p is the total transmit power of every BS. Also, s_{n_k} represents the data symbol for user n_k in cell k with $\mathbb{E}\left\{|s_{n_k}|^2\right\} = 1$, $z_{n_k} \sim \mathcal{CN}\left(0, \sigma_{n_k}^2\right)$ is the complex additive white Gaussian noise with variance $\sigma_{n_k}^2$ and zero mean, $\mathbf{\Phi} = \text{diag}\left\{e^{j\theta_1}, e^{j\theta_2}, \cdots, e^{j\theta_N}\right\}$ represents the diagonal phase shift matrix of the RIS, $\theta_n \in [0, 2\pi)$ is the phase shift of the n-th RIS unit, $\mathbf{w}_{n_k} \in \mathbb{C}^{M\times 1}$ is the beamforming vector at BS k for its user n_k satisfying $\|\mathbf{w}_{n_k}\|^2 = 1$, while $\mathbf{H}_k \in \mathbb{C}^{N\times M}$ and $\mathbf{h}_{k,n_k} \in \mathbb{C}^{N\times 1}$ are the channels from BS k to the RIS and from the RIS to user n_k in cell k, respectively. In this paper, we consider the uncorrelated Rician fading model. Thus, the channel matrix (or vector) can be modeled as

$$\mathbf{H}_k = \sqrt{1/(\alpha_k+1)}\tilde{\mathbf{H}}_k + \sqrt{\alpha_k/(\alpha_k+1)}\bar{\mathbf{H}}_k, \tag{2}$$

$$\mathbf{h}_{k,n_k} = \sqrt{1/(\beta_{n_k}+1)}\tilde{\mathbf{h}}_{k,n_k} + \sqrt{\beta_{n_k}/(\beta_{n_k}+1)}\bar{\mathbf{h}}_{k,n_k}, \tag{3}$$

where α_k is the Rician factor of the BS k to RIS link, β_{n_k} is the Rician factor of the RIS to user n_k link, $\tilde{\mathbf{H}}_k$ and $\tilde{\mathbf{h}}_{k,n_k}$ are respectively a random matrix and vector with independent and identically distributed (i.i.d) zero mean and unit variance complex Gaussian elements; $\bar{\mathbf{H}}_k$ and $\bar{\mathbf{h}}_{k,n_k}$ represent the line-of-sight (LoS) components modeled as

$$\bar{\mathbf{H}}_k = \mathbf{a}_N\left(\varphi_k^A, \theta_k^A\right)\mathbf{b}_M^H\left(\varpi_k\right), \tag{4}$$

$$\bar{\mathbf{h}}_{k,n_k} = \mathbf{a}_N\left(\varphi_{k,n_k}^D, \theta_{k,n_k}^D\right), \tag{5}$$

where

$$\begin{aligned} \mathbf{a}_N\left(\varphi,\theta\right) =&[1, \cdots, e^{j2\pi(N_v-1)\frac{d_R}{\lambda}\sin(\varphi)}]^H \otimes \\ &[1, \cdots, e^{j2\pi(N_h-1)\frac{d_R}{\lambda}\cos(\varphi)\sin(\theta)}]^H, \end{aligned} \tag{6}$$

$$\mathbf{b}_M\left(\varpi\right) =[1, \cdots, e^{j2\pi(M-1)\frac{d_B}{\lambda}\sin(\varpi)}]^H. \tag{7}$$

In the above, φ_k^A and θ_k^A denote the elevation and azimuth angle-of-arrival (AoA) at the RIS from BS k, φ_{k,n_k}^D and θ_{k,n_k}^D denote the elevation and azimuth angle-of-departure (AoD) from the RIS towards user n_k in cell k, ϖ_k represents the AoD from BS k to RIS, λ is the carrier wavelength, d_R and d_B are the distances between the adjacent reflecting elements at the RIS and the adjacent antennas at the BSs, respectively.

Assuming only statistical CSI at the BSs and RISs, we derive phase and user scheduling criteria with the goal of maximizing the ergodic spectral efficiency. The ergodic SE of user n_k in cell k can be written as

$$R_{n_k} = \mathbb{E}\left\{\log_2\left(1+\gamma_{n_k}\right)\right\}, \tag{8}$$

where

$$\gamma_{n_k} = \frac{p\rho_{UE,n_k}\rho_{BS,k}|\mathbf{h}_{k,n_k}^H\mathbf{\Phi}\mathbf{H}_k\mathbf{w}_{n_k}|^2}{p\rho_{UE,n_j}\rho_{BS,j}|\mathbf{h}_{k,n_k}^H\mathbf{\Phi}\mathbf{H}_j\mathbf{w}_{n_j}|^2 + \sigma^2}. \tag{9}$$

Then, the ergodic sum SE of the system can be obtained as $R_{\text{sum}} = \sum_{k=1}^2 R_{n_k}$. With a selected user in each cell, the RIS phase shift, and BS beamforming vectors can be optimized to maximize the ergodic sum SE. However, the joint design of scheduling, RIS phase shift and BS beamforming has rarely been studied. In this paper, we try to jointly optimize the beamforming vectors, phase shift matrix and user scheduling.

III. BEAMFORMING DESIGN AND USER SCHEDULING

Note that it is quite difficult to optimize the ergodic sum SE due to the lack of a closed-form expression. In this section, we apply the ergodic SE approximation obtained in [8], and investigate the beamforming design and user scheduling based on this approximation.

A. Problem Formulation

From [8], the ergodic sum SE in (8) can be approximated as

$$R_{n_k} \approx \bar{R}_{n_k} = \log_2\left(1+\bar{\gamma}_{n_k}\right), \tag{10}$$

where $\bar{\gamma}_{n_k}$ is given in (11) at the bottom of the current page with $A_{n_k,j} = \frac{p_j\rho_{UE,n_k}\rho_{BS,j}\beta_{n_k}\alpha_j}{\left(\beta_{n_k}+1\right)(\alpha_j+1)}$, $B_{n_k,j} = \frac{p_j\rho_{UE,n_k}\rho_{BS,j}\alpha_j}{\left(\beta_{n_k}+1\right)(\alpha_j+1)}$ and $C_{n_k,j} = \frac{p_j\rho_{UE,n_k}\rho_{BS,j}}{\alpha_j+1}$.

Considering the design of the BS beamforming vector for the scheduled user n_k in cell k, we aim to maximize its effective signal power, which is the numerator of (11). It can be concluded that the optimal beamforming vector under this criterion is $\mathbf{w}_{n_k} = \frac{\mathbf{b}_M(\varpi_k)}{\|\mathbf{b}_M(\varpi_k)\|}$, which ensures that the transmit beam is aligned towards the RIS. In this way, the design of the beamforming vector at the BS can be decoupled from the RIS phase shift design to avoid the complex iterative optimization among them. Then, the interference coordination problem is left to the RIS phase shift design and user scheduling algorithm. To avoid the situation that the users far from the RIS/BS will never be scheduled [10], in the following analysis, we only consider the small scale fading coefficients of each user and treat the coefficients of users in the same cell as identical, i.e., $\rho_{UE,n_k} = \rho_{UE,k}$. Then, some parameters simplify to $A_{n_k,j} = \frac{p_j\rho_{UE,k}\rho_{BS,j}\beta_{n_k}\alpha_j}{\left(\beta_{n_k}+1\right)(\alpha_j+1)}$, $B_{n_k,j} = \frac{p_j\rho_{UE,k}\rho_{BS,j}\alpha_j}{\left(\beta_{n_k}+1\right)(\alpha_j+1)}$, $C_{k,j} = \frac{p_j\rho_{UE,k}\rho_{BS,j}}{\alpha_j+1}$, and the approximation of the ergodic SE can be further expressed as

$$R_{n_k} \approx \hat{R}_{n_k} = \log_2\left(1+\hat{\gamma}_{n_k}\right), \tag{12}$$

$$\bar{\gamma}_{n_k} = \frac{(A_{n_k,k}|\bar{\mathbf{h}}_{k,n_k}^H\mathbf{\Phi}\mathbf{a}_N(\varphi_k^A,\theta_k^A)|^2|\mathbf{b}_M^H(\varpi_k)\mathbf{w}_{n_k}|^2 + NB_{n_k,k}|\mathbf{b}_M^H(\varpi_k)\mathbf{w}_{n_k}|^2 + NC_{n_k,k})}{(A_{n_k,j}|\bar{\mathbf{h}}_{k,n_k}^H\mathbf{\Phi}\mathbf{a}_N(\varphi_j^A,\theta_j^A)|^2|\mathbf{b}_M^H(\varpi_j)\mathbf{w}_{n_j}|^2 + NB_{n_k,j}|\mathbf{b}_M^H(\varpi_j)\mathbf{w}_{n_j}|^2 + NC_{n_k,j}) + \sigma^2} \tag{11}$$

where $\hat{\gamma}_{n_k}$ is in (13) at the bottom of the next page.

Thus, in this paper, we try to design the RIS phase shift matrix and schedule users properly to maximize the approximated sum SE, i.e.,

$$\begin{aligned}
\text{(P1)} : \max \ & \sum\nolimits_{k=1}^{2} \hat{R}_{n_k}, && \text{(14a)}\\
\text{s.t.} \ & |\phi_n| = 1, n = 1, \ldots, N, && \text{(14b)}\\
& n_k \in \Pi_k, k = 1, 2, && \text{(14c)}
\end{aligned}$$

where Π_k is the set of users to be scheduled in cell k.

B. User scheduling and RIS phase shift design

Note that maximizing the SE can be achieved by maximizing the effective signal power and minimizing the interference. Let us first consider the maximization of the effective signal power. Define $\mathbf{v}^H = \left[e^{j\theta_1}, e^{j\theta_2}, \cdots, e^{j\theta_N}\right]$, then, from (13) the scheduled user's effective signal can be expressed as

$$S_{n_k} \triangleq MA_{k,k}\left|\mathbf{v}^H \mathbf{f}_{n_k}\right|^2 + MNB_{k,k} + NC_{k,k}, \tag{15}$$

where

$$\begin{aligned}
\mathbf{f}_{n_k} \triangleq & \operatorname{diag}\{\mathbf{a}_N^H(\varphi_{k,n_k}^D, \theta_{k,n_k}^D)\}\mathbf{a}_N(\varphi_k^A, \theta_k^A)\\
=&[1, \cdots, e^{j[\sin(\varphi_{k,n_k}^D) - \sin(\varphi_k^A)]\pi(N_v - 1)}]^T \otimes\\
& [1, \cdots, e^{j[\varpi(\varphi_{k,n_k}^D, \theta_{k,n_k}^D) - \varpi(\varphi_k^A, \theta_k^A)]\pi(N_h - 1)}]^T.
\end{aligned} \tag{16}$$

To maximize the effective signal power of the scheduled user n_k, we should set $\mathbf{v} = e^{j\angle\left(\mathbf{f}_{n_k}\right)} e^{j\varphi}$, where φ could be any value. Thus, to achieve high ergodic SE we should schedule the users satisfying $e^{j\angle\left(\mathbf{f}_{n_1}\right)} = e^{j\angle\left(\mathbf{f}_{n_2}\right)}$, so that S_{n_1} and S_{n_2} can be maximized by the same $\mathbf{v}$. We use the following expression to measure the correlation between users

$$\mu_{n_1,n_2} = \left|\mathbf{f}_{n_1}^H \mathbf{f}_{n_2}\right|^2. \tag{17}$$

It can be deduced that the scheduled user pair will satisfy $e^{j\angle\left(\mathbf{f}_{n_1}\right)} = e^{j\angle\left(\mathbf{f}_{n_2}\right)}$ when μ_{n_1,n_2} reaches its maximum, i.e., N^2. Therefore, in order to maximize the effective signal power, we could schedule the user pair that has the highest correlation coefficient μ_{n_1,n_2}. In this case, we set the RIS phase shift simply as $\mathbf{v}_{\text{cor}}$ which means that the phase shifts are designed according to the scheduled users with the largest correlation coefficient.

$$\begin{aligned}
\mathbf{v}_{\text{cor}} &= e^{j\frac{\angle(\mathbf{f}_{n_1}) + \angle(\mathbf{f}_{n_2})}{2}}\\
&= [1, \cdots, e^{j\phi_v(N_v - 1)}]^T \otimes [1, \cdots, e^{j\phi_h(N_h - 1)}]^T,
\end{aligned} \tag{18}$$

where

$$\begin{aligned}
\phi_v = & 0.5\angle\left(e^{j\left[\sin(\varphi_{k,n_k}^D) - \sin(\varphi_k^A)\right]\pi}\right)\\
& + 0.5\angle\left(e^{j\left[\sin(\varphi_{j,n_j}^D) - \sin(\varphi_j^A)\right]\pi}\right),
\end{aligned} \tag{19}$$

$$\begin{aligned}
\phi_h = & 0.5\angle\left(e^{j\left[\varpi(\varphi_{k,n_k}^D, \theta_{k,n_k}^D) - \varpi(\varphi_k^A, \theta_k^A)\right]\pi}\right)\\
& + 0.5\angle\left(e^{j\left[\varpi(\varphi_{j,n_j}^D, \theta_{j,n_j}^D) - \varpi\left(\varphi_j^A, \theta_j^A\right)\right]\pi}\right),
\end{aligned} \tag{20}$$

and $\varpi\left(\varphi, \theta\right) = \cos\varphi \sin\theta$. Now, the first term of (15), which contains the RIS phase shift, can be further expressed as

$$\left|\mathbf{v}_{\text{cor}}^H \mathbf{f}_{n_k}\right|^2 = \left|\sum_{n_v=1}^{N_v} e^{j a_{n_k}(n_v - 1)}\right|^2 \cdot \left|\sum_{n_h=1}^{N_h} e^{j b_{n_k}(n_h - 1)}\right|^2, \tag{21}$$

where

$$\begin{aligned}
a_{n_k} = & 0.5\angle\left(e^{j[\sin(\varphi_{k,n_k}^D) - \sin(\varphi_k^A)]\pi}\right)\\
& - 0.5\angle\left(e^{j[\sin(\varphi_{j,n_j}^D) - \sin(\varphi_j^A)]\pi}\right),
\end{aligned} \tag{22}$$

$$\begin{aligned}
b_{n_k} = & 0.5\angle\left(e^{j[\varpi(\varphi_{k,n_k}^D, \theta_{k,n_k}^D) - \varpi(\varphi_k^A, \theta_k^A)]\pi}\right)\\
& - 0.5\angle\left(e^{j[\varpi(\varphi_{j,n_j}^D, \theta_{j,n_j}^D) - \varpi(\varphi_j^A, \theta_j^A)]\pi}\right),
\end{aligned} \tag{23}$$

and $a_{n_k}, b_{n_k} \in [-\pi, \pi]$. Notice that, with the constraint of $a \in [-\pi, \pi]$, $\left|\sum\limits_{n=1}^{N} e^{ja(n-1)}\right|^2$ is maximized when $a = 0$. This validates that when the user pair correlation coefficient μ_{n_1,n_2} reaches its maximum, i.e. a_{n_k} and b_{n_k} tend to 0, and then the effective signal in (21) also reaches its maximum. Therefore, in the point of signal power maximization, we should schedule the user pair that has the highest correlation coefficient μ_{n_1,n_2}.

C. Effect of RIS location

Based on the above scheduling scheme, we now analyze the asympotic ergodic sum SE with repect to the number of users in each cell. Let us define the RIS phase shift in (19) and (20)

$$\phi_v = \angle\left(e^{j[\sin(\varphi_{k,n_k}^D) - \sin(\varphi_k^A)]\pi}\right) - a_{n_k}, \tag{24}$$

$$\phi_h = \angle\left(e^{j[\varpi(\varphi_{k,n_k}^D, \theta_{k,n_k}^D) - \varpi(\varphi_k^A, \theta_k^A)]\pi}\right) - b_{n_k}. \tag{25}$$

Under the condition that the scheduled user pair is perfectly matched, i.e., $e^{j\angle\left(\mathbf{f}_{n_1}\right)} = e^{j\angle\left(\mathbf{f}_{n_2}\right)}$, and thus a_{n_k} and b_{n_k} approach 0, we can convert the interference term containing the RIS phase shift in (13) to

$$\begin{aligned}
&\left|\mathbf{v}_{\text{cor}}^H \operatorname{diag}\left\{\mathbf{a}_N^H\left(\varphi_{k,n_k}^D, \theta_{k,n_k}^D\right)\right\}\mathbf{a}_N\left(\varphi_j^A, \theta_j^A\right)\right|^2\\
&= \left|\sum_{n_v=1}^{N_v} e^{j(n_v - 1)\left[a_{n_k} + \angle\left(e^{j\left[\sin\left(\varphi_j^A\right) - \sin\left(\varphi_k^A\right)\right]\pi}\right)\right]} \times \right.\\
&\qquad \left.\sum_{n_h=1}^{N_h} e^{j(n_h - 1)\left[b_{n_k} + \angle\left(e^{j\left[\varpi\left(\varphi_j^A, \theta_j^A\right) - \varpi\left(\varphi_k^A, \theta_k^A\right)\right]\pi}\right)\right]}\right|^2\\
&= \left|\mathbf{a}_N^H\left(\varphi_k^A, \theta_k^A\right)\mathbf{a}_N\left(\varphi_j^A, \theta_j^A\right)\right|^2.
\end{aligned} \tag{26}$$

Finally, by substituting (21) and (26) into (13), we can obtain the final SE of user n_k, which is given in (27) at the bottom of this page.

$$\hat{\gamma}_{n_k} = \frac{MA_{n_k,k}|\mathbf{v}^H \operatorname{diag}\{\mathbf{a}_N^H(\varphi_{k,n_k}^D, \theta_{k,n_k}^D)\}\mathbf{a}_N(\varphi_k^A, \theta_k^A)|^2 + MNB_{n_k,k} + NC_{k,k}}{MA_{n_k,j}|\mathbf{v}^H \operatorname{diag}\{\mathbf{a}_N^H(\varphi_{k,n_k}^D, \theta_{k,n_k}^D)\}\mathbf{a}_N(\varphi_j^A, \theta_j^A)|^2 + MNB_{n_k,j} + NC_{k,j} + \sigma^2} \tag{13}$$

$$\hat{R}_{n_k}^{\text{lim}} = \log_2\left(1 + \frac{MN^2 A_{n_k,k} + MNB_{n_k,k} + NC_{k,k}}{MA_{n_k,j}|\mathbf{a}_N^H(\varphi_k^A, \theta_k^A)\mathbf{a}_N(\varphi_j^A, \theta_j^A)|^2 + MNB_{n_k,j} + NC_{k,j} + \sigma^2}\right) \tag{27}$$

From (27), it can be seen that we only need to reasonably adjust the AoAs of two cell's BS-RIS links to make $\mathbf{a}_N\left(\varphi_k^A, \theta_k^A\right)$ and $\mathbf{a}_N\left(\varphi_j^A, \theta_j^A\right)$ orthogonal to each other, so that the interference can be sufficiently small. We notice that

$$\begin{aligned} &\mathbf{a}_N^H\left(\varphi_k^A, \theta_k^A\right)\mathbf{a}_N\left(\varphi_j^A, \theta_j^A\right) \\ &= \Lambda\left(\pi\left[\sin\left(\varphi_k^A\right) - \sin\left(\varphi_j^A\right)\right], N_v\right) \times \\ &\Lambda\left(\pi\left[\varpi\left(\varphi_k^A, \theta_k^A\right) - \varpi\left(\varphi_j^A, \theta_j^A\right)\right], N_h\right), \end{aligned} \tag{28}$$

where $\Lambda\left(x, N\right) \triangleq \frac{\sin\left(\frac{N}{2}x\right)}{\sin\left(\frac{1}{2}x\right)} e^{-j\frac{(N-1)}{2}x}$, and $\Lambda\left(x, N\right) = 0$ when $x = \frac{2k\pi}{N}, k \in \{\pm 1, \cdots, \pm\left(N-1\right)\}$. Thus, we only need to satisfy one of the conditions in (29) and (30); then, (28) can be equal to 0:

$$\sin\left(\varphi_k^A\right) - \sin\left(\varphi_j^A\right) = \frac{2m}{N_v}, \tag{29}$$

$$\varpi\left(\varphi_k^A, \theta_k^A\right) - \varpi\left(\varphi_j^A, \theta_j^A\right) = \frac{2n}{N_h}, \tag{30}$$

where $m \in \{\pm 1, \cdots, \pm(N_v - 1)\}$ and $n \in \{\pm 1, \cdots, \pm(N_h - 1)\}$.

Thus, based on the above analysis, we conclude that the location of RIS should satisfy the constraint (29) or (30). Under this constraint, we propose a joint user scheduling and RIS shift design in Section III-B, which is summarized as Algorithm 1. [2] [3]

Algorithm 1 User Scheduling and RIS phase shift design

```
Require: user pair $\{n_1^*, n_2^*\}$ and RIS phase shift vector $\mathbf{v}$
for $n_1 = 1$ to $K_1$ do
    for $n_2 = 1$ to $K_2$ do
        $\mu_{n_1,n_2} = \left|\mathbf{f}_{n_1}^H \mathbf{f}_{n_2}\right|^2$
    end for
end for
$\{n_1^*, n_2^*\} = \arg\max_{n_1 \in \Pi_1, n_2 \in \Pi_2} \mu_{n_1,n_2}$
$\mathbf{v} = e^{j\frac{\angle(\mathbf{f}_{n_1^*}) + \angle(\mathbf{f}_{n_2^*})}{2}}$
```

D. User scheduling based on DFT codebook

The above scheduling and RIS shift design is under the assumption of continuous phase shift RIS. Note that every RIS has finite resolution in practice. Thus, in this subsection we consider a more practical discrete RIS phase shift design based on a DFT codebook and the algorithm proposed above. The N dimensional DFT codebook can be expressed as

$$\mathbf{C} = \left\{\mathbf{c}_{1,1}, \ldots, \mathbf{c}_{1,N_v}, \ldots, \mathbf{c}_{N_h,1}, \ldots, \mathbf{c}_{N_h,N_v}\right\}, \tag{31}$$

where each codeword can be expressed as $\mathbf{c}_{m,k} = \mathbf{c}_k^v \otimes \mathbf{c}_m^h, k = 1, \ldots, N_v, m = 1, \ldots, N_h$, and

$$\mathbf{c}_m^h = \left[1, e^{j\frac{2\pi}{N_h}(m-1)}, \cdots, e^{j\frac{2\pi}{N_h}(m-1)(N_h-1)}\right], \tag{32}$$

$$\mathbf{c}_k^v = \left[1, e^{j\frac{2\pi}{N_v}(k-1)}, \cdots, e^{j\frac{2\pi}{N_v}(k-1)(N_v-1)}\right]. \tag{33}$$

When we get the user pair with the greatest correlation, we need to exhaustively search the codebook to select a codeword that is closest to the continuous phase shift (17), i.e. select the codeword that maximizes $|(\mathbf{c}_{m,k})^H \mathbf{v}_{\mathrm{cor}}|^2$. From (30) and (17) we can obtain that

$$|(\mathbf{c}_{m,k})^H \mathbf{v}_{\mathrm{cor}}|^2 = |(\mathbf{c}_k^v)^H \mathbf{v}_{\mathrm{cor},v}|^2 \cdot |(\mathbf{c}_m^h)^H \mathbf{v}_{\mathrm{cor},h}|^2, \tag{34}$$

where $\mathbf{v}_{\mathrm{cor},v} = \left[1, \cdots, e^{j\phi_v(N_v-1)}\right]^T$ and $\mathbf{v}_{\mathrm{cor},h} = \left[1, \cdots, e^{j\phi_h(N_h-1)}\right]^T$. Thus, we can select the optimal codeword according to two separated dimensions. The specific operations are as follows

$$(\mathbf{c}_k^v)^{\mathrm{opt}} = \underset{k \in \{1,..,N_v\}}{\arg} \max\{|(\mathbf{c}_k^v)^H \mathbf{v}_{\mathrm{cor},v}|^2\}, \tag{35}$$

$$\left(\mathbf{c}_m^h\right)^{\mathrm{opt}} = \underset{m \in \{1,..,N_h\}}{\arg} \max\{|\left(\mathbf{c}_m^h\right)^H \mathbf{v}_{\mathrm{cor},h}|^2\}, \tag{36}$$

$$\left(\mathbf{c}_{m,k}\right)^{\mathrm{opt}} = \left(\mathbf{c}_k^v\right)^{\mathrm{cor}} \otimes \left(\mathbf{c}_m^h\right)^{\mathrm{cor}}. \tag{37}$$

Note that although our scheduling scheme might not be optimal, it is of low computation complexity. If we want to obtain the optimal solution, we need to sweep across all user pairs and select the optimal codeword under each user pair. The complexity of the optimal solution is $O\left(K_1 K_2 N\right)$, while the complexity of our scheme is $O\left(K_1 K_2 + N_v + N_h\right)$. Simulation results show that our scheme is very close to the optimal solution.

IV. NUMERICAL RESULTS

In this section, simulation results are provided to verify the performance of the proposed joint user scheduling and RIS phase shift design. In all simulations, $M = 8$, $N = 8 \times 4$, $\sigma^2 = -90$ dBm, $\alpha_k = 10$ dB, $\beta_{n_k} = 6$ dB. The large-scale fading path loss model for $\rho_{BS,k}$ and ρ_{UE,n_k} in (1) is given by $\rho{=}10^{\frac{PL_0}{10}}\left(\frac{d}{d_0}\right)^{-\tilde{\alpha}}$, where PL_0 is the path-loss at the reference distance d_0, d is the distance of the BS-RIS link or the RIS-user link, $\tilde{\alpha}$ is the path-loss exponent. In our simulations, we set $PL_0 = -30$ dB and $d_0 = 1$ m. The distance of the BS-RIS link is $d_{BI} = 150$ m, and the distance of the RIS-user link is $d_{IU} = 10$ m. The path-loss exponents of the BS-RIS link and the RIS-user link are set to $\tilde{\alpha}_{BI} = 2.5$ and $\tilde{\alpha}_{IU} = 2.3$. We set $\Delta \triangleq \sin\left(\varphi_1^A\right) - \sin\left(\varphi_2^A\right)$ to different values to observe the effect of RIS location on system performance. Each cell has 10 single antenna users with weak coverage. All the results are averaged over 500 user drops.

In this paper, we compare the following five scheduling algorithms:

1) **RIS-CCM-User-opt**: Exhaustively search all user pairs, and under each user pair, we use statistical MRT beamforming, while the RIS phase shift is optimized by the complex circle manifold (CCM).
2) **RIS-pmean-User-cor**: This is the phase shift design and scheduling algorithm based on user correlation we proposed in Section III-B (Algorithm 1). Note that statistical MRT beamforming is applied at each BS.
3) **BF-AO-RIS-CCM-User-cor**: The scheduled users are the same with the "RIS-pmean-User-cor" algorithm, while

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[2] To apply this proposed algorithm in order to serve multiple users at each BS, we can divide the users of different cells into groups, so that each group contains one user in each cell and these users are mostly correlated with each other. Then, these groups of users can be served in turn in different time slots.

[3] Although fairness is not considered in this work, the proposed algorithm can be easily extended to take fairness into account. We can introduce a priority to each user, and divide the users into groups using the proposed scheduling method as mentioned in the above footnote. Then, we can schedule the user group that contains the user with the highest priority. The priority value can be set according to the scheduling history or each user's previous throughput.

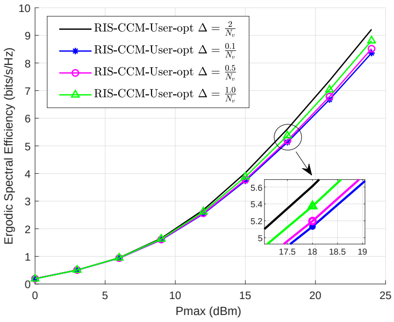

Fig. 1. The effect of different RIS locations.

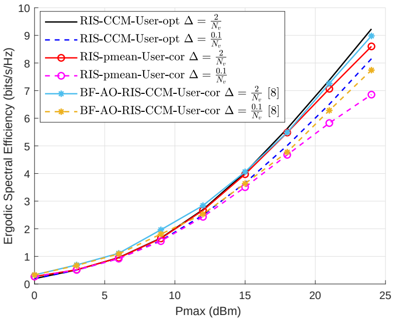

Fig. 2. Comparison of different continuous RIS phase shift algorithms.

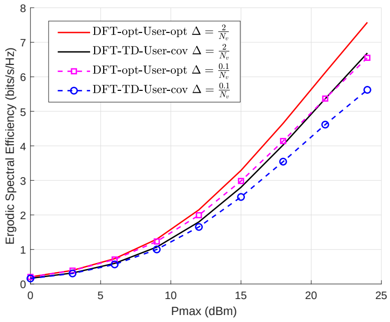

Fig. 3. Comparison of different DFT codebook algorithms.

the RIS phase shift design is obtained by Alternative Optimization (AO) and CCM algorithm proposed in [8].

4) **DFT-opt-User-opt**: Exhaustively search all user pairs, and under each user pair, the DFT codebook is sweeped to select the optimal codeword for the RIS phase shift.
5) **DFT-TD-User-cor**: This algorithm is proposed in Section III-D, which selects the user pair according to user correlation, and then searches the DFT codebook in two separated dimensions.

In Fig. 1, we observe the effect of different RIS locations considering the CCM based scheduling algorithm. The results show that the RIS location satisfying the condition (29) yields better performance than the RIS location not satisfying the condition (29), which corroborates our conclusions in Section III-C.

In Fig. 2, we compare the performance of different scheduling algorithms with continuous RIS phase shift. Note that we also evaluate the performance of the beamforming and phase shift design algorithm proposed in [8], which is labeled as “BF-AO-RIS-CCM-User-cor” algorithm. We set $\Delta = \frac{2}{N_v}$ and $\Delta = \frac{0.1}{N_v}$ here, i.e., only the former satisfies condition (29). It is observed that for the same scheduled users, the performance of the proposed “RIS-pmean-User-cor” algorithm is slightly inferior to “BF-AO-RIS-CCM-User-cor” algorithm, but the computation complexity of the latter is much higher because of the AO and CCM algorithms. Moreover, as can be observed, under the same MRT beamforming design, “RIS-CCM-User-opt” is slightly superior to “RIS-pmean-User-cor”, but the computation complexity of RIS phase shift design and user scheduling is much higher than that of the proposed algorithm. When condition (29) is not met, there is a certain gap between the algorithm we proposed and “RIS-CCM-User-opt” under high transmission power. This is mainly because of the remaining interference between the scheduled users.

Figure 3 compares the scheduling algorithm with exhaustive search of the DFT codebook and our proposed algorithm for selecting codewords in two separated dimensions. In this figure, we also set $\Delta = \frac{2}{N_v}$ and $\Delta = \frac{0.1}{N_v}$. Although the performance of our algorithm is slightly worse than that of the optimal algorithm, the complexity of the former is significantly lower. Since the DFT codeword is selected according to the continuous phase shift (17), it can be seen that the change trend of the algorithm we proposed in Figs. 2 and 3 is consistent. It can be observed that, under high transmission power, the system performance will be significantly compromised if the RIS position does not meet the condition (29).

V. CONCLUSION

In this paper, we investigated user scheduling in a RIS assisted downlink multi-cell system exploiting only statistical CSI. Based on a closed-form ergodic sum SE approximation, we simplified the design of RIS phase shift by scheduling users with similar channel phases and ensure the maximum effective signal of scheduling users in each cell. Then, we derived the optimal condition for designing the RIS phase shift that would cause the lowest interference among different cells, in order to maximize the achievable SE. We also proposed a low complexity RIS phase shift design under a practical DFT codebook. Our simulation results validated the performance of the proposed algorithms.

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