Sacrificing CSI for a Greater Good: RIS-enabled Opportunistic Rate Splitting

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Abstract-In reconfigurable intelligent surface (RIS)-assisted systems, the optimization of the phase shifts requires separate acquisition of the channel state information (CSI) for the direct and RIS-assisted channels, posing significant design challenges. In this paper, a novel scheme is proposed, which considers practical limitations like pilot overhead and channel estimation (CE) errors to increase the net performance. More specifically, at the cost of unpredictable interference, a portion of the CSI for the RISassisted channels is sacrificed in order to reduce the CE time. By alternating the CSI between coherence blocks and employing rate splitting, it becomes possible to mitigate the interference, thereby compensating the adverse effect of the sacrificed CSI. Numerical simulations validate that the proposed scheme exhibits better performance in terms of achievable net rate, resulting in gains of up to 160% compared non-orthogonal multiple access (NOMA), when CE time and CE errors are considered.

Index Terms—Reconfigurable intelligent surface (RIS), intelligent reflecting surface (IRS), rate splitting (RS), interference management, channel estimation, network topology, opportunistic communication.

I. INTRODUCTION

The reconfigurable intelligent surface (RIS) is a surface that is composed of a large number of passive reflect elements, which enable the ability to shape beams from incident signals [1]. This is achieved by controlling the phase shifts of each element individually, enhancing the signals constructively at intended users and destructively at unintended users. However, due to the passive nature of the RIS, new challenges arise regarding the separate acquisition of the channel state information (CSI) of direct and reflected links, which is a necessity for beneficial adjustment of the RIS. State-of-theart channel estimation (CE) methods, which support separate CSI acquisition, require a prohibitively high number of pilot symbols to do so, due to the proportionality to the number of deployed elements [2–4].

To overcome this limitation, we develop a transmission scheme, which essentially cuts the proportionality to the number of reflect elements in half, thereby reducing the time required for CE substantially. Enabled by the controllability of the RIS, the known channels are used for enhancing the channel strength through proper selection of the phase shifts at the cost of unpredictable interference caused by the unknown channels. However, alternating the CSI knowledge between coherence blocks facilitates the use of rate splitting (RS) [5, 6], which is able to negate the harmful impact of the interference, while interacting synergistically with the RIS [7, 8]. In fact, we show that the proposed scheme reaps the benefits of both, the increased downlink (DL) time as well as RS.

II. SYSTEM MODEL

In this work, we consider RIS-assisted 2-user communications in a single cell, where the RIS is deployed to improve the DL communications between a multi-antenna base station (BS) and a set of K = 2 single-antenna users $\mathcal{K} \in \{1, 2\}$. The number of transmit antennas at the BS and the reflect elements of the RIS are denoted with L and N, respectively. We assume that the RIS is equipped with a smart controller enabling individual real-time adjustments of the reflect coefficient (RC) at each element [9]. Furthermore, the quasi-static flat-fading model is adopted for all links. The direct DL channels to user k in coherence block (CB) t are denoted as $h_{t,k} \in \mathbb{C}^{L \times 1}$. Similarly, the channels spanning from BS to RIS and RIS to user k in block t are denoted as $U_t \in \mathbb{C}^{L \times N}$ and $q_{t,k} \in \mathbb{C}^{N \times 1}$, respectively. Furthermore, by denoting the phase shifts at the RIS in t as $\theta_t \in \mathbb{C}^{N \times 1}$ and the transmit signal vector as $\boldsymbol{x}_t \in \mathbb{C}^{L \times 1}$, the received signal at user k can be written as

$$r_{t,k} = (\boldsymbol{h}_{t,k} + \underbrace{\boldsymbol{U}_t \operatorname{diag}(\boldsymbol{q}_{t,k})}_{\boldsymbol{H}_{t,k}} \boldsymbol{\theta}_t)^{\mathsf{H}} \boldsymbol{x}_t + v_{t,k}, \qquad (1)$$

where $H_{t,k}$ denotes the cascaded BS-RIS-user channels to user k and $v_{t,k} \sim C\mathcal{N}(0, \sigma_v^2)$ is the receiver noise. In this work, we aim to optimize the RC at the RIS, which necessitates the CSI acquisition of each direct and reflected channel within the system. To this end, we utilize the generalized discrete Fourier transformation (DFT)-based CE method introduced in [4], where the quality of the estimates $\hat{h}_{t,k}$ and $\hat{H}_{t,k}$ of $h_{t,k}$ and $H_{t,k}$, respectively, is dependent on the noise power at the BS σ_z^2 and the uplink (UL) pilot power P_{UL} . In order to estimate all channels, this method requires at least $\tau_{\text{all}} = (N+1)K$ pilot symbols. This can potentially limit the application of this CE method for scenarios, where a large number of reflect elements is deployed.

III. PROPOSED OPPORTUNISTIC RATE SPLITTING (ORS)

In this section, we derive the ORS scheme. By utilizing this scheme, we reduce the duration of the CE time to $\tau_{half} = (\frac{N}{2} + 1)K$ by neglecting the RIS-assisted channels of one user in each CB in an alternating fashion. This not only increases the available time for the DL data transmission per CB, but also imparts new properties to the system, which can be leveraged to increase the system's performance over multiple CBs [10]. To this end, we define two sets of users in each CB, namely

This work was funded in part by the Federal Ministry of Education and Research (BMBF) of the Federal Republic of Germany (Förderkennzeichen 16KIS1235, MetaSEC). K. Weinberger and A. Sezgin are with the Ruhr-Universität Bochum, Germany Email:{kevin.weinberger, aydin.sezgin}@rub.de.

$$\mathcal{G}_t^{\mathsf{P}} = \{ k \in \mathcal{K} \, | \, \hat{\boldsymbol{H}}_{t,k} \text{ is known} \}, \tag{2}$$

$$\mathcal{G}_t^{\mathsf{N}} = \{ k \in \mathcal{K} \, | \, \hat{\boldsymbol{H}}_{t,k} \text{ is unknown} \}, \tag{3}$$

where we assume alternating CSI knowledge of $\hat{H}_{t,k}$ between each CB, i.e., $\mathcal{G}_{t+1}^{P} = \mathcal{G}_{t}^{N}$ and $\mathcal{G}_{t+1}^{N} = \mathcal{G}_{t}^{P}$. Moreover, we assume that the sets have the same cardinality, i.e., $|\mathcal{G}_{t}^{P}| =$ $|\mathcal{G}_{t}^{P}| = \frac{K}{2}, \forall t \in \{1, 2\}$. Due to the known BS-IRS-user channels of one user, we are able to optimize the phase shifts at the RIS such that they add constructively at this user. We can therefore assume that the user in \mathcal{G}_{t}^{P} in CB t has a better *link* strength then the user in \mathcal{G}_{t}^{N} from a topological perspective [11], if a practical number of reflect elements is deployed. Additionally, the system inherits symmetrically alternating CSI knowledge, as the same CB lengths are considered. In this paper, we utilize the alternating knowledge of CSI to counteract the undesired effects of the unknown channels by employing a rate splitting strategy.

To this end, the BS splits the requested message of each user k in the group $\mathcal{G}_t^{\mathsf{P}}(\mathcal{G}_t^{\mathsf{N}})$, denoted as $e_{t,k}^{\mathsf{P}}(e_{t,k}^{\mathsf{N}})$ in each CB t into two sub-messages, a private part $(e_{t,k}^{\mathsf{N}})^p$ $((e_{t,k}^{\mathsf{N}})^p)$ and a common part e_t^c . The BS afterwards encodes the respective parts into a private symbol $s_{t,k}^{\mathsf{P}}(s_{t,k}^{\mathsf{N}})$ and a common symbol s_t^c . After encoding the symbols, the BS creates the beamformers of the private messages $\omega_{t,k}^{\mathsf{P}}, \omega_{t,k}^{\mathsf{N}}$ and the common message w_t^c and constructs the overall transmit vector \boldsymbol{x}_t defined as

$$\boldsymbol{x}_{t} = \sum_{k \in \mathcal{G}_{t}^{\mathsf{P}}} \boldsymbol{w}_{t,k}^{\mathsf{P}} + \sum_{n \in \mathcal{G}_{t}^{\mathsf{N}}} \boldsymbol{w}_{t,n}^{\mathsf{N}} + \boldsymbol{w}_{t}^{c}, \qquad (4)$$

subject to the power constraint $\mathbb{E}\{x_t^{\mathsf{H}}x_t\} \leq P^{\mathsf{Tr}}$, where P^{Tr} is the available transmit power. Using (4), the power constraint can be reexpressed as

$$\sum_{k \in \mathcal{G}_{t}^{\mathsf{P}}} \left\| \boldsymbol{w}_{t,k}^{\mathsf{P}} \right\|_{2}^{2} + \sum_{n \in \mathcal{G}_{t}^{\mathsf{N}}} \left\| \boldsymbol{w}_{t,n}^{\mathsf{N}} \right\|_{2}^{2} + \left\| \boldsymbol{w}_{t}^{c} \right\|_{2}^{2} \le P^{\mathsf{Tr}}, \, \forall t \in \{1,2\}.$$
(5)

Note that $\boldsymbol{w}_{t,k}^{\mathsf{P}} = \boldsymbol{0}_L, \forall k \in \mathcal{G}_t^{\mathsf{N}}$ and $\boldsymbol{w}_{t,k}^{\mathsf{N}} = \boldsymbol{0}_L, \forall k \in \mathcal{G}_t^{\mathsf{P}}$, where $\boldsymbol{0}_L$ denotes a column vector of length L with all zero entries.

A. Transmission Scheme

We proceed to derive the ORS scheme, where, without loss of generality, we assume that the user in $\mathcal{G}_t^{\mathsf{P}}$, gets the same index assigned as the current CB, i.e., $\mathcal{G}_1^{\mathsf{P}} = \{1\}$ and $\mathcal{G}_2^{\mathsf{P}} = \{2\}$. At t = 1 the transmitter sends the private message $s_{1,1}^{\mathsf{P}}$ intended for user 1 and $s_{1,2}^{\mathsf{N}}$ intended for user 2. However, the transmitter only knows the direct channels $h_{1,1}$ and $h_{1,2}$ of both users and the RIS channels $H_{1,1}$ of user 1. As the RIS channels $H_{1,2}$ of user 2 are unknown, as defined in (3), sending the private message $s_{1,1}^{P}$ towards user 1 will cause undesirable interference at user 2. Similarly, in CB t = 2 the unknown reflected channels $\hat{H}_{2,1}$ of user 1 cause undesirable interference at user 1 when transmitting the private message $s_{2,2}^{P}$ of user 2. To tackle the problem of the undesired interference, the transmitter sends the same common message s_t^c in both CBs, i.e., $s_1^c = s_2^c$. This enables user 1 to decode the common message in t = 1 and use successive interference cancellation (SIC) in t = 2. Similarly, user 2 decodes the common message in t = 2 and employs SIC to the previously received signal in t = 1. Using this scheme requires an *opportunistic* transmission of s_1^c in order to exploit the property of alternating CSI knowledge as it assures that user 2 is able to decode s_2^c , when its channels are known, and mitigate their negative impact, when they are not.

Consequently, the user, whose channels are completely known in CB t, i.e., the user in $\mathcal{G}_t^{\mathsf{P}}$, first decodes the common message and then utilizes the successive decoding strategy before decoding its private message. For this case, we can formulate the received signals for $k \in \mathcal{G}_t^{\mathsf{P}}$, $n \in \mathcal{G}_t^{\mathsf{N}}$ and $\forall t \in \{1, 2\}$ as

$$r_{t,k}^{\mathsf{P}} = \underbrace{\left(\boldsymbol{h}_{t,k}^{\mathsf{eff}}\right)^{\mathsf{H}}\left(\boldsymbol{w}_{t,k}^{\mathsf{P}} + \boldsymbol{w}_{t}^{c}\right)}_{\text{signals that are decoded}} + \underbrace{\left(\boldsymbol{h}_{t,k}^{\mathsf{eff}}\right)^{\mathsf{H}}\boldsymbol{w}_{t,n}^{\mathsf{N}} + v_{t,k}}_{\text{interference plus noise}}, \quad (6)$$

where $h_{t,k}^{\text{eff}} = h_{t,k} + H_{t,k}\theta_t$ denotes the combination of the direct and reflected channels of user k in CB t as an effective channel. In contrast, the user, whose reflected channels are unknown, employs SIC based on the common message decoded in the other CB, which enables the formulation of the following received signal for $k \in \mathcal{G}_t^{\mathsf{P}}$, $n \in \mathcal{G}_t^{\mathsf{N}}$ and $\forall t \in \{1, 2\}$

$$r_{t,n}^{\mathsf{N}} = \underbrace{\left(\boldsymbol{h}_{t,n}^{\mathsf{eff}}\right)^{\mathsf{H}}\left(\boldsymbol{w}_{t,n}^{\mathsf{N}}\right)}_{\text{signals that are decoded}} + \underbrace{\left(\boldsymbol{h}_{t,n}^{\mathsf{eff}}\right)^{\mathsf{H}}\boldsymbol{w}_{t,k}^{\mathsf{P}} + v_{t,n}}_{\text{interference plus noise}}.$$
 (7)

Let $\gamma_{t,k}^{\mathsf{P}}$ ($\gamma_{t,n}^{\mathsf{N}}$) denote the signal-to-interference-plus-noise ratio (SINR) of the user in $\mathcal{G}_{t}^{\mathsf{P}}$ ($\mathcal{G}_{t}^{\mathsf{N}}$) decoding its private message and let $\gamma_{t,k}^{c}$ denote the SINR of the user in $\mathcal{G}_{t}^{\mathsf{P}}$ decoding the common message. Based on the equations (6) and (7) we can write for the case $k \in \mathcal{G}_{t}^{\mathsf{P}}$ and $n \in \mathcal{G}_{t}^{\mathsf{N}}$

$$\boldsymbol{\gamma}_{t,k}^{\mathsf{P}} = \frac{|\left(\boldsymbol{h}_{t,k}^{\mathsf{eff}}\right)^{\mathsf{H}} \boldsymbol{\omega}_{t,k}^{\mathsf{P}}|^{2}}{|\left(\boldsymbol{h}_{t,k}^{\mathsf{eff}}\right)^{\mathsf{H}} \boldsymbol{\omega}_{t,n}^{\mathsf{N}}|^{2} + \sigma_{v}^{2}},\tag{8}$$

$$\gamma_{t,k}^{c} = \frac{|\left(\boldsymbol{h}_{t,k}^{\text{eff}}\right)^{\mathsf{H}} \boldsymbol{\omega}_{t}^{c}|^{2}}{|\left(\boldsymbol{h}_{t,k}^{\text{eff}}\right)^{\mathsf{H}} \boldsymbol{\omega}_{t,k}^{\mathsf{P}}|^{2} + |\left(\boldsymbol{h}_{t,k}^{\text{eff}}\right)^{\mathsf{H}} \boldsymbol{\omega}_{t,n}^{\mathsf{N}}|^{2} + \sigma_{v}^{2}}, \qquad (9)$$

$$\gamma_{t,n}^{\mathsf{N}} = \frac{|(\boldsymbol{h}_{t,n}^{\mathsf{eff}})^{\mathsf{H}} \boldsymbol{\omega}_{t,n}^{\mathsf{N}}|^{2}}{|(\boldsymbol{h}_{t,n}^{\mathsf{eff}})^{\mathsf{H}} \boldsymbol{\omega}_{t,k}^{\mathsf{P}}|^{2} + \sigma_{v}^{2}}.$$
(10)

The total achievable net rate within two CBs is then

$$R^{\text{net}} = \frac{1}{2} \sum_{t = \{1,2\}} \overbrace{k \in \mathcal{G}_t^{\mathsf{P}}}^{\mathsf{P}} R_{t,k}^{\mathsf{P}} + \sum_{n \in \mathcal{G}_t^{\mathsf{N}}} R_{t,n}^{\mathsf{N}} + \frac{1}{2} R^c, \quad (11)$$

where $R^c = \min_{t \in \{1,2\}, k \in \mathcal{G}_t^p} \{R_{t,k}^c\}$ is shared by both users such that each user k is allocated a portion C_k , i.e., $R_c = \sum_{k \in \mathcal{K}} C_k$ is satisfied. Moreover, to guarantee that the common rate R_c is successfully decoded by both users in both CBs, the actual transmission rate in t = 1 must not exceed the rate in t = 2, i.e., $R_{1,1}^c \leq R_{2,2}^c$. Let B denote the DL transmission bandwidth, $T_{\rm coh}$ denote the number of symbols within one CB, τ denote the number of symbols required for channel estimation and $B^{\rm DL} = B(1 - \frac{\tau}{T_{\rm coh}})$. The rates introduced in (11) satisfy the following achievability conditions:

$$R_{t,k}^{\mathsf{P}} \le B^{\mathsf{DL}} \log_2(1+\gamma_{t,k}^{\mathsf{P}}), \forall k \in \mathcal{G}_t^{\mathsf{P}}, \forall t \in \{1,2\},$$
(12)

$$R_{t,k}^c \le B^{\mathsf{DL}} \log_2(1+\gamma_{t,k}^c), \forall k \in \mathcal{G}_t^\mathsf{P}, \forall t \in \{1,2\},$$
(13)

$$R_{t,n}^{\mathsf{N}} \le B^{\mathsf{DL}} \log_2(1+\gamma_{t,n}^{\mathsf{N}}), \forall n \in \mathcal{G}_t^{\mathsf{N}}, \forall t \in \{1,2\}.$$
(14)

IV. PROBLEM FORMULATION AND OPTIMIZATION FRAMEWORK

A. Problem Formulation

This paper considers maximizing the achievable net rate, while adressing important practical issues, i.e., CE time, CE errors and causality of the formulated problem. The key observation leading to our proposed solution is the fact that it becomes challenging to incorporate the unknown channels directly into the optimization framework. More precisely, note that for one user in each CB the estimated effective channel misses the unknown reflected channels, specifically

$$\hat{\boldsymbol{h}}_{t,j}^{\mathsf{eff}} = \begin{cases} \hat{\boldsymbol{h}}_{t,j} + \hat{\boldsymbol{H}}_{t,j} \boldsymbol{\theta}_t & , j \in \mathcal{G}_t^{\mathsf{P}} \\ \hat{\boldsymbol{h}}_{t,j} & , j \in \mathcal{G}_t^{\mathsf{N}}. \end{cases}$$
(15)

This lack of information introduces a tradeoff between the allocation of power towards $\omega_{t,k}^{P}$ and ω_{t}^{c} . On the one hand increasing the power of $\omega_{t,k}^{P}$ will have a negative impact on $R_{t,n}^{N}$ as the unknown channels cause interference in (10). On the other hand, although ω_{t}^{c} does not cause any interference, ORS requires the same common message to be send is in both CBs, effectively halving the influence of R^{c} on the net rate (as seen in (11)). Additionally, R^{c} is dependent on $R_{t,k}^{c}$ in both CBs but can only be allocated in the first CB in practice due to the system's causality. Let $\omega_{t} = [\{\omega_{t,k}^{P}\}_{k\in\mathcal{G}_{t}^{P}}^{\mathsf{T}}, \{\omega_{t,n}^{P}\}_{n\in\mathcal{G}_{t}^{\mathsf{N}}}^{\mathsf{T}}, (\omega_{t}^{c})^{\mathsf{T}}]^{\mathsf{T}}$ denote the stacked beamformers in CB t. Under consideration of the aspects above, we formulate the following problem for each CB t:

$$\max_{\theta_t, \omega_t} \quad (P1)$$

s.t. (5), (12) - (14)

$$|\theta_{t,n}| = 1, \quad \forall n \in \{1, \dots, N\}, \, \forall t \in \{1, 2\}, \quad (16)$$

 $\hat{R}_{1,k}^c - \hat{R}_{2,j}^c \le 0, \, \forall k \in \mathcal{G}_1^{\mathsf{P}}, \, \forall j \in \mathcal{G}_2^{\mathsf{P}}, \, \forall t \in \{2\}, \quad (17)$

where $(\hat{\cdot})$ denotes the usage of the estimated (and missing) channels $\hat{h}_{t,j}^{\text{eff}}$ according to (15) instead of $h_{t,j}^{\text{eff}}$. Here, the unit-modulus constraints in (16) ensure that the RIS only applies phase shifts to the reflected signal, while constraint (17) guarantees that the common rate in t = 2 is always able to match the common rate allocated in t = 1. Note that (P1) defines two temporally-uncoupled problems, which satisfy causality, as (17) only applies for t = 2. However, problem (P1) mathematically captures the redundant nature of R_c , but ignores the interference the unknown channels may cause because they are unaccounted for in (15). Consequently, the allocation of resources towards R_c becomes sub-optimal, when solving (P1) in t = 1. To address this problem, this paper considers a predefined portion of the achievable private rate R_{1k}^{P} in t = 1 to be transmitted *opportunistically* as common rate instead, allowing the users to mitigate part of the interference the BS is unaware of. To this end, by denoting α^{ORS} as ORS-ratio, we extend (P1) with the following constraint:

$$\max_{\substack{\theta_{t}, \omega_{t}}} R_{t}$$
(P1')
s.t. (5), (12) - (14), (16), (17)
$$\alpha^{\text{ORS}} \hat{R}_{t,k}^{\text{P}} - \hat{R}_{t,k}^{c} \le 0, \forall k \in \mathcal{G}_{t}^{\text{P}}, \forall t \in \{1\}.$$
(18)

B. Optimization Framework

To deal with the non-convexity of the rate constraints (12) - (14), we rewrite them by introducing slack variables $\{\xi_{t,k}^c\}_{t\in\{1,2\}}^{k\in\mathcal{G}_t^p}, \{\xi_{t,k}^\mathsf{P}\}_{t\in\{1,2\}}^{k\in\mathcal{G}_t^p}, \{\xi_{t,n}^\mathsf{N}\}_{t\in\{1,2\}}^{n\in\mathcal{G}_t^N} \text{ for the rates and } \\ \{\beta_{t,k}^c\}_{t\in\{1,2\}}^{k\in\mathcal{G}_t^P}, \{\beta_{t,k}^\mathsf{P}\}_{t\in\{1,2\}}^{k\in\mathcal{G}_t^P}, \{\beta_{t,n}^\mathsf{N}\}_{t\in\{1,2\}}^{n\in\mathcal{G}_t^N} \text{ for the SINRs as }$ $\xi_{t,k}^{\mathsf{P}} \le B^{\mathsf{DL}} \log_2(1 + \beta_{t,k}^{\mathsf{P}}), \quad \forall k \in \mathcal{G}_t^{\mathsf{P}}, \forall t \in \{1, 2\},$ (19) $\xi_{t,k}^c \le B^{\mathsf{DL}} \log_2(1 + \beta_{t,k}^c), \quad \forall k \in \mathcal{G}_t^\mathsf{P}, \forall t \in \{1, 2\},$ (20) $\xi_{t,n}^{\mathsf{N}} \leq B^{\mathsf{DL}} \log_2(1 + \beta_{t,n}^{\mathsf{N}}), \quad \forall n \in \mathcal{G}_t^{\mathsf{N}}, \forall t \in \{1, 2\},$ (21) $\boldsymbol{\xi}_t \geq 0, \, \boldsymbol{\beta}_t \geq 0, \,$ $\forall t \in \{1, 2\},\$ (22) $\beta_{t,k}^{\mathsf{P}} \leq \gamma_{t,k}^{\mathsf{P}}, \quad \forall k \in \mathcal{G}_t^{\mathsf{P}}, \forall t \in \{1,2\},$ (23) $\beta_{t,k}^c \le \gamma_{t,k}^c, \quad \forall k \in \mathcal{G}_t^\mathsf{P}, \forall t \in \{1,2\},$ (24)

$$\beta_{t,n}^{o} \le \gamma_{t,n}^{\mathsf{N}}, \quad \forall n \in \mathcal{G}_{t}^{\mathsf{N}}, \forall t \in \{1, 2\}, \quad (25)$$

where (22) captures that all the introduced slack variables are non-negative, i.e., β_t , ξ_t are defined as stacked vectors of the introduced slack variables in CB t. Due to the coupling of ω_t and θ_t in (23) – (25), we continue by utilizing an alternative optimization approach, thus decoupling the problem. This is achieved by fixing one of the variables, while optimizing the other.

C. Beamforming Design

For the duration of designing the beamformers, we assume the phase shifters at the RIS to be fixed, enabling the removal of the constraint (16) due to its sole dependency on θ_t . By plugging (8) - (10) (which are now only dependent on ω_t) in the constraints (23) - (25), they can be approximated by using the first-order Taylor approximation around a feasible point $(\tilde{\omega}_t), \forall t \in \{1, 2\}$ as follows [8, (23) - (30)]

$$\frac{|(\boldsymbol{h}_{t,k}^{\text{eff}})^{\text{H}}\boldsymbol{\omega}_{t,k}^{o}|^{2}}{\beta_{t,k}^{o}} \geq \frac{2\text{Re}\{(\tilde{\boldsymbol{\omega}}_{t,k}^{o})^{\text{H}}\boldsymbol{h}_{t,k}^{\text{eff}}(\boldsymbol{h}_{t,k}^{\text{eff}})^{\text{H}}\boldsymbol{\omega}_{t,k}^{o}\}}{\tilde{\beta}_{t,k}^{o}} - (26)$$

$$\frac{|(\boldsymbol{h}_{t,k}^{\text{eff}})^{\mathsf{H}}\boldsymbol{\omega}_{t}^{c}|^{2}}{\beta_{t,k}^{c}} \geq \frac{2\text{Re}\{(\tilde{\boldsymbol{\omega}}_{t}^{c})^{\mathsf{H}}\boldsymbol{h}_{t,k}^{\text{eff}}(\boldsymbol{h}_{t,k}^{\text{eff}})^{\mathsf{H}}\boldsymbol{\omega}_{t}^{c}\}}{|(\boldsymbol{h}_{t,k}^{\text{eff}})^{\mathsf{H}}\boldsymbol{\omega}_{t}^{c}|^{2}} \geq \frac{2\text{Re}\{(\tilde{\boldsymbol{\omega}}_{t}^{c})^{\mathsf{H}}\boldsymbol{h}_{t,k}^{\text{eff}}(\boldsymbol{h}_{t,k}^{\text{eff}})^{\mathsf{H}}\boldsymbol{\omega}_{t}^{c}\}}{\tilde{\beta}_{t,k}^{c}} - (27)$$

Thus, we write the convex approximations of (23) - (25) as

$$\begin{aligned} |\left(\boldsymbol{h}_{t,k}^{\text{eff}}\right)^{\mathsf{H}}\boldsymbol{\omega}_{t,n}^{\mathsf{N}}|^{2} + \sigma_{v}^{2} - f_{t,k}^{\mathsf{P}}, \ \forall k \in \mathcal{G}_{t}^{\mathsf{P}}, \forall n \in \mathcal{G}_{t}^{\mathsf{N}}, \ (28)\\ |\left(\boldsymbol{h}_{t,n}^{\text{eff}}\right)^{\mathsf{H}}\boldsymbol{\omega}_{t,k}^{\mathsf{P}}|^{2} + \sigma_{v}^{2} - f_{t,n}^{\mathsf{N}}, \ \forall k \in \mathcal{G}_{t}^{\mathsf{P}}, \forall n \in \mathcal{G}_{t}^{\mathsf{N}}, \ (29)\\ |\left(\boldsymbol{h}_{t,k}^{\text{eff}}\right)^{\mathsf{H}}\boldsymbol{\omega}_{t,k}^{\mathsf{P}}|^{2} + |\left(\boldsymbol{h}_{t,k}^{\text{eff}}\right)^{\mathsf{H}}\boldsymbol{\omega}_{t,n}^{\mathsf{N}}|^{2} + \sigma_{v}^{2} - f_{t,k}^{c}, \\ \forall k \in \mathcal{G}_{t}^{\mathsf{P}}, \forall n \in \mathcal{G}_{t}^{\mathsf{N}}. \ (30)\end{aligned}$$

With the approximations defined above, the problems (P1') when optimizing the beamformers w_t can be approximated as

$$\max_{\substack{\omega_{t},\xi_{t},\beta_{t}}} \xi_{t}^{\text{obj}} = \sum_{k \in \mathcal{G}_{t}^{\text{P}}} (\xi_{t,k}^{\text{P}} + \frac{\rho_{t}}{2} \xi_{t,k}^{c}) + \sum_{n \in \mathcal{G}_{t}^{\text{N}}} \xi_{t,n}^{\text{N}} \quad (\text{P2})$$
s.t. (5), (19) - (22), (28) - (30),

$$\alpha^{\text{ORS}} \xi_{t,k}^{\text{P}} - \xi_{t,k}^{c} \le 0, \forall k \in \mathcal{G}_{t}^{\text{P}}, \forall t \in \{1\}, \quad (31)$$

$$\xi_{1,k}^c - \xi_{2,j}^c \le 0, \, \forall k \in \mathcal{G}_1^\mathsf{P}, \, \forall j \in \mathcal{G}_2^\mathsf{P}, \, \forall t \in \{2\}, \quad (32)$$

where $\rho_t = 1$ if t = 1, otherwise $\rho_t = 0$.

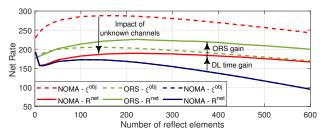


Figure 1. Net rates for perfect CSI

D. Phase Shift Design

During the design on the phase shifts we assume the beamformers ω_t to be fixed. To obtain the optimal phase shift, we utilize the same successive convex approximation (SCA) framework, on which the beamforming design is based on. We can show that $|(\mathbf{h}_{t,i}^{\text{eff}})^{\text{H}}\omega_{t,k}|^2 = |\tilde{h}_{t,i,k}^o + \tilde{H}_{t,i,k}^o \theta_t|^2$, where $\tilde{h}_{t,i,k}^o = (\omega_{t,k}^o)^{\text{H}} \mathbf{h}_{t,i}$ and $\tilde{H}_{t,i,k}^o = (\omega_{t,k}^o)^{\text{H}} \mathbf{H}_{t,i}$ and derive the first-order Taylor approximations for (23) – (25) around the feasible point $(\tilde{\theta}_t)$ in a similar fashion. Problem (P1') for phase shift optimization can thus be approximated as

$$\max_{\theta_{t}, \xi_{t}, \beta_{t}} \xi_{t}^{\mathsf{obj}} - 2\kappa \left| \sum_{j=1}^{N} \theta_{t,j}^{(i-1)} (\theta_{t,j} - \theta_{t,j}^{(i-1)}) \right|$$
(P3)
s.t. (5), (19) - (22), $(\hat{23}) - (\hat{25})$, (31), (32)

where constraint (16) has been added as a penalty term to the objective function [12] and $(\widetilde{\cdot})$ denotes the first order Taylor approximations around $(\tilde{\theta}_t)$. Here, κ is a large positive constant and the superscript (i-1) denotes the value of the variable at the previous iteration.

The proposed algorithm for acquiring optimal w_t^* and θ_t^* in each CB by solving (P1') is outlined in Algorithm 1, where we initialize the SCAs with random phase shifters and maximum ratio transmission (MRT) beamformers.

Algorithm 1 Procedure to determine ω_t^* and θ_t^* of (P1')	
for $t = \{1, 2\}$ do	
Initialize: κ , ϵ , $\hat{\theta}_t^0$, $\hat{\omega}_t^0$, $i \leftarrow 0$, calculate SINRs β_t^0 and rates $\boldsymbol{\xi}_t^0$	1
while the increase of the objective ξ_{\pm}^{obj} is above ϵ do	
Obtain $\widehat{\omega}_t^{i+1}, \beta_t^{i+1}, \xi_t^{i+1}$ solving (P2) with $\theta_t^i, \beta_t^i, \xi_t^i$.	
Obtain $\widehat{\omega}_{t}^{i+1}, \beta_{t}^{i+1}, \xi_{t}^{i+1}$ solving (P2) with $\theta_{t}^{i}, \beta_{t}^{i}, \xi_{t}^{i}$. Obtain $\widehat{\theta}_{t}^{i+1}, \beta_{t}^{i+1}, \xi_{t}^{i+1}$ solving (P3) with $\widehat{\omega}_{t}^{i+1}, \beta_{t}^{i+1}, \xi_{t}^{i+1}, \theta_{t}^{i+1}$	p_{t}^{i} .
Set $i \leftarrow i + 1$.	0
end while, $oldsymbol{\omega}_t^* \leftarrow \widehat{oldsymbol{\omega}}_t^i, oldsymbol{ heta}_t^* \leftarrow \widehat{oldsymbol{ heta}}_t^i$	
end for	

V. NUMERICAL RESULTS

For the simulations we assume the BS is equipped with L = 8 antennas. The BS and RIS are assumed to be 400 m apart and facing each other, while the users are randomly positioned in a circle with a 50 m radius, whose centerpoint is 100 m away from the RIS position. Moreover, we assume the reflect elements at the RIS to be deployed in a rectangular grid with $\frac{\lambda}{8}$ spacing [13], where $\lambda = 0.1$ m is the wavelength. Consequently, we employ the correlated channel model introduced in [14], where the average attenuation intensity is modeled after [15, Eq.(23)]. We assume the reflected (direct) channels to be in line-of-sight (non-line-of-sight) and BS antennas with $\frac{\lambda}{2}$ spacing. For the channel estimation, we consider two scenarios: 1) perfect CSI and 2) imperfect CSI, where we estimate the channels according

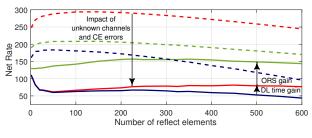


Figure 2. Net rates for imperfect CSI (legend as in Fig. 1)

to the DFT-based method in [4] with $\sigma_z^2 = -100$ dBm, $P_{\text{UL}} = 30$ dBm. Further, we assume a bandwidth of B = 10MHz, $P^{\text{Tr}} = 40$ dBm, $T_{\text{coh}} = 2000$ and $\sigma_v^2 = -100$ dBm, $\kappa = 10^4$, $\epsilon = 1$. As a baseline approach, we consider nonorthogonal multiple access (NOMA), where only the private messages are transmitted. In order to visualize the impact of the unknown channels, we compare the actual net rate R^{net} (calculated with $h_{t,k}^{\text{eff}}$) with the average objective function of (P1') over both CB $\xi^{\text{obj}} = (\hat{R}_1 + \hat{R}_2)/2$ (calculated with $\hat{h}_{t,k}^{\text{eff}}$ in (15)). For determining α^{ORS} , we assume large scale fading (LSF) knowledge of the unknown user from the previous CB in t = 1, denoted by LSF_k , calculate $\Gamma = \max\{\frac{LSF_1}{LSF_2}, \frac{LSF_2}{LSF_1}\}$ and set $\alpha^{\text{ORS}} = (\log_2(\frac{1+\Gamma}{1+\Gamma-1}))^{-1}$.

Fig. 1 compares the net rates of using ORS and NOMA with perfect CSI. The figure shows that for a large number of reflect elements, the impact of estimating only half the channels, i.e., reducing τ_{all} to τ_{half} to obtain more DL time, is beneficial even for the baseline scheme of NOMA. When utilizing the ORS scheme, a 20% gain over NOMA can be observed, when a practical number for N is chosen, specifically $N \ge 25$. Fig. 2 depicts the impact of imperfect CSI on the studied schemes. When compared to the curves for R^{net} in Fig. 1, it becomes apparent that the additional CE error has a major impact on the NOMA schemes. The rationale behind this observation is that the optimization of (P1') will recover a combination of ω_t and θ_t , which suppress interference at each user. In Fig. 1 the interference impacting R^{net} is only caused by the unknown channels. In Fig. 2 however both, the unknown channels and the estimation errors cause interference at the users, resulting in heavily reduced performance. By contrast, the negative impact on the performance of the ORS scheme is less pronounced due to the inherent robustness of rate splitting against interference. This results in gains of up to 115% and up to 160% in terms of net rate for imperfect CSI, compared to NOMA with partial and full CSI knowledge, respectively.

VI. CONCLUSION

In this paper, we propose the ORS scheme, which counteracts practical limitations of RIS by combining opportunistic communications with RS. By sacrificing CSI knowledge of the RIS channels alternatively between each coherence block, we not only increase the available time for DL transmissions, but also guarantee that each user successfully mitigates the interference caused by the unknown CSI. Simulation results show that ORS provides a substantial performance uplift under practical assumptions, culminating in gains of up to 160% over NOMA in terms of net rate.

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