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Promising Practical Infrastructure Solutions for 6G Based on RIS and Cell Free Massive MIMO network

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Abstract

Cell free massive MIMO system is a promising candidate to overcome the shortcomings of the conventional cellular system and a suitable technique to achieve the goals of the sixth generation (6G) networks. Costs of implementing on a large scale is one of the major disadvantages of this system. Recently, with the emergence of reconfigurable intelligent surfaces (RIS), we can hope for the reduction of these costs and the practical implementation of this system. In this regard, in this paper we have investigated the spectral performance of the scalable form of cell free with and without RISs. Lower bounds of uplink spectral efficiency involving imperfect channel estimation and pilot contamination effects for L-MMSE and LP-MMSE decoders is derived. The simulation results confirm the superior spectral efficiency performance of RIS-based proposed system (especially in centralized RIS- cell free mode) compared to the Scalable cell free system.
Keywords

Cell-free, Massive MIMO, RIS, Spectral efficiency, Dynamic cooperation clustering (DCC), Direct and cascaded channels.

1. Introduction

Cell free massive MIMO system and RIS technology are potential physical structures to achieve the goals of 6G wireless networks [1, 2]. Some of the disadvantages of conventional cellular systems, including intercellular interference and poor service to edge cell users, are eliminated by cell free system [3], [4]. This performance improvement comes at the cost of increasing the hardware implementation complexity and power resources due to the widespread distribution of base stations(BSs) in the environment. Also, according to [3], cell free system outperforms the cellular system only when using minimum mean square error (*MMSE*) or local *MMSE* decoders, which isn't considered in most papers. In the conventional cell free system, is assumed that the BSs have all the channel state information(CSI) of the environment and can transmit to all users [5, 6, 7], these factors affect the practical implementation of this system. The proposed approaches for scalability of this system fall into two categories: user-centric and network-centric [8, 9].

To reduce the cell free system implementation costs, backhauling traffic, guarantee good quality of service in poor scattering environments, and improve system energy efficiency, The use of RIS technology is suggested [10]. Also, RIS can improve users' coverage by improving array gain. All of these reasons make RIS-aided cell free massive MIMO an acceptable system. Combining RIS and cell free makes a controllable digital link, which quality of this link is proportional to each RIS units. For proper design of decoder and precoder matrices in BSs and RIS phase shift coefficients, an accurate estimation of CSI is required [11, 12, 13]. Because RIS is a passive system, so transmit and receiving the pilots isn't possible for it. Most of the works presented in RIS-aided cell free system, CSI estimation, are based on the BS-RIS-user cascaded channel. In RIS-aided cell free massive MIMO system number of users, BSs, and number of each RIS and BS antennas are numerous. For this reason, in cascaded channel estimation the pilot overhead is high. Various channel estimation methods have been proposed to reduce the pilot overhead [11, 13]. One of the most effective methods for estimating CSI to reduce pilot overhead in [13] is presented, which is a method called two timescale channel estimation. In this method, because the locations of the BSs and RIS are fixed, the BS-RIS channel can be considered quasi-static.

Also, because of mobility of users, the BS-users and RIS-users channels are time-varying. Therefore, BS-users, RIS-users and BS-RIS channels can be estimated in small, small and large timescales, respectively.

In most related works about RIS-aided cell free, the effects of imperfect channel estimation error have not been considered and have been solved and optimized under perfect CSI (deterministic channels). As well, in most papers, the conventional cell free massive MIMO system is studied, which implies that backhauling traffic and computational complexity of central processing unit (CPU) and each BS, to process data related to all users grow (linearly or faster) with the number of users. Also, it is considered that all BSs and RISs are coordinated and all network controlling, transmission and planning tasks is performed by CPU [10, 14, 15]. The stated cases make the practical implementation of this system impossible. Therefore, It can be said that conventional form of cell free massive MIMO system is unscalable.

In this paper cell free massive MIMO system employing RIS, with the necessary requirements for practical implementation, is considered. The main contribution is as:

- Systems can be implemented in practice if accurate insights from their physical environment are incorporated into the theory. In [16, 17], it's shown that these system channels don't follow the uncorrelated Rayleigh fading channel model. Therefore, the spatial correlated Rayleigh fading channel is used to observe practical considerations.
- Lower bound of uplink spectral efficiency, for ($L-MMSE$) and local partial MMSE ($LP\text{–}MMSE$) decoders is derived with taking into account imperfect channel estimation error and pilot contaminations.
- The performance of this system employing RIS is compared with scalable conventional cell free system in several viewpoints.

The rest of the paper is organized as follows. Section 2 describes the system model and channel estimation, section 3 explains the uplink SE performance in centralized and distributed approach, whereas the performance evaluation is provided in Section 4.

Notation: Vectors and matrices are written in bold lowercase and uppercase letters, respectively. *T,H* and ||.|| denote the Transpose, Hermitian and Euclidean norm, respectively. $\mathbf{I}_{K\times K}$ is identity matrix, $\mathbb{E}$ denote the expectation of random variable. Also we use *Car*(.) to show cardinality of a set.

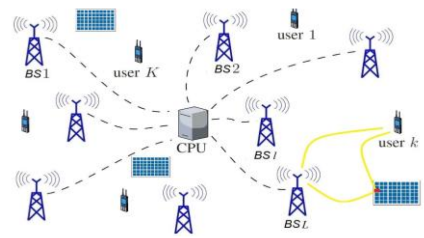

Figure 1: RIS-based cell free massive MIMO network.

2. SYSTEM MODEL

We consider uplink mode of the cell free massive MIMO network. According to Fig. 1, K single antenna users are served by L BS, each of them is equipped with M antennas. It's assumed that BSs work in full-duplex mode. As mentioned, S RIS with the N antennas in each is used to improve the cell free system performance. Therefore, a RIS-aided cell free massive MIMO system is formed. As shown in Fig. 1, each BS receives users data in both direct and reflected paths. For any arbitrary BS in uplink we have:

$$\mathbf{y}_l=\sum_{k=1}^{K}\sqrt{p_k}\left(\left[\sum_{s=1}^{S}\mathbf{H}_{l,r}^{s}\,\mathrm{diag}\left(\phi^{s}\right)\mathbf{f}_{r,k}^{s}\right]+\mathbf{f}_{l,k}\right)x_k+\mathbf{n}_l \quad (1)$$

$$=\sum_{k=1}^{K}\sqrt{p_k}\left(\left[\underbrace{\sum_{s=1}^{S}\mathbf{H}_{l,r}^{s}\,\mathrm{diag}\left(\mathbf{f}_{r,k}^{s}\right)}_{\text{Cascaded channel}}\phi^{s}\right]+\mathbf{f}_{l,k}\right)x_k+\mathbf{n}_l$$

Where $\mathbf{C}_{l,k}=\sum_{s=1}^{S}\mathbf{H}_{l,r}^{s}\,\mathrm{diag}(\mathbf{f}_{r,k}^{s})$ is cascaded channel, $\mathbf{y}_l\in C^{M\times 1}$ is received uplink signal in l-th BS, $\mathbf{H}_{l,r}^{s}\in C^{M\times N}$ is l-th BS and s-th RIS channel, $\phi^{s}\in C^{N\times 1}$ is reflection coefficients vector of s-th RIS elements, $\mathbf{f}_{r,k}^{s}\in C^{N\times 1}$ is s-th RIS-user channel, $\mathbf{f}_{l,k}\in C^{M\times 1}$ is BS-user direct channel, k-th user transmitted signal is $x_k\in C$, $(|x_k|=1, k=1\ldots K)$ and $\mathbf{n}_l\in C^{M\times 1}$ with distribution $\mathbf{n}_l\sim\mathcal{N}_{\mathbb{C}}\left(\mathbf{0},\sigma^2\mathbf{I}_M\right)$ is the noise vector in l-th BS.

According to [16, 17], RISs in isotropic scattering environments don't follow (i.i.d.) Rayleigh fading channel model. So to consider the more realistic channel, spatially correlated Rayleigh fading model in [17, 16] for direct and cascaded channels is used. Therefore, $\mathbf{f}_{r,k}\sim\mathcal{CN}\left(\mathbf{0},\mathbf{R}_{f_{r,k}}\right)$, $\mathbf{f}_{l,k}\sim\mathcal{CN}\left(\mathbf{0},\mathbf{R}_{f_{l,k}}\right)$, where $\mathbf{R}_{f_{r,k}}\in C^{N\times N},\mathbf{R}_{f_{l,k}}\in C^{M\times M}$ are the channels spatial correlation matrices, which based on, large scale fading $(\beta=\mathrm{tr}\left(\mathbf{R}^{M\times M}\right)/M)$ is defined. Also, according to the Kronecker model [18]:

$$\mathbf{H}_{l,r} = \sqrt{\mathbf{R}^{l}_{H_{l,r}}}\,\mathbf{H}_{l,r}\sqrt{\mathbf{R}^{s}_{H_{l,r}}} \tag{2}$$

where, $\mathbf{R}^{l}_{H_{l,r}} \in C^{M\times M}$, $\mathbf{R}^{s}_{H_{l,r}} \in C^{N\times N}$ are spatial correlation matrices in l-th BS and s-th RIS ends, respectively. Also, $\mathbf{H}_{l,r} \in C^{M\times N}$ is (i.i.d.) circulary symmetric complex Gaussian random variables. It should be noted that general form of spatial correlation matrices are considered and can be particularized based on system design, for example, [16, 19], suggest some models to describe correlation between RIS units.

Due to hardware implementation limitations, some certain conditions in reflection coefficients must be satisfied. In practice, these coefficients are randomly chosen from finite number of discrete values. Therefore, to include practical limitations, we assume ϕ^s vector coefficients are randomly selected from $\{-1,0,+1\}$ [20].

2.1. Channel Estimation

As mentioned, two timescale channel estimation method in [13] is used to achieve CSI. Due to fixed location of BSs and RISs, BSs-RIS channels are quasi-static, therefore can be estimated in large timescales. BS-users and RIS-users channels are time varying and Should be estimated in small timescales. If τ_{large}, τ_c, are channel coherence time of large and small timescales channels, we have $\tau_{large} \gg \tau_c$.

According to two timescale channel estimation, in first phase $\mathbf{H}_{l,r}$, ϕ and then in second phase $\mathbf{f}_{l,k}$, $\mathbf{f}_{r,k}$ channels are estimated. In first phase because RISs are passive elements and can't transmit or receive pilots therefore, an Innovative dual-link pilot transmission scheme is introduced. In this scheme BSs Simultaneously transmit downlink pilots to RISs and receive uplink pilots reflected by RISs. Then, with coordinate descent-based algorithm BS-RIS is recovered. Then in second phase, conventional channel estimation methods like TDD protocol can be used to BS-users and RIS-users channels. More details of the first phase are described in [13].

Without loss of generality, it's assumed that the first phase channel estimation is done and BS-RIS channel coefficients are in hand. In second phase(small timescale channel estimation), we use TDD protocol. For channel estimation, τ_p mutually orthogonal τ_p-length pilots ($\psi_1,\ldots,\psi_{\tau p}$) with $\left\|\boldsymbol{\psi}_p\right\|^2 = 1$ is assumed. With $\tau_p \geq K$, there is no pilot contamination but for the sake of observing all the practical limitations $K \geq \tau_p$ is assumed(more than one user is assigned with same pilot) . we use $\mathcal{T}_p \subset \{1,\ldots,K\}$ to show the subset of users assigned with pilot p.

$\mathbf{H}_{l,r}$, ϕ coefficients are estimated in first phase and $\mathbf{f}_{r,k}$, $\mathbf{f}_{l,k}$ easily can be estimated with least square(LS) or $MMSE$ algorithms. we assume $\sqrt{\tau_p}\boldsymbol{\psi}_i$ is assigned pilot for k-th user. In l-th BS we have:

$$\mathbf{Y}^{p}_{l} = \sum_{i=1}^{K}\sqrt{p_i\tau_p}\left[\mathbf{H}_{l,r}\,\mathrm{diag}\left(\hat{\phi}\right)\mathbf{f}_{r,i} + \mathbf{f}_{l,i}\right]\boldsymbol{\psi}_i^{\mathrm{T}} + \mathbf{N}^{p}_{l} \tag{3}$$

where, p_i is transmit power of each user, $\mathbf{Y}^{p}_{l} \in C^{M\times \tau_p}$ is received pilot signals in l-th BS and $\mathbf{N}^{p}_{l} \in C^{M\times \tau_p}$ is received noise in l-th BS. $\mathbf{H}_{l,r}$ and $\hat{\phi}$ are estimated coefficients in first phase. k-th user received signal in l-th BS is as follow:

$$\begin{aligned}
&\mathbf{Y}^{p}_{l,k} = \\
&\sum_{i=1}^{K}\sqrt{p_i\tau_p}\left[\hat{\mathbf{H}}_{l,r}\,\mathrm{diag}\left(\hat{\phi}\right)\mathbf{f}_{r,i} + \mathbf{f}_{l,i}\right]\boldsymbol{\psi}_i^{\mathrm{T}}\boldsymbol{\psi}_k^{*} + \frac{1}{\sqrt{\tau_p}}\mathbf{N}^{p}_{l}\boldsymbol{\psi}_k^{*} \\
&= \sum_{i\in\mathcal{T}_p}\sqrt{p_i\tau_p}\left[\hat{\mathbf{H}}_{l,r}\,\mathrm{diag}\left(\hat{\phi}\right)\mathbf{f}_{r,i} + \mathbf{f}_{l,i}\right] + \mathbf{n}^{p}_{l,k} \\
&= \sum_{i\in\mathcal{T}_p}\sqrt{p_i\tau_p}\,\boldsymbol{\Lambda}_t\begin{bmatrix}\mathbf{f}_{r,i}\\ \mathbf{f}_{l,i}\end{bmatrix} + \mathbf{n}^{p}_{l,k} \\
&\hat{\boldsymbol{\Lambda}}_t = \begin{bmatrix}\hat{\mathbf{H}}_{l,r}\,\mathrm{diag}\left(\hat{\phi}_t\right) & \mathbf{I}_M\end{bmatrix}
\end{aligned} \tag{4}$$

We can use both LS or $MMSE$ algorithms for channel coefficients estimation. Unlike $MMSE$, simplicity and no need to know the statistical features of channels are some advantages of LS but $MMSE$ decoder outperforms in both Rayleigh and Rician channels. Coexistence of direct and cascaded links (projected signals), results in applying $MMSE$ decoder as a nontrivial approach [17, 21]. The major parameters that affect this case is ϕ^s and $\mathbf{H}^{s}_{l,r}$. Because these parameters are pre-computed in large timescales, so using $MMSE$ is allowed. For LS, we have:

$$\begin{bmatrix}\hat{\mathbf{f}}_{r,k}\\ \hat{\mathbf{f}}_{l,k}\end{bmatrix} = \sqrt{p_k\tau_p}\left(\boldsymbol{\Lambda}_t^{H}\boldsymbol{\Lambda}_t\right)^{-1}\boldsymbol{\Lambda}_t^{H}\mathbf{y}^{p}_{l,k} \tag{5}$$

For $MMSE$ we have:

$$\begin{bmatrix}\hat{\mathbf{f}}_{r,k}\\ \hat{\mathbf{f}}_{l,k}\end{bmatrix} = \sqrt{p_k\tau_p}\,\boldsymbol{\Gamma}_{l,k}\boldsymbol{\Delta}^{-1}_{l,k}\mathbf{y}^{p}_{l,k} \tag{6}$$

$$\boldsymbol{\Delta}_{l,k} = \mathbb{E}\left\{\mathbf{y}^{p}_{l,k}\mathbf{y}^{p^{\mathrm{H}}}_{l,k}\right\} = \sum_{i\in\mathcal{T}_p}\tau_p p_i\boldsymbol{\Gamma}_{l,i}(\boldsymbol{\Lambda}_t\boldsymbol{\Lambda}_t^{H}) + \sigma^2\mathbf{I}_M$$

where, $\boldsymbol{\Gamma}_{l,k}$ is spatial correlation matrix of $\begin{bmatrix} \mathbf{f}_{r,k} \\ \mathbf{f}_{l,k} \end{bmatrix}$. In *MMSE* algorithm, $\boldsymbol{\Gamma}_{l,k}$ matrix must be known in any BS (precomputed coefficients); some methods to estimate them available in [21].

After estimating all of channels coefficients, for cascaded and direct channels we have:

$$\begin{bmatrix} \tilde{f}_{r,k} \\ \tilde{f}_{l,k} \end{bmatrix} \sim \mathcal{CN}(0,\ \Gamma_{L,K} - p_k \tau_k \Gamma_{l,k} \Delta_{l,k}^{-1} \Gamma_{l,k}) \tag{7}$$

where, (8), denote the channel estimation error vector between l-th BS and k-th user in cascaded and direct channels. For simplicity in equations it's assumed: $\mathbf{g}_{l,k} = (\mathbf{C}_{l,k}\boldsymbol{\Phi}_l + \mathbf{f}_{l,k})$. Also, we know $\mathbf{C}_{l,k} = \hat{\mathbf{C}}_{l,k} + \tilde{\mathbf{C}}_{l,k}$ *and* $\mathbf{f}_{l,k} = \hat{\mathbf{f}}_{l,k} + \tilde{\mathbf{f}}_{l,k}$ *, therefore,* $\mathbf{g}_{l,k} = \hat{\mathbf{g}}_{l,k} + \tilde{\mathbf{g}}_{l,k}$ *. In* Subsequent sections, uplink transmission under practical considerations is investigated.

3. UPLINK TRANSMISSION

As mentioned, conventional cell free massive MIMO system is unscalable when the number of BSs and especially the number of users is numerous [8, 9]. The factors that affect the scalability of conventional cell free system has been reviewed in many papers, among which we can mention [8, 9, 22, 23].

However, there are practical implementation limitations of each of these, like, [8, 22], do not guarantee that all users will be served by at least one BS and complexity of [22] growths with increasing BSs and users numbers. To the best of our knowledge, in all the works done in this subject, the most efficient model for practical implementation of cell-free system is [9]. In [9], is assumed that any BS isn't allowed to assign each pilot to more than one user and any user selects its master BS based on (l = arg minimize $\beta_{l,k}$, l = 1,...,L). Also, after selecting master BS for any user, this master BS assigns τ_k pilot for k-th user, based on measuring of which pilot causes the least pilot contamination in it for k-th user. [9], claims that all of these user centric approaches are subsets of framework called dynamic cooperation clustering (DCC). According to DCC framework, backhauling traffic and computational complexity of cell free system will be independent of the K but proportional to L. More details about pilot assignment and initial network access are given in [9]. DCC framework is defined based on $\mathbf{Q}_{k,l} \in C^{M\times M}$ for (k = 1,...,K) and (l = 1,...,L). If j-th diagonal entry of $\mathbf{Q}_{k,l}$ is 1, indicate that j-th antenna of l-th BS is allowed to receive and transmit to k- user. According to above statements, we pursue same notation to the subset of users are served by l-th BS:

$$Ql = \{i : \mathbf{Q}_{l,i} = \mathbf{I}_M,\ i = 1,...,K\} \tag{8}$$

where, we consider only L BSs that serve the user with all its M antennas. Therefore, uplink transmission of RIS-aided cell free massive MIMO system is:

$$\mathbf{y}_l = \sum_{k=1}^{K} \sqrt{p_k}\mathbf{Q}_{l,k}(\mathbf{C}_{l,k}\boldsymbol{\Phi}_l + \mathbf{f}_{l,k})x_k + \mathbf{n}_l \tag{9}$$

where, $\boldsymbol{\Phi}_l = [\phi_l^{s^T}, \ldots \phi_l^{S^T}]^T$ and $\mathbf{n}_l \in C^{M\times 1}$ is the noise vector in l-th BS. As mentioned, Despite the shortcomings of [9], this system has the most efficient model for practical implementations. In the following, we will investigate the network initialization, pilot and resource allocation for an arbitrary user according to [9].

Assume that BSs, RISs and users are uniformly distributed. Their optimal locations is beyond the scope of this paper. According [9], to reduce pilot contamination, $Car(Q_l) \le \tau_p$ condition must be satisfied, which means that any BS isn't allowed to assign each pilot to more than one user.

The initialization phase for an arbitrary user is as:

- In first step, any arbitrary user measures the $\beta_{l,k}$ with all nearest BSs in both direct and cascaded channels. Then, according to (l = arg minimize $\beta_{l,k}$, l = 1,...,L), l-th BS is appointed as master BS for user.
- In second step, the master BS based on ($\tau_t = \arg\text{minimize}\, \boldsymbol{\Delta}_{l,t}, t = 1\ldots\tau_p$), appoints τ_t pilot for user. In other words, master BS selects τ_t based on the observation of which pilot causes the least pilot contamination.
- In third step, master BS informs the nearest BSs, which one of them wants to serve the user with Pilot τ_t. The nearest BSs will be responsible for servicing the new user with Pilot τ_t in two ways:

– If at that moment they don't serve any user with Pilot τ_t.

– Or the new user with Pilot τ_t has a stronger channel than the previous user.

This process is repeated for all users and BSs. More content on this topic is available on [9]. In [3], four level of cooperation between BSs and CPU is defined that according to their similarities can be divided into two categories. In the following, we consider performance of this system in two mode: centralized and distributed.

3.1. Centralized Mode

In this mode BSs Behavior is like relays by sending all the data signals and pilots to the CPU. All the signal detection and channel estimation tasks perform in CPU. The CPU can select a desired decoder based on each user's CSI. In CPU for k-th user we have:

$$\hat{s}_k = \sum_{l=1}^{L} \sqrt{p_k} \mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,k} x_k + \mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{n}_l \tag{10}$$

$$= \sum_{l=1}^{L} \left(\sqrt{p_k} \underbrace{\mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,k} x_k}_{\text{desired signal}} + \sum_{t=1,t\neq k}^{K} \sqrt{p_t} \underbrace{\mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,t} x_t}_{\text{interference}} + \underbrace{\mathbf{n}_l}_{\text{noise}} \right)$$

Where $\mathbf{w}_{l,k}$ is cascaded an direct links decoders, designed based on both cascaded and direct channels estimations and $\mathbf{n}_l = (\mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k}) \mathbf{n}_l$. In this level, spectral efficiency (*SE*) is:

$$\mathrm{SE}_k^{(level1)} = \frac{\tau_u}{\tau_c} \mathbb{E}\left\{ \log_2 \left(1 + \mathrm{SINR}_k^{(level1)}\right) \right\}$$

$$\mathrm{SINR}_k^{(level1)} = \frac{p_k \sum_{l=1}^{L} (\left| \mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,k} \right|^2}{x_1 + x_2} \tag{11}$$

$$x_1 = \sum_{l=1}^{L} (\sum_{t=1,t\neq k}^{K} p_i \left| \mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,t} \right|^2)$$

$$x_2 = \sum_{l=1}^{L} (\mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \left(\sum_{i=1}^{K} p_i (\mathbf{g}_{l,i} \mathbf{g}_{l,i}^{H}) + \sigma^2 \mathbf{I}_M \right) \mathbf{Q}_{l,k} \mathbf{w}_{l,k})$$

where, $\mathbf{w}_{l,k}^{\mathrm{H}}$ can be any desired decoders. According to [17, 9], this equation can be maximized with *MMSE* decoder. The method of proving spectral efficiency equation has a utterly similar approach to [17], section **C.3.1, Proof of Theorem 4.1**, and their rewriting has been omitted.

Although each user is served by limited number of BSs, according to [9], for k-th user, all ($\mathbf{g}_{l,k}, l = 1, \ldots, L$) must be estimated for the *MMSE* decoder, which in this case, if $k \to \infty$ the system will be unscalable. [24] states interference is made only between the users that they are served by the same BSs. Therefore, for k-th user, we consider only users that are served by same BSs as interference:

$$\mathcal{A}_k = \left\{ i : \mathbf{Q}_{l,k} \mathbf{Q}_{l,i} \neq \mathbf{0}_M, (l = 1, \ldots, L), i \neq k \right\}$$

Accordin to [17, 9], *partial − MMSE* decoder for direct channel $\mathbf{f}_{l,k}$, is defined as:

$$\mathbf{w}_{l,k}^{\mathrm{P-MMSE}} = p_k \sum_{l=1}^{L} \left(\sum_{i \in \mathcal{A}_k} p_i \mathbf{Q}_{l,k} \mathbf{g}_{l,i} \mathbf{g}_{l,i}^{\mathrm{H}} \mathbf{Q}_{l,k} + \mathbf{U}_{l,k}^{'} \right)^{-1} \mathbf{Q}_{l,k} \mathbf{g}_{l,k} \tag{12}$$

With

$$\mathbf{U}_{l,k}^{'} = \mathbf{Q}_{l,k} \left(\sum_{i \in \mathcal{A}_k} p_i (\mathbf{g}_{l,i} \mathbf{g}_{l,i}^{H}) + \sigma^2 \mathbf{I}_M \right) \mathbf{Q}_{l,k}$$

If the k-th user is served by all BSs, then *MMSE* and *P −MMSE* decoders will be equivalent.

3.2. Distributed Mode

In this mode, each BS instead of sending pilot and data signals to CPU, select a local decoder to decode these signals.

$$\tilde{s}_{l,k} = \underbrace{\sqrt{p_k} \mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,k} x_k}_{\text{desired signals}} + \underbrace{\sum_{t=1,t\neq k}^{K} \sqrt{p_t} \mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,t} x_t}_{\text{interference}} + \underbrace{\mathbf{n}_l}_{\text{noise}}$$

where, $\mathbf{n}_l = (\mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k}) \mathbf{n}_l$. Therefore, based on DCC framework and (16), The subset of BSs that jointly serve the k-th user send their local estimates to the CPU.

$$\hat{s}_k = \sum_{l=1}^{L} a_{l,k} \tilde{s}_{l,k}$$

where, $\mathrm{a}_{l,k}$ are weighting coefficients that the CPU selects them based on the channels statistics sent by the BSs. Due to local computations performed at BSs in this level, the CPU does not have estimated channels and only has its statistics. The CPU can improve *SE* by utilizing and optimizing these coefficients [22].

As mentioned, due to the local computations of the channels at each BS, we can't use (17) for *SINR* calculation. In this case, because the statistics of estimated channels are available by adding-subtracting the $\mathbb{E}\left\{ \mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,k} \right\}$ term, *SINR* can be calculated as:

$$\hat{s}_k = \sum_{l=1}^{L} a_{l,k} \sqrt{p_k} (\mathbb{E}\left\{ \mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,k} \right\})$$
$$+ \sum_{l=1}^{L} a_{l,k} \sum_{i=1}^{K} \sqrt{p_i} (\mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,i}) s_i$$
$$- \sum_{l=1}^{L} a_{l,k} \sqrt{p_k} (\mathbb{E}\left\{ \mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,k} \right\}) + \sum_{l=1}^{L} \mathbf{n}_l$$

Finally, according to [17], SE is:

$$\mathrm{SE}_k^{(level2)} = \frac{\tau_u}{\tau_c} \log_2 \left(1 + \mathrm{SINR}_k^{(level2)}\right)$$

$$\mathrm{SINR}_k^{(level2)} = \frac{v_0}{v_1 - v_2 + v_3}$$

$$v_0 = p_k \left| \sum_{l=1}^{L} (\mathbb{E}\left\{ \mathbf{w}_{l,k}^{\mathrm{H}} \mathbf{Q}_{l,k} \mathbf{g}_{l,k} \right\}) \right|^2$$

$$v_1 = \sum_{l=1}^{L}\sum_{i=1}^{K} p_i \mathbb{E}\left\{\left|\mathbf{w}_{l,k}^{\mathrm{H}}\mathbf{Q}_{l,k}\mathbf{g}_{l,i}\right|^2\right\}$$

$$v_2 = p_k \left|\sum_{l=1}^{L} \mathbb{E}\left\{\mathbf{w}_{l,k}^{\mathrm{H}}\mathbf{Q}_{l,k}\mathbf{g}_{l,k}\right\}\right|^2$$

$$v_3 = \sigma^2 \sum_{l=1}^{L} \mathbb{E}\left\{\left\|\mathbf{w}_{l,k}^{\mathrm{H}}\mathbf{Q}_{l,k}\right\|^2\right\}$$

The method of proving spectral efficiency equation has a completely similar approach to [17], section **C.3.4, Proof of Theorem 4.4**, and their rewriting has been omitted. Unlike level 1, for example, in this mode, in direct channel, any BS can only use its own local estimations $\hat{\mathbf{f}}_{l,k}, k \in \mathcal{Q}_l$, for design decoder. Inspired by centralized mode, for direct channel, we have:

$$\mathbf{v}_{l,k}^{\mathrm{LP-MMSE}} = p_k \left(\sum_{i \in \mathcal{Q}_l} p_i \left(\hat{\mathbf{f}}_{l,i} \hat{\mathbf{f}}_{l,i}^{\mathrm{H}} + (\mathbf{g}_{l,i} \mathbf{g}_{l,i}^{H}) \right) + \sigma^2 \mathbf{I}_M \right)^{-1} \hat{\mathbf{f}}_{l,k}$$

Also, for cascaded channel, $LP-MMSE$ decoder is defined as the direct channel case.

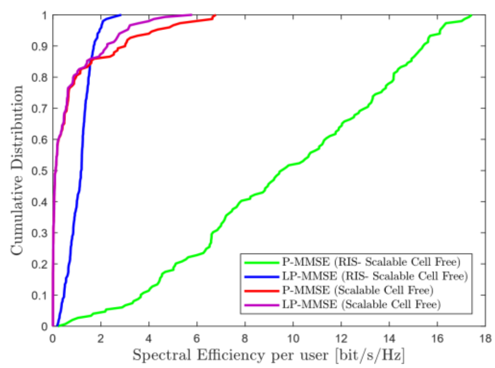

Figure 2: The cumulative distribution of SE per user with τ_p=5

4. NUMERICAL RESULTS

In this section uplink transmission mode of RIS-aided cell free massive MIMO system is evaluated. To assess performance of this system, we consider

($L = 3$, $M = 10$) BSs, $K = 3$ single antenna users and one RIS with $N = 50$ antennas, which are randomly and uniformaly distributed in wrap around area. Also, $\tau_c = 20$, $BW = 20MHz$ and noise with τ_p =5 variance and large scale fading is defined as:

$$noisevariance = -174 + 10\log_{10} BW + noisefigure$$

$$\beta_{l,k} = \zeta - 10\alpha \log_{10}\left(\frac{d_{l,k}}{1\mathrm{m}}\right) + \mathcal{N}(0, \sigma_{shadowing}^2)$$

where, ζ, α, $d_{l,k}$ are median channel gain at a reference distance of $1m$, pathloss exponent, distance between (BS- user or BS- RIS or RIS- user), respectively, and second term models the shadowing effects. Without loss of generality, for simplicity, we assume $\mathbf{R}_{f_{r,k}} \in C^{N\times N}$, $\mathbf{R}_{H_{l,r}}^{s} \in C^{N\times N}$ is equal to $\beta \mathbf{I}_{N\times N}$, which β describes large scale fading in RIS- user, BS- RIS directions, respectively.

Figs. 2 and 3 present cumulative distribution of *SE* per user for uplink transmission for scalable cell free [9] and RIS-aided cell free systems with ($L = 3$, $M = 10$) and $\tau_p = 5, \tau_p = 2$, respectively. As can be seen, centralized form of the RIS-aided cell free outperforms all modes. If we look closely at the Figs, we can see that in 90% likely (when CDF is 0.1) spectral efficiency points, centralized RIS-aided cell free performs best. The distributed form of RIS-aided cell free performance is better than scalable cell free system in $\tau_p = 5$. When K is greater than pilot sequences, curves are crossing each other and make evaluating more complicated but differences between them is negligible. Also, there is no significant difference between the centralized and distributed form of scalable cell free, which can be attributed to the small number of BSs.

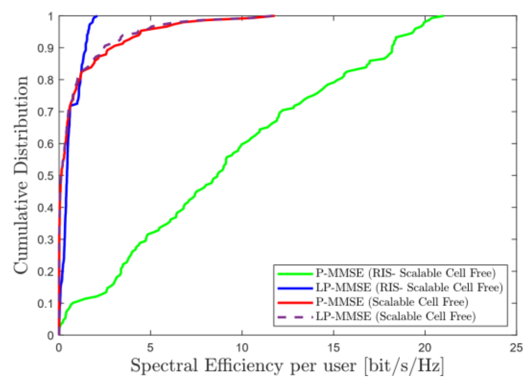

Figure 3: The cumulative distribution of SE per user with τ_p=2

5. Conclusion

In this paper, RIS-scalable cell free massive MIMO system performance in centralized and distributed modes of implementation is evaluated. Spectral efficiency equations is derived for two modes by involving imperfect channel and pilot contamination effects. By simulating the considered system, it was shown that RIS-based cell free system is promising technique to improve scalable cell free system in terms of spectral efficiency, implementations costs and good service in poor scattering environments. However, the proposed methods for estimating the channel of this system have many challenges, like backhauling link balancing, which can be examined more precisely for future works.

6. References

[1] Rajatheva, I. Atzeni, S. Bicais, E. Bjornson, A. Bourdoux, S. Buzzi, C. D'Andrea, J.-B. Dore, S. Erkucuk, M. Fuentes, et al., "Scoring the terabit/s goal: Broadband

connectivity in 6G", *arXiv preprint arXiv:2008.07220*, 2020.

[2] I. F. Akyildiz, A. Kak, S. Nie, "6G and beyond: The future of wireless communications systems", *IEEE Access* , vol.8 , pp.133995–134030, 2020.

[3] E. Björnson, L. Sanguinetti, "Making cell-free massive mimo competitive with mmse processing and centralized implementation", *IEEE Transactions on Wireless Communications,* vol.19, pp. 77-90, 2019.

[4] A. M. Saray, J. Pourrostam, "Spectral efficiency analysis and optimal power allocation for uplink multi-user cell-free massive mimo networks employing stbcs", *Computer Communications*, vol. 170, pp. 42–49, 2021

[5] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, T. L. Marzetta, "Cellfree massive mimo versus small cells", *IEEE Transactions on Wireless Communications* , vol.16, pp.1834–1850, 2017

[6] A. M. Saray, J. Pourrostam, S. H. Mousavi, M. M. Feghhi, "A lowcomplexity space time block codes detection for cell free massive mimo systems", *in: 2020 28th Iranian Conference on Electrical Engineering (ICEE), IEEE*, pp. 1–5, 2020.

[7] A. M. Saray, A. Ebrahimi, "Max-min power control of cell free massive mimo system employing deep learning", *in: 2022 4th West Asian Symposium on Optical and Millimeter-wave Wireless Communications (WASOWC), IEEE*, pp. 1–4, 2022.

[8] S. Buzzi, C. D'Andrea, "Cell-free massive mimo: User-centric approach", *IEEE Wireless Communications Letters*, vol.6, pp.706–709, 2017.

[9] E. Björnson, L. Sanguinetti, "Scalable cell-free massive mimo systems*", IEEE Transactions on Communications*, vol.68, pp.4247–4261, 2020.

[10] Y. Zhang, B. Di, H. Zhang, J. Lin, C. Xu, D. Zhang, Y. Li, L. Song, Beyond cell-free mimo: energy efficient reconfigurable intelligent surface aided cell-free mimo communications, IEEE Transactions on Cognitive Communications and Networking 7 (2021) 412–426.

[11] X. Wei, D. Shen, L. Dai, Channel estimation for ris assisted wireless communications—part i: Fundamentals, solutions, and future opportunities, IEEE Communications Letters 25 (2021) 1398–1402.

[12] D. Mishra, H. Johansson, Channel estimation and low-complexity beamforming design for passive intelligent surface assisted miso wireless energy transfer, in: ICASSP 2019-2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), IEEE, 2019, pp. 4659–4663.

[13] C. Hu, L. Dai, S. Han, X. Wang, Two-timescale channel estimation for reconfigurable intelligent surface aided wireless communications, IEEE Transactions on Communications (2021).

[14] Z. Zhang, L. Dai, A joint precoding framework for wideband reconfigurable intelligent surface-aided cell-free network, IEEE Transactions on Signal Processing (2021).

[15] Q. N. Le, V.-D. Nguyen, O. A. Dobre, R. Zhao, Energy efficiency maximization in ris-aided cell-free network with limited backhaul, IEEE Communications Letters (2021).

[16] E. Björnson, L. Sanguinetti, Rayleigh fading modeling and channel hardening for reconfigurable intelligent surfaces, IEEE Wireless Communications Letters 10 (2020) 830–834.

[17] E. Björnson, J. Hoydis, L. Sanguinetti, Massive mimo networks: Spectral, energy, and hardware efficiency, Foundations and Trends in Signal Processing 11 (2017) 154–655.

[16] D.-S. Shiu, G. J. Foschini, M. J. Gans, J. M. Kahn, Fading correlation and its effect on the capacity of multielement antenna systems, IEEE Transactions on communications 48 (2000) 502–513.

[17] H. Alwazani, A. Kammoun, A. Chaaban, M. Debbah, M.-S. Alouini, et al., Intelligent reflecting surface-assisted multi-user miso communication: Channel estimation and beamforming design, IEEE Open Journal of the Communications Society 1 (2020) 661–680.

[18] Q. Wu, R. Zhang, Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming, IEEE Transactions on Wireless Communications 18 (2019) 5394–5409.

[19] T. L. Marzetta, H. Q. Ngo, Fundamentals of massive MIMO, Cambridge University Press, 2016.

[20] M. Bashar, K. Cumanan, A. G. Burr, M. Debbah, H. Q. Ngo, On the uplink max–min sinr of cell-free massive mimo systems, IEEE Transactions on Wireless Communications 18 (2019) 2021–2036.

[21] O. Y. Bursalioglu, G. Caire, R. K. Mungara, H. C. Papadopoulos, C. Wang, Fog massive mimo: A user-centric seamless hot-spot architecture, IEEE Transactions on Wireless Communications 18 (2018) 559–574.

[22] E. Nayebi, A. Ashikhmin, T. L. Marzetta, B. D. Rao, Performance of cell-free massive mimo systems with mmse and lsfd receivers, in: 2016 50th Asilomar Conference on Signals, Systems and Com