Leakage-Based Coordinated Beamforming for Reconfigurable Intelligent Surfaces-Aided Dynamic TDD Systems

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***Abstract*—The integration of dynamic time-division-duplexing (DTDD) and reconfigurable intelligent surfaces (RISs) has been proposed as a solution to meet the small cells traffic fluctuations and to tune the wireless propagation channels in real-time. The most critical problem of an RIS-aided DTDD system is cross-link interference. Therefore, in this paper we jointly optimize the base stations transmit precoders and the RIS reflection vector to maximize the sum signal-to leakage-plus-noise ratio (SLNR), with the objective of improving communication efficiency while reducing the impact of cross-link interference. Our numerical results demonstrate a significant performance improvement using the proposed method as compared to some baseline schemes.**

***Index Terms*—Dynamic TDD, MIMO communications, small cells, reconfigurable intelligent surface.**

I. Introduction

Extremely high reliability, low latency and ultra high data rate are among the key requirements for the beyond fifth-generation (B5G) wireless communication systems. The dense deployment of small cell networks has emerged as an effective way to meet the exponential growth of traffic demands for 5G and future wireless networks. Small cells using low-power nodes are meant to be deployed in hot spots, where the number of users varies strongly with time and between adjacent cells [1]. As a result, small cells are expected to have burst-like traffic, which makes the static time division duplex (TDD) frame configuration strategy, where a common TDD pattern is selected for the whole network, not able to meet the users' requirements and the traffic fluctuations. This inadvertently leads to a high drop rate for the small cells [2]. Dynamic time division duplex (DTDD) has been proposed as a solution to satisfy the asymmetric and dynamic traffic demand of small cells [1]. In a DTDD enabled wireless communication system, each cell individually decides its schedule for the uplink and downlink mode operation across different time slots, based on its instantaneous traffic demand and/or interference status [3].

However, the main challenge brought by DTDD is the cross-link interference issue, because adjacent cells may use at a given time different TDD frame configurations according to traffic needs, thereby giving rise to opposite transmission directions among neighboring cells. There are two kinds of cross-link interference: base station-to-base station (BS-to-BS) and user equipment-to-user equipment (UE-to-UE) interference, which may degrade the system performance significantly. Among the two, the BS-to-BS interference is extremely detrimental due to the large transmit power and line-of-sight (LOS) propagation characteristics. Hence, an efficient cross-link interference management scheme is desirable.

Reconfigurable intelligent surfaces (RISs) have gained significant attention recently, as a low-cost and compact transformational technology for future wireless systems [4]-[7]. In a passive RIS-aided communication system, where the RIS has no radio-frequency chains, the phase shifts of the RIS elements can be adjusted to meet a certain cost function, e.g., the reflected signals add constructively at the intended users and/or destructively at the unintended users. Leveraging upon the intelligent spectrum control of the RIS, it was shown that the cross-link BS-to-BS interference can be effectively mitigated by the joint design of active transmit beamforming vectors and the passive RIS reflection vector, thereby improving the overall system spectral efficiency, for an RIS-aided DTDD system [8,9]. Although most of the works on RIS-aided communication systems have focused on the ideal RIS case, wherein the phase-shifts of the RIS are assumed to be continuous-valued, in practice these phases admit only certain discrete values [10].

In this paper, we consider the discrete phase-shift model for the RIS and the concept of signal *leakage* for the design of the transmit beamforming for an RIS-aided DTDD system controlled by a central processing unit (CPU). Maximizing the signal-to-leakage-and-noise ratio (SLNR) for all the users in the downlink cells is an efficient way of designing the transmit beamforming vectors because it limits the search space and also lowers the complexity involved in finding efficient transmit beamformers [11]-[13]. The resulting optimization problem is solved by decoupling it among the variables, and we propose a low-complexity and non-iterative method, similar to the work in [8], for the design of the RIS refection vector and the Rayleigh-Ritz [14] method for the design of the transmit beamforming vectors. Moreover, we assume that the directions of the small cells have been optimized *a priori*, e.g., using the proposed cell reconfiguration method in [15], and are known at the CPU.

II. System Model

In this paper[1], we consider an RIS-aided mmWave DTDD system consisting of Q small cells, where each cell has a BS with a uniform linear array (ULA) of N antennas serving a single UE[2] that is equipped with a single-antenna. As shown in Fig. 1, we assume that the communication is aided by an RIS with M passive reflection elements, where the BSs and the RIS are controlled by a CPU via backhaul connections. Let $\mathcal{Q} \triangleq \{1, \cdots, Q\}$ denote the set of BSs (cells). At the considered time instant, we assume that there are $|\mathcal{Q}^{\text{ul}}|$ cells operating in the uplink (UL) direction and $|\mathcal{Q}^{\text{dl}}|$ cells operating in the downlink (DL) direction, such that $|\mathcal{Q}^{\text{ul}}| + |\mathcal{Q}^{\text{dl}}| = Q$ and $\mathcal{Q}^{\text{ul}} \bigcap \mathcal{Q}^{\text{dl}} = \emptyset$.

Let $\mathbf{H}_q \in \mathbb{C}^{M\times N}$ be the channel matrix from the qth BS to the RIS, $\mathbf{h}_q \in \mathbb{C}^M$ be the channel vector from the qth UE to the RIS, $\mathbf{G}_{r,q} \in \mathbb{C}^{N\times N}$ be the channel matrix from the qth BS to the rth BS, $\mathbf{g}_{r,q} \in \mathbb{C}^N$ be the channel vector from the qth BS to the rth UE, and $g_{r,q} \in \mathbb{C}$ be the channel scalar from qth UE to the rth UE. Denote b as the number of quantization bits of the RIS, such that the number of phase levels is 2^b. The resulting discrete phase shifts of the RIS are expressed as

$$\mathcal{F} \triangleq \left\{0, \frac{2\pi}{2^b}, 2\frac{2\pi}{2^b}, \cdots, (2^b-1)\frac{2\pi}{2^b}\right\} \tag{1}$$

The received signal by the UE in the qth DL cell, i.e., $q \in \mathcal{Q}^{\text{dl}}$, can be expressed as

$$y_q^{(\text{dl})} = \sum_{\forall k\in\mathcal{Q}^{\text{dl}}} (\mathbf{h}_{q,k}^{\text{BS-UE}})^{\mathsf{H}}\mathbf{f}_k x_k + \sum_{\forall r\in\mathcal{Q}^{\text{ul}}} h_{q,r}^{\text{UE-UE}}\sqrt{p_r^{\text{ul}}}x_r + z_q, \tag{2}$$

where $\mathbf{h}_{q,k}^{\text{BS-UE}} = (\mathbf{h}_q^{\mathsf{H}}\boldsymbol{\Theta}\mathbf{H}_k + \mathbf{g}_{q,k}^{\mathsf{H}})^{\mathsf{H}}$, $h_{q,r}^{\text{UE-UE}} = \mathbf{h}_q^{\mathsf{H}}\boldsymbol{\Theta}\mathbf{h}_r + g_{q,r}$, $\boldsymbol{\Theta} = \text{diag}(\boldsymbol{\theta})$ is the RIS reflection diagonal matrix, $\boldsymbol{\theta} = [e^{j\phi_1}, \cdots, e^{j\phi_M}]^{\mathsf{T}} \in \mathbb{C}^M$ with $\phi_m \in \mathcal{F}$, $\mathbf{f}_k \in \mathbb{C}^N$ is the transmit precoding vector with $\|\mathbf{f}_k\|_2^2 = p_k^{\text{dl}}$, x_k is the unit-norm transmit symbol, z_q is additive white Gaussian noise with variance σ_q^2, and p_r^{X} is the transmit power in the $\text{X} \in \{\text{dl, ul}\}$ direction.

On the other hand, the total received BS-BS interference power at the rth UL BS, i.e., $r \in \mathcal{Q}^{\text{ul}}$, from the DL BSs, can be expressed as

$$\text{IP}_r = \sum_{\forall q\in\mathcal{Q}^{\text{dl}}} \|\mathbf{H}_{r,q}^{\text{BS-BS}}\mathbf{f}_q\|^2, \tag{3}$$

where $\mathbf{H}_{r,q}^{\text{BS-BS}} = \mathbf{H}_r^{\mathsf{H}}\boldsymbol{\Theta}\mathbf{H}_q + \mathbf{G}_{r,q}$.

In this paper, we assume that the above defined channels $\{\mathbf{H}_q, \mathbf{h}_q, \mathbf{G}_{r,q}, \mathbf{g}_{r,q}, g_{r,q}\}$ are modeled according to the well-known mmWave Saleh-Valenzuela geometric channel model [16]-[17], where every channel is modeled as a summation of $L \ll \max\{M, N\}$ paths, each has a distinctive direction-of-departure (DoD) and/or direction-of-arrival (DoA) and a complex path gain. Under this assumption, we have that $\text{rank}\{\mathbf{H}_q\} \leq L, \forall q$ and $\text{rank}\{\mathbf{G}_{r,q}\} \leq L, \forall r, q$. We assume the availability of the channel state information (CSI) at the BSs. The CSI can be estimated using for example, the channel estimation method in [18].

[1] *Notation:* Vectors and matrices are written as lowercase and uppercase boldface letters, respectively. The notation $\diamond$ is used to denote the Khatri-Rao product. The transpose and the conjugate transpose (Hermitian) of $\mathbf{X}$ are represented by $\mathbf{X}^{\mathsf{T}}$ and $\mathbf{X}^{\mathsf{H}}$, respectively. The $\text{diag}(\mathbf{x})$ forms a matrix by placing $\mathbf{x}$ on its main diagonal, and $\text{vec}(\mathbf{X})$ vectorizes $\mathbf{X}$ by stacking its columns on top of each other.

[2] The extension of our proposed solution to multi-user scenarios is straightforward.

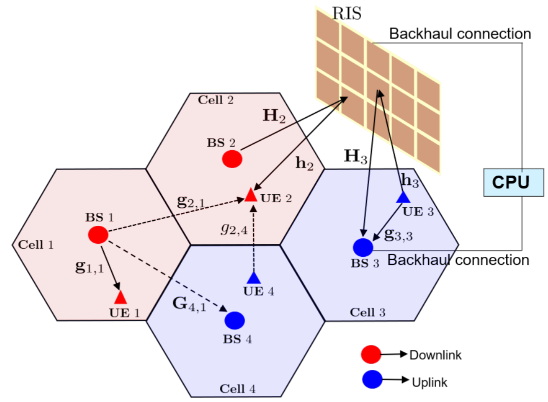

Fig. 1: An RIS-aided DTDD system comprising $Q = 4$ cells

III. Problem Formulation

Our main goal is to design the passive reflection vector of the RIS and the active transmit beamforming vectors of the DL BSs to maximize the sum SLNR, which can be formulated as[3]

$$\begin{aligned} \max_{\mathbf{f}_q,\boldsymbol{\theta}} \quad & \sum_{q\in\mathcal{Q}^{\text{dl}}} \Omega_q^{(\text{dl})} \\ \text{s.t} \quad & (\text{C1}): \|\mathbf{f}_q\|_2^2 \leq p_q^{\text{dl}},\ \forall q \in \mathcal{Q}^{\text{dl}} \\ & (\text{C2}): |[\boldsymbol{\theta}]_{[m]}|^2 = 1,\ m = 1, \cdots, M, \\ & (\text{C3}): \phi_m \in \mathcal{F} \end{aligned} \tag{4}$$

where (C1) is the DL transmit power constraint and (C2) are the constant modulus constraints (CMCs) for the RIS reflection coefficients. $\Omega_q^{(\text{dl})}$ denotes the SLNR at the qth DL cell, i.e., $q \in \mathcal{Q}^{\text{dl}}$, which can be expressed as

$$\Omega_q^{(\text{dl})} = \frac{|(\mathbf{h}_{q,q}^{\text{BS-UE}})^{\mathsf{H}}\mathbf{f}_q|^2}{\|\mathbf{A}_q\mathbf{f}_q\|^2 + \sigma_q^2} \tag{5}$$

where $\mathbf{A}_q = \text{stack}\{\mathbf{A}_q^{\text{BS-UE}}, \mathbf{A}_q^{\text{BS-BS}}\} \in \mathbb{C}^{U\times N}$ is a matrix containing all the channels from the qth UE in the qth DL cell to other users in the DTDD system, where

$$\mathbf{A}_q^{\text{BS-UE}} = \text{stack}\{(\mathbf{h}_{1,q}^{\text{BS-UE}})^{\mathsf{H}}, \cdots, (\mathbf{h}_{|\mathcal{Q}^{\text{dl}}|-1,q}^{\text{BS-UE}})^{\mathsf{H}}, (\mathbf{h}_{|\mathcal{Q}^{\text{dl}}|+1,q}^{\text{BS-UE}})^{\mathsf{H}}\}$$

$$\mathbf{A}_q^{\text{BS-BS}} = \text{stack}\{\mathbf{H}_{1,q}^{\text{BS-BS}}, \cdots, \mathbf{H}_{|\mathcal{Q}^{\text{ul}}|,q}^{\text{BS-BS}}\}$$

where we define $\mathbf{X} = \text{stack}\{\mathbf{X}_i\}_{\forall i\in\mathcal{I}} = [\mathbf{X}_1^{\mathsf{T}}, \cdots, \mathbf{X}_{|\mathcal{I}|}^{\mathsf{T}}]^{\mathsf{T}}$, i.e., a function that stacks the input matrices over each other. Therefore, it is easy to verify that $U = |\mathcal{Q}^{\text{dl}}| - 1 + |\mathcal{Q}^{\text{ul}}|N$.

To obtain a solution for the non-convex problem (4), we propose in the following a non-iterative solution by decoupling the optimization between the problem variables. Specifically, given the channel matrices, we design the RIS passive reflection vector $\boldsymbol{\theta} \in \mathbb{C}^M$. After that, for a given $\boldsymbol{\theta}$, we design the BSs' transmit active beamformers $\mathbf{f}_q, \forall q \in \mathcal{Q}^{\text{dl}}$, using the Rayleigh-Ritz method [14].

[3] In [11]-[13], it has been shown that the SLNR is a reasonable metric to balance the complexity and performance in massive MIMO systems and leads to an optimal closed-form characterization of the BS precoders.

IV. RIS Reflection Design Method

From Property 1 [4], we first note that the vectorized form of the above defined effective desired and leakage channels can be expressed as

$$\mathbf{h}_{q,q}^{\text{BS-UE}} = \mathbf{H}_{q,q}^{\text{BS-UE}}\boldsymbol{\theta} + \mathbf{g}_{q,q},\ \forall q \in \mathcal{Q}^{\text{dl}} \tag{6}$$

$$\mathbf{h}_{k,q}^{\text{BS-UE}} = \mathbf{H}_{k,q}^{\text{BS-UE}}\boldsymbol{\theta} + \mathbf{g}_{k,q},\ \forall k, q \in \mathcal{Q}^{\text{dl}}, k \neq q \tag{7}$$

$$\text{vec}\{\mathbf{H}_{r,q}^{\text{BS-BS}}\} = \bar{\mathbf{H}}_{r,q}^{\text{BS-BS}}\boldsymbol{\theta} + \text{vec}\{\mathbf{G}_{r,q}\},\ \forall r\mathcal{Q}^{\text{ul}}, \forall q \in \mathcal{Q}^{\text{dl}} \tag{8}$$

where we define $\mathbf{H}_{q,q}^{\text{BS-UE}} = (\mathbf{H}_q^{\mathsf{T}} \diamond \mathbf{h}_q^{\mathsf{T}}) \in \mathbb{C}^{N\times M}$, $\mathbf{H}_{k,q}^{\text{BS-UE}} = (\mathbf{H}_q^{\mathsf{T}} \diamond \mathbf{h}_k^{\mathsf{T}}) \in \mathbb{C}^{N\times M}$, and $\bar{\mathbf{H}}_{r,q}^{\text{BS-BS}} = (\mathbf{H}_q^{\mathsf{T}} \diamond \mathbf{H}_r^{\mathsf{T}}) \in \mathbb{C}^{N^2\times M}$. Note that $\text{rank}\{\mathbf{H}_{k,q}^{\text{BS-UE}}\} \leq L$ and $\text{rank}\{\bar{\mathbf{H}}_{r,q}^{\text{BS-BS}}\} \leq L^2$. Next, we define the following matrices

$$\mathbf{D}_{\text{DS}}^{\text{BS-UE}} = \text{stack}\{\mathbf{H}_{q,q}^{\text{BS-UE}}\}_{\forall q \in \mathcal{Q}^{\text{dl}}} \tag{9}$$

$$\mathbf{C}_{\text{DL-leak}}^{\text{BS-UE}} = \text{stack}\{\mathbf{H}_{k,q}^{\text{BS-UE}}\}_{\forall k,q \in \mathcal{Q}^{\text{dl}}, k\neq q} \tag{10}$$

$$\mathbf{C}_{\text{UL-leak}}^{\text{BS-BS}} = \text{stack}\{\bar{\mathbf{H}}_{r,q}^{\text{BS-BS}}\}_{\forall r \in \mathcal{Q}^{\text{ul}}, \forall q \in \mathcal{Q}^{\text{dl}}} \tag{11}$$

From the above, we propose to design the RIS reflection vector $\boldsymbol{\theta} \in \mathbb{C}^M$ as a solution to

$$\begin{aligned} \max_{\boldsymbol{\theta}} \quad & \|\mathbf{D}_{\text{DS}}^{\text{BS-UE}}\boldsymbol{\theta}\|_2^2 \\ \text{s.t} \quad & (\text{C2}): |[\boldsymbol{\theta}]_{[m]}|^2 = 1,\ m = 1, \cdots, M \\ & (\text{C3}): \phi_m \in \mathcal{F}, \\ & (\text{C4}): \mathbf{C}_{\text{leak}}\boldsymbol{\theta} = \mathbf{0} \end{aligned} \tag{12}$$

where $\mathbf{C}_{\text{leak}} = \text{stack}\{\mathbf{C}_{\text{DL-leak}}^{\text{BS-UE}}, \mathbf{C}_{\text{UL-leak}}^{\text{BS-BS}}\}$. The problem in (12) is non-convex due to (C2) and (C3). In the following, we propose a low-complexity non-iterative solution to obtain a feasible and efficient RIS reflection vector.

Remark 1: Given the above mmWave channel model, then the following inequality is satisfied:

$$\text{rank}\{\mathbf{C}_{\text{leak}}\} \leq L_{\text{DL-leak}}^{\text{BS-UE}} + L_{\text{UL-leak}}^{\text{BS-BS}}, \tag{13}$$

where $L_{\text{DL-leak}}^{\text{BS-UE}} \leq (|\mathcal{Q}^{\text{dl}}|^2 - |\mathcal{Q}^{\text{dl}}|)L$, from (10), $L_{\text{UL-leak}}^{\text{BS-BS}} \leq |\mathcal{Q}^{\text{dl}}||\mathcal{Q}^{\text{ul}}|L^2$, from (11).

We propose to relax (C2) and to address the discrete non-convex constraint in (C3). To this end, we exclude the limitation of the discrete phase shifts, and thereafter map the obtained continuous phase shifts to the nearest discrete phase value in $\mathcal{F}$. The resulting problem is given as

$$\begin{aligned} \max_{\boldsymbol{\theta}} \quad & \|\mathbf{D}_{\text{DS}}^{\text{BS-UE}}\boldsymbol{\theta}\|_2^2 \\ \text{s.t} \quad & (\text{C4}): \mathbf{C}_{\text{leak}}\boldsymbol{\theta} = \mathbf{0} \\ & (\text{C5}): \|\boldsymbol{\theta}\|_2^2 = 1. \end{aligned} \tag{14}$$

We propose to solve (14) by first assuming that $\boldsymbol{\theta}$ is decomposed into $|\mathcal{Q}^{\text{dl}}|$ sub-vectors as

$$\boldsymbol{\theta} = \boldsymbol{\theta}_1 + \boldsymbol{\theta}_2 + \cdots + \boldsymbol{\theta}_{|\mathcal{Q}^{\text{dl}}|}, \tag{15}$$

where $\|\boldsymbol{\theta}_q\|_2^2 = 1, \forall q$. Given the above decomposition, we propose to design the qth sub-vector $\boldsymbol{\theta}_q$ as

$$\begin{aligned} \max_{\boldsymbol{\theta}_q} \quad & \|\mathbf{H}_{q,q}^{\text{BS-UE}}\boldsymbol{\theta}_q\|_2^2 \\ \text{s.t} \quad & (\text{C5}): \|\boldsymbol{\theta}_q\|_2^2 = 1 \\ & (\text{C6}): \boldsymbol{\Pi}_q^{\text{INT}}\boldsymbol{\theta}_q = \mathbf{0}, \end{aligned} \tag{16}$$

where $\boldsymbol{\Pi}_q^{\text{INT}} = \text{stack}\{\mathbf{D}_{\text{DS-INT}}^{\text{BS-UE}}, \mathbf{C}_{\text{leak}}\}$ and

$$\mathbf{D}_{\text{DS-INT}}^{\text{BS-UE}} = \text{stack}\{\mathbf{H}_{r,r}^{\text{BS-UE}}\}_{\forall r \in \mathcal{Q}^{\text{dl}}, r\neq q}, \tag{17}$$

i.e., a matrix containing all blocks of $\mathbf{D}_{\text{DS}}^{\text{BS-UE}}$ in (9) except for the qth sub-block. Note that $\text{rank}\{\boldsymbol{\Pi}_q^{\text{INT}}\} \leq \text{rank}\{\mathbf{C}_{\text{leak}}\} + L_{\text{DS-INT}}^{\text{BS-UE}}$, where $L_{\text{DS-INT}}^{\text{BS-UE}} \leq (|\mathcal{Q}^{\text{dl}}| - 1)L$. A solution to the qth sub-problem in (16) is given as

$$\boldsymbol{\theta}_q^{\text{FD}} = \mathbf{V}_{\text{INT},q}^{\text{NS}}\mathbf{v}_{\text{max},q}^{\text{BS-UE}} \in \mathbb{C}^M, \tag{18}$$

where $\mathbf{V}_{\text{INT},q}^{\text{NS}}$ holds the basis for the null-space (NS) of $\boldsymbol{\Pi}_q^{\text{INT}}$, which can be obtained from the signular value decomposition of $\boldsymbol{\Pi}_q^{\text{INT}}$ [19] and $\mathbf{v}_{\text{max},q}^{\text{BS-UE}}$ is the right singular vector corresponding to the maximum singular value of $\mathbf{H}_{q,q}^{\text{BS-UE}}\mathbf{V}_{\text{INT},q}^{\text{NS}}$. Let $\boldsymbol{\Theta}^{\text{FD}} = [\boldsymbol{\theta}_1^{\text{FD}}, \cdots, \boldsymbol{\theta}_Q^{\text{FD}}] \in \mathbb{C}^{M\times Q}$. Then, it can be easily shown that

$$\mathbf{D}_{\text{DS}}^{\text{BS-UE}}\boldsymbol{\Theta}^{\text{FD}} = \begin{bmatrix} \mathbf{e}_1 & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{e}_Q \end{bmatrix} \in \mathbb{C}^{QN\times Q}, \tag{19}$$

where $\boldsymbol{e}_q \in \mathbb{R}^N$. Let $\boldsymbol{\theta}^{\text{FD}} = \frac{\boldsymbol{\theta}_1^{\text{FD}} + \cdots + \boldsymbol{\theta}_Q^{\text{FD}}}{\|\boldsymbol{\theta}_1^{\text{FD}} + \cdots + \boldsymbol{\theta}_Q^{\text{FD}}\|}$, then we have,

$$\mathbf{D}_{\text{DS}}^{\text{BS-UE}}\boldsymbol{\theta}^{\text{FD}} = \text{stack}\{\bar{\mathbf{e}}_1, \ldots, \bar{\mathbf{e}}_Q\}, \tag{20}$$

where $\bar{\mathbf{e}}_q = \frac{\mathbf{e}_q}{\|\boldsymbol{\theta}_1^{\text{FD}} + \cdots + \boldsymbol{\theta}_Q^{\text{FD}}\|}$. The obtained continuous phase shifts given as $\phi_m = \angle\boldsymbol{\theta}^{\text{FD}}(m)$ are mapped to the discrete ones. This operation can be expressed as

$$\tilde{\phi}_m = \arg\min_{\phi\in\mathcal{F}} |\phi - \phi_m|, \tag{21}$$

where the periodicity with 2π is taken into account. Finally, to satisfy the constant modulus constraints of (C2) in (12), we apply the element-wise projection function as

$$\tilde{\boldsymbol{\theta}}^{\text{CMC}} \longleftarrow \text{P}\left(\tilde{\boldsymbol{\theta}}^{\text{FD}}\right). \tag{22}$$

V. Transmit Beamforming Design

For a given $\boldsymbol{\theta}$, we design the transmit beamforming vectors $\mathbf{f}_q, \forall q \in \mathcal{Q}^{\text{dl}}$, as the solution to the problem given as

$$\begin{aligned} \max_{\mathbf{f}_q} \quad & \sum_{q\in\mathcal{Q}^{\text{dl}}} \Omega_q^{(\text{dl})} \\ \text{s.t} \quad & (\text{C1}): \|\mathbf{f}_q\|_2^2 \leq p_q^{\text{dl}},\ \forall q \in \mathcal{Q}^{\text{dl}} \end{aligned} \tag{23}$$

It is routine to verify that we can decompose problem (23) into $|\mathcal{Q}^{\text{dl}}|$ sub-problems, which have simple closed-form solutions. According to the generalized Rayleigh-Ritz quotient method [14], the optimal $\mathbf{f}_q$ is given as

$$\mathbf{f}_q = \sqrt{p_q^{\text{dl}}}\mathbf{v}_{\max}\left(\left(\mathbf{A}_q^{\mathsf{H}}\mathbf{A}_q + \frac{\sigma_q^2}{p_q^{\text{dl}}}\mathbf{I}_N\right)^{-1}\mathbf{h}_{q,q}^{\text{BS-UE}}(\mathbf{h}_{q,q}^{\text{BS-UE}})^{\mathsf{H}}\right) \tag{24}$$

where $\mathbf{v}_{\max}\{\cdot\}$ is the eigenvector corresponding to the largest eigenvalue of the matrix.

Complexity analysis: Since the complexity of computing the SVD of a $m \times n$ matrix, with $m \geq n$, is on the order of $\mathcal{O}\{n^2\}$, then the complexity of calculating $\tilde{\boldsymbol{\theta}}^{\text{CMC}}$ is on the order of $\mathcal{O}\{|\mathcal{Q}^{\text{dl}}|M^2\}$. The computational complexity of the leakage-based transmit precoding vectors $\mathbf{f}_q, \forall q \in \mathcal{Q}^{\text{dl}}$, is on the order of $\mathcal{O}\{|\mathcal{Q}^{\text{dl}}|N^3\}$.

Achievable sum rate: The system spectral efficiency (SE) for the RIS-aided DTDD system is given as

$$\text{SE} = \sum_{\forall q\in\mathcal{Q}^{\text{dl}}} \log_2\left(1 + \text{SINR}_q^{(\text{dl})}\right) + \sum_{\forall r\in\mathcal{Q}^{\text{ul}}} \log_2\left(1 + \text{SINR}_r^{(\text{ul})}\right)$$

[4]Property 1: $\text{vec}(\mathbf{A}\text{diag}(\mathbf{b})\mathbf{C}) = (\mathbf{C}^{\mathsf{T}} \diamond \mathbf{A})\mathbf{b}$.

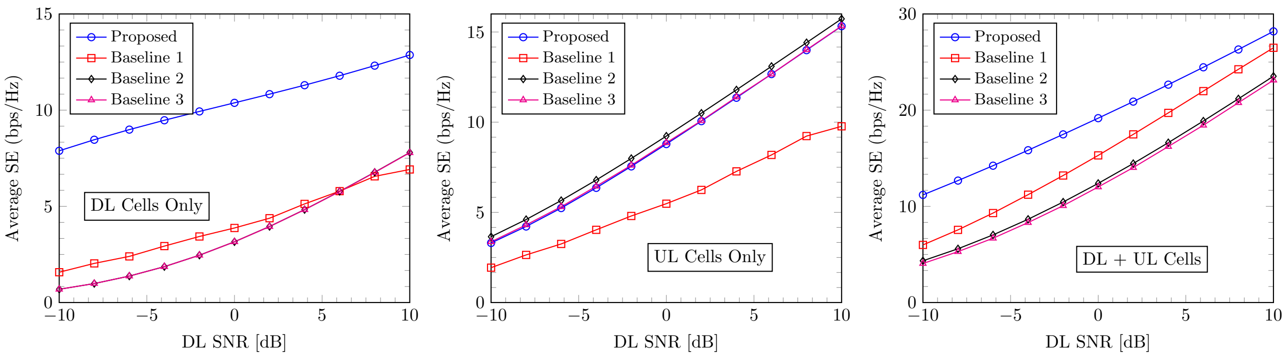

Fig. 2: SE versus DL SNR, assuming $M = 256$, $b = 2$, and $N = 16$.

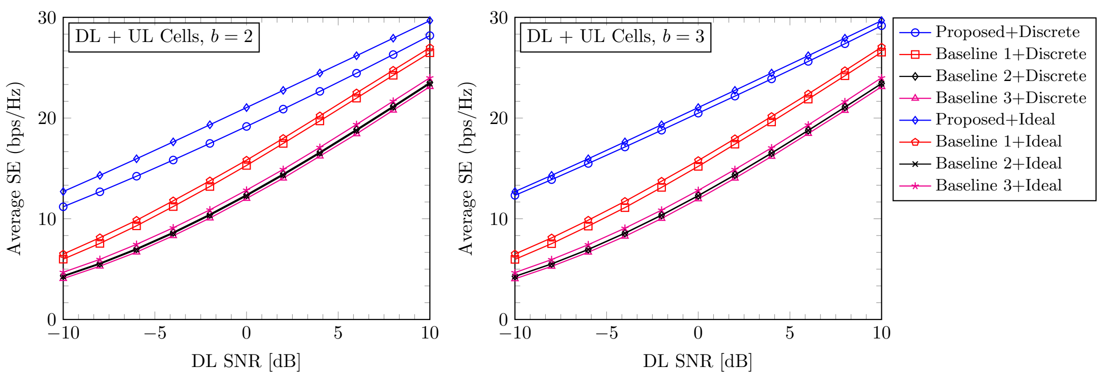

Fig. 3: SE versus DL SNR, assuming $M = 256$ and $N = 16$.

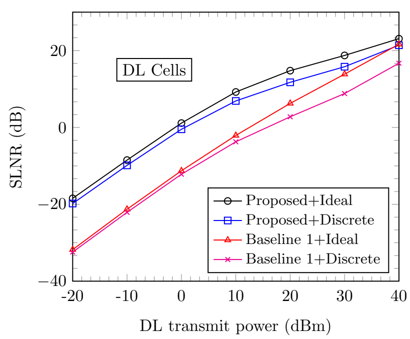

Fig. 4: SLNR versus DL transmit power, assuming $M = 256$ and $N = 16$.

VI. Numerical Results

In this section, we show simulation results to evaluate the performance of our proposed method as compared to baseline schemes. We consider a system with $Q = 4$ cells, as shown in Fig. 1, where $|\mathcal{Q}^{\text{dl}}| = 2$ and $|\mathcal{Q}^{\text{ul}}| = 2$. We set $p_r^{\text{ul}} = 23\,\text{dBm}$ and assume that the number of channel paths $L = 4$, where the corresponding DoDs and/or DoAs are uniformly distributed in $[0, 2\pi]$. For performance comparison purposes, we include results for the following baseline cases: 1) **Baseline 1**, the SLNR-max problem (4) is solved by adopting an alternating-optimization (AO) approach according to [20]. The obtained continuous phase shifts are then mapped to the nearest discrete phase; 2) **Baseline 2**, where the entries of the RIS reflection vector $\boldsymbol{\theta} \in \mathbb{C}^M$ are designed as proposed in (22), and the zero-forcing (ZF) scheme [21] is used to design the transmit beamforming $\mathbf{f}_q, \forall q \in \mathcal{Q}^{\text{dl}}$, and 3) **Baseline 3**, where we adopt AO approach and using the SQUAREM-MM algorithm to design the RIS reflection vector as in [20]. Then we adopt the ZF scheme for the design of the transmit precoder $\mathbf{f}_q, \forall q \in \mathcal{Q}^{\text{dl}}$, for a given $\boldsymbol{\theta} \in \mathbb{C}^M$.

In Fig. 2, we show the SE versus the DL SNR, while assuming that the RIS has $M = 256$ passive reflecting elements and each BS has $N = 16$ antennas. The number of quantization bits used for the discrete phase levels is $b = 2$. We plot the achievable SE of the DL and the UL cells separately and then combine them to better understand the difference between the proposed and the baseline methods. From the figure, we can clearly see that the proposed method has better SE performance compared to the other baseline schemes.

Fig. 3 compares the SE performance of the considered schemes upper-bounded by their ideal RIS cases (continuous phases) for different values of b. There is a performance gap in the achievable SE between the ideal case and the discrete case for the considered schemes as a result of the quantization, which reduces with an increase in the number of quantization bits. The proposed method outperforms the other baseline schemes in both scenarios. Moreover, we can see from Fig. 4 that the proposed method achieves higher SLNR compared to Baseline 1, when the number of quantization bits used for the discrete phase levels is $b = 2$.

VII. Conclusions

In this paper, we have considered the active and passive beamforming design problem in an RIS-aided DTDD wireless network to maximize the signal-to-leakage-and-noise ratio. We have proposed a centralized low-complexity and non-iterative solution for the design of the RIS reflection vector and the constrained optimization of the SLNR for the design of the transmit beamforming vectors. The provided simulation results have shown that the proposed method achieves satisfactory performance compared to other baseline schemes.

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