RIS-Aided Communications Over Dirty MAC: Capacity Region and Outage Probability

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Abstract—We characterize the capacity region of a two-user multiple access channel (MAC) in a reconfigurable intelligent surface (RIS)-aided communication system with side information (SI) at the transmitters. We consider two uplink communication scenarios: (i) a double dirty MAC where the interferences are known non-causally to both users; and (ii) a single dirty MAC model where only one of the users knows the interference. Considering that each of the users is assisted by a different RIS with $M_i$ elements, we derive closed-form expressions for the capacity region and the outage probability (OP) for both system models. Results show that the use of RISs is beneficial to extend the capacity region and improve the OP in both scenarios.

Index Terms—Reconfigurable intelligent surface, multiple access channel, side information, capacity region, outage probability.

I. INTRODUCTION

RECONFIGURABLE intelligent surfaces (RISs) have the capability to enhance coverage area and provide high spectral/energy efficiency [1] in future wireless networks. Specifically, RISs are artificial metasurfaces with a large number of low-cost passive reflecting elements; each of these elements can independently introduce a phase shift on the reflected signal. By smartly adjusting the phase shifts, RISs can adaptively control the wireless signal propagation environment to maximize the desired signal quality. Therefore, the achievable performance of the corresponding transmission can be improved. On the other hand, the use of side information (SI) at the transmitter has the potential to help meet the reliability constraint in future wireless networks. Such SI (e.g., either channel state information (CSI) or interference awareness) can be leveraged to intelligently encode their information. Considering SI knowledge at the transmitters in multi-user systems can reduce the destructive effects of the interference and provide reliable communication at higher rates [2], [3], [4]. Hence, investigation of the RIS-aided communication systems in the presence of SI at the transmitters can be worthy of attention.

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Recently, RIS-related research activities have been focused on phase shift design and performance analysis in single-user [5], [6], [7], [8] and multi-user [9], [10], [11], [12], [13], [14] scenarios. On the contrary, information-theoretic aspects of RIS communications have been scarcely addressed in the literature. In this regard, the capacity characterization for RIS-aided multiple-input multiple-output (MIMO) systems in a single-user setup was investigated in [15] and [16], while the capacity region for more complex RIS-aided multi-user systems was only studied in [17]. The authors in [17] considered a two-user clean1 multiple access channel (MAC), where users send independent messages to a common receiver aided by reflecting elements of RIS. By proposing two strategies for RIS location, they provided capacity and achievable rate regions with practical orthogonal multiple access schemes, showing that RISs significantly improve the system performance.

To the best of the authors’ knowledge, the role of SI in RIS-aided MAC remains an open challenge, despite being a key building block for information-theoretic characterization [2]. For this purpose, and motivated by the recent advances in RIS and joint communications and sensing to enable advanced SI capabilities [18], we extend the RIS-aided two-user clean MAC considered in [17] to a RIS-aided two-user dirty MAC model by assuming known SI at the transmitters. In particular, we consider two uplink communication scenarios under RIS deployment: (i) a doubly dirty (DD)-MAC where the interferences are known non-causally to both users; (ii) a single dirty (SD)-MAC model where only one of the users knows the interference, and the other one is not aware of the interference. By considering two separate RIS with $M_i$ reflecting elements near to each user, we derive the capacity region for both DD-MAC and SD-MAC models, and derive closed-form expressions for the outage probability.

II. SYSTEM MODEL

A. DD-MAC

We consider a wireless two-user MAC with known interferences $S_i$, $i \in \{1, 2\}$ as shown in Fig. 1(a). We assume two single-antenna users $u_i$ that are sufficiently far apart from each other, who aim to send independent inputs $X_i$ to a common single-antenna receiver $r$, respectively. We assume that the interference signals $S_i$ with variances $Q_i$ ($S_i \sim \mathcal{N}(0, Q_i)$) are known non-causally to the transmitters2 of users $u_i$, respectively. The inputs $X_i$ sent by users $u_i$ over the channels

1I.e., without SI at the transmitters.

2We assume that the interfering sequence $S_i$ available as SI at the transmitter is injected from an external dominant source that exhibits a strong line-of-sight condition with reduced fading fluctuation [19, Fig. 5]. Hence, we use this unfaded counterpart approximation for the fading coefficients corresponding to the interfering signals in our analysis.
are subject to the average power constraint as \( \mathbb{E} \left| X_i \right|^2 \leq P_i \) respectively. Although deploying a single (but larger) RIS to serve both users may have some benefits at the expense of a greater complexity [17], it is hard in practice to ensure a RIS orientation that satisfies the normal incidence assumption for both users. Hence, we consider two RISs that contain \( M_i \geq 1 \) passive reflecting elements in the vicinity of user \( u_i \). Each RIS element is designed to be able to induce an independent phase shift to the incident signal for collaboratively altering the effective channels between the users and the receiver. Given the assumption that the users are sufficiently far apart, the signal transmitted by user \( u_i \) and reflected by the serving RIS to user \( u_j \), \( i \neq j \) is negligible at the receiver \( r \) due to the severe path-loss, and also due to RIS orientation. The equivalent channel observed by receiver \( r \) from the \( i \)-th user accommodates the cases with/without direct link from user \( u_i \), and the reflected link by its serving RIS. We also assume perfect CSI availability so that RISs phase shifts are optimally configured\(^3\) as in the distributed deployment scenario in [17].

Under such assumptions, the received signal \( Y \) at the receiver \( r \) can be defined as:

\[
Y = \sum_{i=1}^{2} \hat{h}_i(\vec{\Phi}_i)X_i + S_i + Z, \tag{1}
\]

where \( \hat{h}_i(\vec{\Phi}_i) = \hat{h}_i + g_i^T \vec{\Phi}_i \hat{h}_i \) and \( \hat{h}_i \in \mathbb{R} \) denote the effective channel and the baseband direct channel from user \( u_i \) to the receiver \( r \), respectively. The term \( Z \) defines the Additive White Gaussian Noise (AWGN) with zero mean and variance \( \mathcal{N}(0, N) \) at the receiver \( r \). Finally, \( \vec{\Phi}_i \in \mathbb{C}^{M_i \times M_i} \) is the adjustable response induced by the \( m \)-th reflecting meta-surface of the \( i \)-th RIS. For the sake of simplicity, we assume that the RISs do not induce attenuation to the signal i.e., \( \phi_{im} = 1, \forall m \in M_i \subset \{1, \ldots, M_i\} \), which is defined as:

\[
\vec{\Phi}_i = \text{diag} \left( e^{j\vec{\phi}_i1}, e^{j\vec{\phi}_i2}, \ldots, e^{j\vec{\phi}_iM_i} \right). \tag{2}
\]

The vector \( \vec{h}_i \in \mathbb{R}^{M_i \times 1} \) contains the channel gains from user \( u_i \) to each element of its serving (nearby) RIS. The vector \( \vec{g}_i \in \mathbb{R}^{1 \times M_i} \) includes the channel gains form each element of its serving RIS to the common receiver \( r \), which are given by \( \vec{h}_i = \left[ h_{i1} e^{-j\theta_i1}, h_{i2} e^{-j\theta_i2}, \ldots, h_{iM_i} e^{-j\theta_iM_i} \right]^T \) and \( \vec{g}_i = \left[ g_{i1} e^{-j\psi_i1}, g_{i2} e^{-j\psi_i2}, \ldots, g_{iM_i} e^{-j\psi_iM_i} \right]^T \). Note that \( h_{iM_i} \) and \( g_{iM_i} \) are the amplitudes of the corresponding channel.

In practice, imperfect CSI due to estimation errors and limited phase resolution at the RIS occurs. The case of optimal phase-shifting is useful as an upper bound for the achievable performance.

gains, and \( e^{-j\theta_iM_i} \) and \( e^{-j\psi_iM_i} \) denote the phase of the corresponding links.

### B. SD-MAC

Here, we consider a wireless MAC that includes a SD user and helper problem as shown in Fig. 1(b). In this case, only user \( u_1 \) knows the interference \( S_1 \) and user \( u_2 \) has no awareness of the interference. Thus, for this set-up, the received signal \( Y \) at the receiver \( r \) can be expressed as:

\[
Y = \sum_{i=1}^{2} \hat{h}_i(\vec{\Phi}_i)X_i + S_1 + Z. \tag{3}
\]

### III. CAPACITY REGION

In this section, we characterize the capacity region of DD and SD-MAC in the presence of strong interferences under RIS consideration, i.e., the achievable rate-pair \( (R_1, R_2) \).

#### A. DD-MAC

For a given set of RIS reflection coefficients (i.e., phase shifts) \( \{\vec{\Phi}_i\} \), the equivalent channels observed by receiver \( r \) from users \( u_i \) over DD-MAC are determined by \( \{\hat{h}_i(\vec{\Phi}_i)\} \) as per (1). Hence, the instantaneous capacity region \( C \left( \{\vec{\Phi}_i\} \right) \) of the two-user DD-MAC with coherent receiver (fading coefficients \( \{\hat{h}_i(\vec{\Phi}_i)\} \) are known at the receiver) under strong interference condition (i.e., \( Q_i \rightarrow \infty \)) is a triangle region [3] including rate pairs that satisfy the following constraint:

\[
R_1 + R_2 \leq \log_2 \left( 1 + \min \left\{ \frac{P_1 \left| \hat{h}_1(\vec{\Phi}_1) \right|^2}{N}, \frac{P_2 \left| \hat{h}_2(\vec{\Phi}_2) \right|^2}{N} \right\} \right). \tag{4}
\]

Note that for any choice of \( \{\vec{\Phi}_i\} \), any rate pair within the union set of \( C^D \left( \{\vec{\Phi}_i\} \right) \) over all possible \( \{\vec{\Phi}_i\} \) can be obtained. Hence, the capacity region of DD-MAC under strong interference and RIS deployment is defined as the convex hull of such a union set:

\[
C^D = \text{Conv} \left( \bigcup_{\vec{\Phi} \in \mathcal{A}} C^D \left( \{\vec{\Phi}_i\} \right) \right), \tag{5}
\]

and \( \mathcal{A} = \left\{ \{\vec{\Phi}_i\} : |\phi_{im}| = 1, \forall i, m \right\} \) is the feasible set of \( \{\vec{\Phi}_i\} \).

In order to determine the closed-form expression of the capacity region for the considered DD-MAC, we first define the effective channel gain for each user \( u_i \) as follows:

\[
|\hat{h}_i(\vec{\Phi}_i)| = |\hat{h}_i + \sum_{m=1}^{M_i} g_{im} \phi_{im} \hat{h}_i|, \tag{6}
\]

\[
= |\hat{h}_i + \sum_{m=1}^{M_i} g_{im} \hat{h}_i e^{j(\varphi_{im} - \theta_{im} - \psi_{im})}|, \tag{7}
\]

\[
\overset{(a)}{=} |\hat{h}_i| + \sum_{m=1}^{M_i} g_{im} \hat{h}_i \overset{\Delta}{=} \hat{h}_i \gamma. \tag{8}
\]

In (8), (a) follows from assuming perfect CSI for RIS configuration, which enables ideal phase shifting (i.e., \( \varphi_{im} = \theta_{im} + \psi_{im} \)) [17]. Now, the closed-from capacity region of DD-MAC under RIS deployment is given as follows.
Theorem 1: The capacity region of the RIS-aided DD-MAC under strong interference scenario is given by
\[
C^D = \{(R_1, R_2) : R_1 + R_2 \leq R_{1,2}^D\},
\]
where
\[
R_{1,2}^D \triangleq \log_2 \left( 1 + \min \left\{ \frac{P_1 h_1^2}{N}, \frac{P_2 h_2^2}{N} \right\} \right) .
\]

Proof: We follow a similar rationale as in [17], but including the effect of the \(\min(\cdot)\) operator in (9) due to strong interference. Noting that the capacity region in (9) is an achievable rate region with \(\{\Phi_i\}\) in (8) and also provides a convex outer bound for all achievable \(C^D(\{\Phi_i\})\) in (4), the proof is completed.

B. SD-MAC

Here, we provide the closed-form capacity region of SD-MAC under RIS deployment. Because of the strong interference scenario, the MAC with a single (strong) dirty user is not an specific case of the DD-MAC with strong interferences [3], since we cannot directly set \(S_2 = 0\). By considering RIS reflection coefficient \(R_i\), the effective channel observed by receiver \(r\) from user \(u_2\) over SD-MAC is given by \(h_2(\Phi_i)\), and the instantaneous capacity region \(C^S(\{\Phi_i\})\) of the SD-MAC with coherent receiver under strong interference case (i.e., \(Q_1 \rightarrow \infty\)) is a triangle/quadrilateral region consisting of rate pairs that satisfy the following constraints:
\[
R_2 \leq \log_2 \left( 1 + \min \left\{ \frac{P_1 h_1^2}{N}, \frac{P_2 h_2^2}{N} \right\} \right),
\]
\[
R_1 + R_2 \leq \log_2 \left( \frac{P_1 h_1^2}{N} \right).
\]

Similar to the DD-MAC, any rate pair within the union set of \(C^S(\{\Phi_i\})\) over all feasible \(\{\Phi_i\}\) can be achieved by flexibly design the RIS reflection coefficients \(\{\Phi_i\}\). Thus, the capacity region of SD-MAC under strong interference case and RIS deployment is defined as the convex hull of such a union set given in (5). Now, exploiting the effective channel gain for each user \(u_i\) given in (7), and setting the phase shift as \(\varphi_{im} = \theta_{im} + \psi_{im}\), we present the following theorem to determine the closed-form capacity region of SD-MAC under RIS deployment.

Theorem 2: The capacity region of the RIS-aided SD-MAC under strong interference scenario is given by
\[
C^S = \{(R_1, R_2) : R_2 \leq R_{2}^S, R_1 + R_2 \leq R_{1,2}^S\},
\]
where
\[
R_{2}^S \triangleq \log_2 \left( 1 + \min \left\{ \frac{P_1 h_1^2}{N}, \frac{P_2 h_2^2}{N} \right\} \right)\quad \text{and} \quad R_{1,2}^S = \log_2 \left( \frac{P_1 h_1^2}{N} \right).
\]

Proof: Similar to the proof of Theorem 1, by noting that the capacity region in (12) provides a convex outer bound for all achievable \(C^S(\{\Phi_i\})\) in (10) and (11), the proof is completed.

IV. OUTAGE PROBABILITY

In this section, by exploiting the capacity regions that we obtained in Section III, we derive closed-from OP expressions for both DD and SD-MAC models under RIS deployment.
where the capacity region for DD/SD-MAC under RIS deployment is given by (24), as shown at the top of the next page.

A. DD-MAC

By exploiting the capacity region given in (9), we define the OP for DD-MAC under RIS deployment as:

\[ P^D_o = \Pr \left( C^D \leq R^D \right), \]

\[ = \Pr \left( \log_2 (1 + \min \{ \gamma_1, \gamma_2 \}) \leq R^D \right), \]

\[ = 1 - F_{\gamma_1} \left( \gamma^D_f \right) F_{\gamma_2} \left( \gamma^D_s \right), \]

where \( F_{\gamma_1} \left( \gamma^D_f \right) = 1 - F_{\gamma_1} \left( \gamma^D_f \right) \) is the complementary CDF of \( \gamma_1 \) and \( \gamma^D_f = 2^{R^D_f} - 1 \). Thus, by plugging \( F_{\gamma_1} \left( \gamma^D_f \right) \) from (17) into (21), the OP for DD-MAC is given by (22), as shown at the top of the next page.

B. SD-MAC

By considering the capacity region given in (12), we express the OP for SD-MAC under RIS deployment as:

\[ P^S_o = \rho P^S_{o1} + (1-\rho) P^S_{o2}, \]

where \( 0 \leq \rho \leq 1 \) is the event probability. \( P^S_{o1} \) can be determined as:

\[ P^S_{o1} = \Pr \left( C^S \leq R^S_1 \right), \]

\[ = \Pr \left( \log_2 (1 + \min \{ \gamma_1, \gamma_2 \}) \leq R^S_1 \right), \]

\[ = 1 - F_{\gamma_1} \left( \gamma^S_f \right) F_{\gamma_2} \left( \gamma^S_s \right), \]

where \( \gamma^S_f = 2^{R^S_f} - 1 \). Now, by inserting \( F_{\gamma_1} \left( \gamma^S_f \right) \) into (28), \( P^S_{o1} \) is given by (23), as shown at the top of the next page.

The term \( P^S_{o2} \) can also be expressed as:

\[ P^S_{o2} = \Pr \left( C^S \leq R^S_1 \right) = \Pr \left( \log_2 (1 + \gamma_1) \leq R^S_1 \right), \]

\[ = F_{\gamma_1} \left( \gamma^S_f \right), \]

where \( \gamma^S_f = 2^{R^S_f} - 1 \). By substituting (17) into (30), \( P^S_{o2} \) is achieved as follows:

\[ P^S_{o2} = \sum_{l=1}^{L} \frac{b_{\ell}}{\gamma_l} \gamma_1 \frac{\tilde{\gamma}_l}{\gamma_l} \left( \Gamma_{\ell} \right) \left( 1 \right) \sum_{l=1}^{L} \frac{b_{\ell}}{\gamma_l} \gamma_1 \frac{\tilde{\gamma}_l}{\gamma_l} \left( \Gamma_{\ell} \right) \left( 1 \right), \]

Finally, inserting \( P^S_{o1} \) and \( P^S_{o2} \) into (25), \( P^S_o \) is given as (24), as shown at the top of the next page.

V. NUMERICAL RESULTS

We now present the numerical results to validate the theoretical expressions previously derived, which are double-checked in all instances with Monte Carlo (MC) simulations. For this purpose, we first suppose that the common receiver \( r \) is located at \((0, 0, 6)\) under a three-dimensional coordinate system. We also consider that users \( u_1 \) and \( u_2 \) are placed at \((d_1, 0, 1)\) and \((-d_2, 0, 1)\), and the corresponding RISs are located at \((d_1, 0, 2)\) and \((-d_2, 0, 2)\), respectively, where \( d_i \) denotes the horizontal distance between \( i \)-th user and the receiver \( r \). We set the path-loss exponents as \( \alpha = 3 \) for the direct channel \( h_i \) from user \( u_i \) to the receiver \( r \), \( \alpha = 3 \) for the reflected channels \( h_i \) from user \( u_i \) to its serving RIS, and \( \alpha = 3.5 \) for the reflected channels from the respective RIS to the receiver \( r \). Fig. 2 shows the capacity region of DD/SD-MAC under Rayleigh fading channels with and without RIS deployment. We see in all three curves that considering RIS provides a larger capacity region as compared with no RIS deployment. We also see that increasing the number of reflecting meta-surface elements \( M_i \) improves the capacity region for both DD and SD-MAC models. Comparing the DD-MAC and SD-MAC cases, we recall that the DD-MAC and SD-MAC capacity regions are coincident when \( P_1 \geq P_2 \) as confirmed in previous studies.

Fig. 2. Capacity region for DD/SD-MAC under RIS deployment when \( N = -10 \text{dBm}, d_1 = d_2 = 20 \text{m}, \) (a) \( P_1 = P_2 = 60 \text{dBm}, P_3 = 60 \text{dBm}; \) (b) \( P_1 = 45 \text{dBm}, P_2 = 60 \text{dBm}; \) (c) \( P_1 = 60 \text{dBm}, P_2 = 45 \text{dBm}. \)

Fig. 3. OP versus average SNR \( \gamma \) for DD/SD-MAC under RIS deployment when \( \gamma_2 = \gamma_1, R^D_2 = 1 \text{bps/Hz}, R^S_1 = 1 \text{bps/Hz}, R^S_2 = 0.5 \text{bps/Hz}, N = -10 \text{dBm}, \) (a) \( P_1 = P_2 = 50 \text{dBm}; \) (b) \( P_1 = 50 \text{dBm}, P_2 = 40 \text{dBm}; \) (c) \( P_1 = 40 \text{dBm}, P_2 = 50 \text{dBm}. \)
we also observe that as the number of meta-surface elements DD and SD-MAC system models in all instances. As expected, improves the system performance in terms of the OP for both activities.

oblique incidence, imperfect phase shifts at the RIS, and multi-

has constructive effects on the capacity region and the OP under RIS deployment. For each of the investigated scenarios, the presence of non-casually known SI at the transmitters extend to the RIS case. Fig. 3 illustrates the behavior of the case explicitly included in Fig. 2(a) and Fig. 2(c). However, for

VI. C

We analyzed the capacity region of the two-user MAC in the presence of non-casually known SI at the transmitters under RIS deployment. For each of the investigated scenarios, namely DD-MAC where both users know the interferences and SD-MAC where interference is only known for one of the users, results show that considering RIS in dirty MAC has constructive effects on the capacity region and the OP performance, i.e., provides a larger capacity region and a lower OP. The consideration of single-RIS deployments under oblique incidence, imperfect phase shifts at the RIS, and multi-antenna processing are interesting lines for future research activities.

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