Double-RIS Communication with DF Relaying for Coverage Extension: Is One Relay Enough?

Zaid Abdullah, Steven Kisseleff, Konstantinos Ntontin, Wallace Alves Martins, Symeon Chatzinotas, and Björn Ottersten

Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg.
E-mails: {zaid.abdullah, steven.kisseleff, kostantinos.ntontin, wallace.alvesmartins, symeon.chatzinotas, bjorn.ottersten}@uni.lu

Abstract—In this work, we investigate the decode-and-forward (DF) relay-aided double reconfigurable intelligent surface (RIS)-assisted networks, where the signal is subject to reflections from two RISs before reaching the destination. Different relay-aided network architectures are considered for maximum achievable rate under a total power constraint. Phase optimization for the double-RIS channels is tackled via the alternating optimization and majorization-minimization (MM) schemes. Moreover, closed-form solutions are obtained for each case. Numerical results indicate that the deployment of two relays, one near each RIS, achieves higher rates at low and medium signal-to-noise ratios (SNRs) compared to placing a single relay between the two RISs; while at high SNRs, the latter approach achieves higher rates only if the inter-relay interference for the former case is considerably high.

Index Terms—Reconfigurable Intelligent surface, decode-and-forward, multihop relaying.

I. INTRODUCTION

Conventional active relaying, such as decode-and-forward (DF), is a well known technology that is used to extend the coverage, and/or to enhance the quality-of-service (QoS) between a pair of transceiving nodes [1]. Ideally, the locations and/or number of relays should be optimized based on a certain cost function, such as to maximize the rate or to minimize the transmit power while satisfying a given QoS constraint [2], [3].

In contrast, the reconfigurable intelligent surface (RIS) technology is a new concept in wireless communications, where a large number of low-cost, nearly-passive reflecting elements are utilized to direct the impinging signal toward a desired destination, such that the multiple signal paths are constructively combined at the receiver [4]. One of the most attractive aspects about RISs is that they do not require power-demanding active radio-frequency chains. Another benefit compared to traditional active relaying is that RISs work on-the-fly, i.e. they do not introduce additional delays due to internal signal processing. Thanks to their low-cost and low power-consumption, it is highly anticipated that RISs will have a key role in future wireless networks [5]–[7].

However, due to the large degradation of the signal power with distance, which is caused by the absence of active amplification at the RIS and the double path-loss, few studies have shown that considerably large surfaces are required to outperform a conventional single-antenna relay [8]–[9]. Motivated by this fact, many researchers started adopting classical relays, such as DF or amplify-and-forward (AF), to enhance the performance of RIS-assisted networks [10]–[17]. However, in all these works, only a single relay was utilized to enhance the RIS-assisted transmission. Moreover, even though the work in [17] considers three RISs, only one of them was deployed near the single relay, whereas the other two were located within short distances of the source and destination.

However, in many real-world scenarios, the signal might go through multiple hops before reaching the destination. Therefore, we aim to find the optimal way of combining relays with RISs when there is more than a single RIS between the two transceiving nodes. In particular, we consider the double-RIS reflection case where the signal is subject to reflections from two RISs before reaching the destination, and we propose three different half-duplex (HD) relay-aided network architectures, and compare their effective rates under a total power constraint. The findings of this work can help understand how to perform optimal route optimization, relay placement, and RIS-relay pairing for future multihop RIS-relay assisted networks.

Notations: Matrices and vectors are denoted by boldface uppercase and lowercase letters, respectively. $x^T$, $x^*$, and $\|x\|$ are the transpose, conjugate, and Euclidean norm of a vector $x$; respectively, $\Re\{x\}$ is the real part of a complex number $x$, and $\Re\{\{X\}\}$ is a vector whose elements are the diagonal of $X$. Finally, $\Re\{x\}$ denotes the real part of a complex number $x$.

II. SYSTEM MODEL AND PHASE OPTIMIZATION

We consider a time division duplex scenario where there is a single-antenna source ($S$) aiming to transmit a signal to a single-antenna destination ($D$) with the help of two RISs ($I_1$ and $I_2$). Due to large distances, obstacles and path-loss, we assume that $S$ has a direct link with only $I_1$, and similarly $D$ has a direct link with only $I_2$.

To enhance the performance of the double-RIS channel, we deploy a single-antenna HD-DF relay(s) between the two
ends. In particular, we investigate three different relay-aided scenarios. The first one corresponds to the case of a single relay (R) present between $I_1$ and $I_2$, and the communication takes place over two time-slots. In the second scenario, we assume that there are two relays $R_1$ and $R_2$, placed near $I_1$ and $I_2$, respectively, and only a single node in the network can transmit at any given time-instant. In the last scenario, we aim to enhance the second scenario by allowing the second relay $R_2$ to transmit to $D$ while $S$ transmits its data to $R_1$. Note that throughout this work, we assume perfect channel estimation for all links 1. We also assume centralized processing for the different double-RIS communication schemes. Fig. 1 shows the different relay-aided double-RIS network configurations, where we compare with the no-relay scenario as a benchmark scheme. We next start formulating the received signals and corresponding achievable rates for each scenario.

A. Transmission through only the RISs

In this scenario, we assume that the transmission is realized through the two RISs only. Therefore, the received signal at the destination can be written as

$$y_D^{(1)}(n) = \sqrt{p} \left( h_{I_2D}^T \Phi G \Theta h_{I_1S} \right) x_s(n) + w_D(n),$$

(1)

where the superscript in $y_D^{(1)}$ indicates that this is a single-hop transmission, $n$ is the time index, $p$ is the total transmit power at any given time-instant, $h_{I_1S} \in \mathbb{C}^M$ and $h_{I_2D} \in \mathbb{C}^M$ are the channels between $S \rightarrow I_1$, and $I_2 \rightarrow D$, respectively, and $M$ is the number of reflecting elements at each RIS. $G \in \mathbb{C}^{M \times M}$ is the channel between the two RISs; while $\Theta = \text{diag}\{\theta\} \in \mathbb{C}^{M \times M}$ and $\Phi = \text{diag}\{\phi\} \in \mathbb{C}^{M \times M}$ are the reflection matrices for $I_1$ and $I_2$, respectively. $x_s$ is the information symbol transmitted from $S$ with $E[|x_s|^2] = 1$, and $w_D \sim CN(0, \sigma^2)$ is the additive white Gaussian noise (AWGN) at the destination. Therefore, the received signal-to-noise ratio (SNR) at the destination is given as

$$\gamma_D^{(1)} = \rho \left| h_{I_2D}^T \Phi G \Theta h_{I_1S} \right|^2,$$

(2)

where $\rho = p/\sigma^2$. The achievable rate in this case is

$$R^{(1)} = \log_2 \left( 1 + \gamma_D^{(1)} \right).$$

(3)

Clearly, the achievable rate depends on both $\Phi$ and $\Theta$. However, to optimize the achievable rate, we first need to reformulate the cascaded channel as follows:

$$\left| h_{I_2D}^T \Phi G \Theta h_{I_1S} \right|^2 = \left| \phi^T \text{diag}\{h_{I_2D}\} G \text{ diag}\{h_{I_1S}\} \theta \right|^2 = \left| \phi^T F \theta \right|^2.$$  

(4)

Now we can present the following optimization problem

$$\text{maximize}_{\theta} \rho \left| \phi^T F \theta \right|^2$$

subject to $||\theta||_m = 1, \quad ||\phi||_m = 1, \quad \forall m \in \mathcal{M}$,  

(5)  

We alternate the optimization process between $\phi$ and $\theta$ until the increment in the achievable rate between two successive iterations falls below a certain threshold, or we reach a maximum number of optimization iterations.

B. Communication through RISs and a single relay

In this case, we assume that there is one HD-DF relay ($R$), placed in the middle between $I_1$ and $I_2$, and the transmission...
is carried out through two time-slots.

1) First-Hop: In the first time-slot, $S$ transmits its data to $R$ through the direct link and the reflected signal from $I_1$. Therefore, the received signal at $R$ is given as

$$y_R^{(2)}(n) = \sqrt{p} \left( h_{SR} + h_{1,R}^T \Theta h_{1,S} \right) x_s(n) + w_R(n),$$

where the superscript in $y_R^{(2)}$ indicates that there are two hops in this case, $h_{1,R} \in \mathbb{C}^M$ is the channel vector between $I_1$ and $R$, $h_{SR} \in \mathbb{C}$ is the channel between $S$ and $R$, and $w_R \sim \mathcal{C}\mathcal{N}(0, \sigma^2)$ is the AWGN at $R$. To maximize the received SNR at $R$, the phase-shifts of $\Theta$ should be selected as follows

$$[\Theta^*]_{m,m} = \exp \left( j \left( \angle(h_{SR}) - \angle([h_{1,R}]_m [h_{1,S}]_m) \right) \right),$$

\forall m \in \mathcal{M}$. Then, the received SNR at $R$ with optimal phase-shifts can be expressed as

$$\gamma^{(2)}_R = p \left( |h_{SR}| + \sum_{m \in \mathcal{M}} |[h_{1,R}]_m [h_{1,S}]_m| \right)^2.$$  

2) Second-Hop: During the second time-slot, the relay re-transmits the signal, with power $p$, to the destination through the direct link and $I_2$. Assuming successful decoding of $x_s$ at the relay, the received signal at $D$ can be given as

$$y_D^{(2)}(n+1) = \sqrt{p} \left( h_{RD} + h_{2,R}^T \Phi h_{2,D} \right) x_s(n) + w_D(n+1),$$

where $h_{RD} \in \mathbb{C}$ and $h_{2,R} \in \mathbb{C}^M$ are the channels between $R \rightarrow D$ and $R \rightarrow I_2$, respectively, and $w_D \sim \mathcal{C}\mathcal{N}(0, \sigma^2)$ is the AWGN at $D$. Assuming perfect phase-shifts at $I_2$ for $\Phi$, the received SNR at $D$ is

$$\gamma^{(2)}_D = p \left( |h_{RD}| + \sum_{m \in \mathcal{M}} |h_{2,D}|_m |h_{2,R}|_m \right)^2,$$

and the corresponding achievable rate is

$$R^{(2)} = \frac{1}{2} \log_2 \left( 1 + \min \{ \gamma^{(2)}_R, \gamma^{(2)}_D \} \right),$$

and the $\frac{1}{2}$ pre-log factor is due to the two-hop transmission.

C. Communication through RISs and two relays

In this case, we assume that there are two HD-DF relays, $R_1$ and $R_2$, to assist the communication between $S$ and $D$. In particular, we assume that $R_1$ is placed in close proximity to $I_1$, while $R_2$ is placed near $I_2$. Furthermore, the transmission takes place over three time-slots, since we assume that only one node can transmit at any given time-instance.

1) First-Hop: In the first-hop, $S$ transmits its signal to $R_1$ through the direct link and $I_1$. Therefore, the received signal at $R_1$ is

$$y_{R_1}^{(3,3)}(n) = \sqrt{p} \left( h_{SR_1} + h_{1,R_1}^T \Theta h_{1,S} \right) x_s(n) + w_{R_1}(n),$$

where the superscript in $y_{R_1}^{(3,3)}$ indicates that there are three hops and $S$ transmits a new block of data every three transmission time-slots, $h_{1,R_1} \in \mathbb{C}^M$ is the channel vector between $I_1$ and $R_1$, and $w_{R_1} \sim \mathcal{C}\mathcal{N}(0, \sigma^2)$ is the AWGN at $R_1$. Assuming perfect phase-optimization for $\Theta$ at $I_1$, the received SNR at $R_1$ is

$$\gamma_{R_1}^{(3,3)} = p \left| h_{SR_1} \right| + \sum_{m \in \mathcal{M}} \left| h_{1,R_1}^m [h_{1,S}]_m \right|^2.$$  

2) Second-Hop: During the second-hop, $R_1$ re-transmits the signal, assuming successful decoding, to $R_2$ through the direct link, direct reflection links from both $I_1$ and $I_2$, as well as double-reflection link. Therefore, and assuming perfect decoding of $x_s$ at $R_1$, the received signal at $R_2$ can be given as shown in (17) at the top of the next page, where we have $h_{1,R_2} \in \mathbb{C}^M$, $h_{I_1R_1} \in \mathbb{C}^M$, $h_{I_2R_2} \in \mathbb{C}^M$ and $h_{R_1R_2} \in \mathbb{C}$ are the channels between $I_1 \rightarrow R_2$, $I_2 \rightarrow R_1$, $I_2 \rightarrow R_2$ and $R_2 \rightarrow R_2$, respectively. $\Psi_1 \in \mathbb{C}^{M \times M}$ and $\Psi_2 \in \mathbb{C}^{M \times M}$ are the reflection matrices for $I_1$ and $I_2$, respectively, during the second-hop, and $w_{R_2} \sim \mathcal{C}\mathcal{N}(0, \sigma^2)$ is the AWGN at $R_2$.

Let $Q = \text{diag} \{ h_{I_2R_2} \}$, the received SNR at $R_2$ can be written as follows:

$$\gamma_{R_2}^{(3,3)} = p \left| h_{I_1R_2} + \psi_1^T u_{I_1} + \psi_2^T u_{I_2} + \psi_2^T Q \psi_1 \right|^2.$$  

Clearly the SNR depends on both $\psi_1$ and $\psi_2$, therefore, we can formulate the following optimization problem

$$\max_{\psi_1, \psi_2} \rho \left| h_{I_1R_2} + \psi_1^T u_{I_1} + \psi_2^T u_{I_2} + \psi_2^T Q \psi_1 \right|^2$$

subject to $\left| \psi^*_m \right| = 1, \, \forall m \in \mathcal{M}, \, i \in \{1,2\},$

the above optimization problem is also non-convex. Accordingly, we adopt an alternating optimization scheme where we fix one of the optimization variables and solve for the other one. In particular, and for a given $\psi_2$, we have

$$\gamma_{R_2}^{(3,3)} = p \left| z^T \psi_1 + c \right|^2,$$

where $z^T = (u_{I_1} + \psi_2^T Q \psi_1)$, and $c = \psi_2^T u_{I_2} + h_{R_1R_2}$. Then, it is straightforward to see that the optimal phase-shift for the $m$th element of $\psi_1$ is

$$[\psi^*_1]_m = \exp \left( j \left( \angle(c) - \angle([z]_m) \right) \right).$$

Similarly, to optimize the phase-shifts of $\psi_2$, we can fix $\psi_1$ to obtain

$$\gamma_{R_2}^{(3,3)} = p \left| v^T \psi_2 + r \right|^2,$$  

where $v = (u_{I_2} + Q \psi_1)$, and $r = (h_{R_2R_2} + \psi_2^T u_{I_2})$. It follows that the optimal phase-shift for the $m$th element of $\psi_2$ is

$$[\psi^*_2]_m = \exp \left( j \left( \angle(r) - \angle([w]_m) \right) \right).$$

3) Third-Hop: After receiving the information, $R_2$ will decode the message and then will retransmit it to $D$ through the direct link and $I_2$. Assuming successful decoding at $R_2$, the received signal at the destination can be written as

$$y_D^{(3,3)}(n+2) = \sqrt{p} \left( h_{R_2D} + h_{I_2D}^T \Phi h_{I_2R_2} \right) x_s(n) + w_D(n+2),$$

Note that there exists another path from $S \rightarrow I_1 \rightarrow I_2 \rightarrow R$, however, this path is neglected here as the received signal through $S \rightarrow I_1 \rightarrow R$ will be dominant due to shorter travel distance and less reflections.
and the corresponding received SNR at $D$, assuming perfect phase-optimization at $I_2$ for $\Phi$, can be expressed as
\[
\gamma_D^{(3,3)} = \rho \left( |h_{R_2D}| + \sum_{m \in \mathcal{M}} |h_{I_2R_2m}| |h_{I_2R_2m}| \right)^2.
\] (23)
and the corresponding achievable rate can be written as
\[
\mathcal{R}^{(3,3)} = \frac{1}{3} \log_2 \left( 1 + \min \{ \gamma_D^{(3,3)} \} \right),
\] (24)
where the spectral efficiency is reduced by a factor of 3 since a new block of data is transmitted every three time-slots.

D. Enhanced transmission with RISs and two-relays

The main setback for the previous scenario is the $\frac{1}{4}$ pre-log factor, which can be costly at high SNRs. Therefore, we further present an enhanced transmission scheme such that while $R_2$ is transmitting its signal to $D$, $S$ transmits a new data packet to $R_1$. Note that for the first two time-slots ($n \in \{1, 2\}$), all equations in the previous subsection hold in terms of SNRs and phase-optimization; as for the subsequent frames (i.e. when $n > 2$), the received signals and transmit powers will change as will be thoroughly explained here.

1) Received signal at $R_1$: At a given odd-time instant $n_o$ ($n_o \geq 3$), both $S$ and $R_2$ transmit data to $R_1$ and $D$, respectively. Our focus here is on the received signal at $R_1$.

Clearly, $R_1$ will receive an interfering signal from $R_2$ in addition to the desired signal from $S$, as shown in (25) at the top of the next page, where the superscript in $\hat{y}_{R_1}^{(3,2)}$ denotes that there are 3 hops, and $S$ transmits a new data packet every two time-slots, $p_1$ and $p_2$ are the transmit powers at $S$ and $R_2$, respectively, with $p_1 + p_2 = p$ to maintain the total transmit power budget, and $\Theta$ and $\Phi$ are the reflection matrices at $I_1$ and $I_2$, respectively. The 2nd term in (25) represents the interference from $R_2$, which can be canceled in different ways. For example, if a global channel state information (CSI) is available, then $R_1$ can cancel this interference perfectly (assuming perfect channel estimation), since the signal transmitted from $R_2$, i.e. $x_s(n_o - 2)$, can be viewed as the signal that $R_1$ transmitted in the previous time-slot. Otherwise, $R_1$ can estimate the overall effective channel between itself and $R_2$. This can be performed according to the maximum-likelihood estimation by multiplying the received signal at $R_1$ with the conjugate of the transmitted signal from $R_1$ at time $n_o - 1$ (which is $x_s(n_o - 2)$), as shown in (26) at the top of the next page. After performing interference cancellation at $R_1$, we can rewrite the received signal in (25) as
\[
\hat{y}_{R_1}^{(3,2)}(n_o) = \sqrt{p} \left[ h_{SR_1} + h_{I_1R_1} \Theta h_{I_1S} \right] x_s(n_o) + h_c x_s(n_o - 2) + w_{R_1}(n_o),
\] (27)
where $h_c = \sqrt{p_2}(h_2 - \bar{h}_2)$ is the residual interference cancellation error at $R_1$, which is usually assumed to follow a normal distribution such that $h_c \sim \mathcal{CN}(0, \sigma_c^2)$. Assuming perfect phase optimization for $\Theta$ at $I_1$ to maximize the power of received signal at $R_1$ from $S$, we can formulate the received signal-to-interference plus noise ratio (SINR) at $R_1$ as follows:
\[
\gamma_{R_1}^{(3,2)} = \frac{p_1 \left[ |h_{SR_1}| + \sum_{m \in \mathcal{M}} |h_{I_1R_1_m}| |h_{I_1S_m}| \right]^2}{\sigma_c^2 + \sigma^2}.
\] (28)
Next we focus on the received signal at the destination.

2) Received signal at $D$: While $S$ is transmitting its data to $R_1$, $R_2$ transmits the decoded signal from $R_1$ in the previous time-slot to $D$. The received signal at $D$ can be expressed as
\[
y_D^{(3,2)}(n_o) = \sqrt{p_1} \left[ h_{SR_1} + h_{I_1D} \Phi h_{I_2R_2} \right] x_s(n_o - 2) + \sqrt{p_1} \left[ h_{I_2D} \Phi G \Theta h_{I_1S} \right] x_s(n_o) + w_D(n_o).
\] (29)
Note that $x_s(n_o)$ is intended for $R_1$, and therefore it represents interference to $D$. As a result, the SINR at $D$ is
\[
\gamma_D^{(3,2)} = \frac{p_2 \left[ |h_{R_2D} + \phi^T a|^2 \right]}{p_1 \left[ \phi^T b^2 + \sigma^2 \right]},
\] (30)
where $b = \text{diag}(h_{I_2D})q, a = \text{diag}(h_{I_2D})h_{I_2R_2}, \phi = \text{diag}(\Phi), \text{and } q = \Phi \Theta h_{I_1S}$. Now we can formulate the following optimization problem:
\[
\begin{align*}
\text{minimize} & \quad u(\phi) = \frac{p_1 \left[ |\phi^T b|^2 + \sigma^2 \right]}{p_2 \left[ |h_{R_2D} + \phi^T a|^2 \right]} \quad \text{subject to } |\phi_m| = 1, \forall m \in \mathcal{M}. \quad (31a) \\
\text{minimize} & \quad p_2 \left[ |h_{R_2D} + \phi^T a|^2 \right] \quad \text{subject to } |\phi_m| = 1, \forall m \in \mathcal{M}. \quad (32a)
\end{align*}
\] (31a)
This problem belongs to fractional programming [20]. As such, we formulate the following parametric program:
\[
\begin{align*}
\text{minimize} & \quad p_2 \left[ |h_{R_2D} + \phi^T a|^2 \right] - \mu \left( p_2 \left[ |h_{R_2D} + \phi^T a|^2 \right] \right) \quad \text{subject to } |\phi_m| = 1, \forall m \in \mathcal{M}. \quad (32b)
\end{align*}
\] (32b)
where $\mu \geq 0$ is an introduced parameter. Although problem (32) is non-convex, it can be solved using the iterative majorization-minimization (MM) method. In particular, we can introduce the following upper-bound of (32) [21], [22]:
\[
f(\phi, \mu) \triangleq p_2 \left[ |h_{R_2D} + \phi^T a|^2 \right] - \mu \left( p_2 \left| h_{R_2D} + \phi^T a \right|^2 \right) \\
= \phi^T X \phi - 2 \mu p_2 \Re \left\{ \phi^T h_{R_2D} a \right\} \quad \text{and} \quad \mu \geq 0.
\] (33)
where $X = (p_2 \mu b b^H - \mu p_2 a a^H), \lambda_{\max}(X)$ is the maximum eigenvalue of $X, L = \lambda_{\max}(X) I_M, \alpha(\phi, \mu) = \phi^T \mu \phi + \phi^T \phi$.

\footnote{Note that the received signal at $R_2$ in the next time-slot (i.e. at time $(n_o + 1)$) will not be affected by this enhanced transmission scheme, since only $R_1$ will be transmitting data to $R_2$ with a power budget of $p$ while the source will be silent. Therefore, we have $\gamma_{R_2}^{(3,2)} = \gamma_{R_2}^{(3,3)}$.}
\[ y_{R_i}^{(3,2)}(n_0) = \sqrt{p_1} \left( h_{SR_i} + h_{1R_i}^T \Theta h_{1S} \right) x_s(n_0) + \sqrt{p_2} \left( h_{R_1R_2} + h_{1R_1}^T \Theta h_{1R_2} + h_{1R_2}^T \Phi h_{1R_2} + h_{1R_1} \Theta \Phi h_{1R_2} \right) x_s(n_0 - 2) + w_{R_i}(n_0). \]

\[ \mathbb{E}\{ y_{R_i}^{(3,2)}(n_0)x_s(n_0 - 2)^* \} = \sqrt{p_1} h_1 \mathbb{E}\{ x_s(n_0)x_s(n_0 - 2)^* \} + \sqrt{p_2} h_2 \mathbb{E}\{ x_s(n_0 - 2)x_s(n_0 - 2)^* \} + \mathbb{E}\{ w_{R_i}(n_0)x_s(n_0 - 2)^* \} = \sqrt{p_2} h_2. \]
two relays can provide a significant performance gain. To be more specific, and regardless of the value of SNR, adopting the enhanced two-relays transmission is always better than the single-relay case as long as the inter-relay interference is sufficiently suppressed, i.e. \( \rho_c \leq 10 \) dB. Otherwise, the choice between a single relay and two relays depends purely on the value of SNR. At low SNRs, deploying two relays such that no two nodes can transmit in the network at the same time, can still achieve higher rates than the single relay case despite the \((1/3)\) pre-log penalty; while at high SNRs, the single relay case leads to higher rates.

Finally, Fig. 3 shows the performance of different transmission schemes for a wide range of number of reflecting elements. Once again, our results indicate that adopting two relays to assist the transmission is highly desirable for the double-RIS assisted communication even when the considered RISs are sufficiently large with hundreds of reflecting elements. For example, to achieve 3 bps/Hz, the enhanced two-relay transmission requires 200 reflecting elements per RIS, compared to 600 and 1000 elements for the single-relay and no-relay cases, respectively, given that the inter-relay interference is suppressed to the noise level.

IV. CONCLUSION AND FUTURE WORK

We investigated the DF relay-aided double-RIS reflection channels for coverage extension. Three different relay-aided network architectures were proposed for effective rate maximization under a total power constraint. Our results demonstrated that deploying two relays for the double-RIS channel achieves higher rates at low and medium SNRs; while at high SNRs, deploying a single relay to assist the two RISs is better only if the inter-relay interference was high. The generalization to multihop with arbitrary numbers of RISs and relays is subject to future investigations.

ACKNOWLEDGMENT

This work was supported by the Luxembourg National Research Fund (FNR) under the CORE project RISOTTI.

APPENDIX A

Let us denote \( p_2[h_{R_2,D} + \phi^T a]_2 \) by \( f_a(\phi), p_1[\phi^T b]_2 + \sigma^2 \) by \( f_b(\phi), \) and the right hand side of (33) by \( g(\phi, \phi, \mu). \) Let \( \phi \) and \( \phi^* \) be the phase-shift values of \( I_2 \) before and after running a single iteration of the MM scheme, and let \( \mu \) denote the value of \( \mu \) that corresponds to \( \phi. \) Then, from the left hand side of (33), we have \( f(\phi, \mu) = f_b(\phi^*) - \mu f_a(\phi^*) \leq g(\phi^*, \mu) \leq g(\phi, \mu) = f(a) - \mu f_a(\phi) \), where (a) holds from (33), (b) holds since \( \phi^* \) minimizes \( g(\phi, \mu) \), and (c) holds from the definition of \( \mu \) in (36). Therefore, we have \( u(\phi^*) = f_b(\phi^*)/f_a(\phi^*) \leq \mu = f_b(\phi)/f_a(\phi) = u(\phi). \)

REFERENCES

[1] J. N. Laneman et al., “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” IEEE Trans. Inf. Theory, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.
[2] Minelli et al., “Optimal relay placement in cellular networks,” IEEE Trans. Wireless Commun., vol. 13, no. 2, pp. 998–1009, Feb. 2014.
[3] H. Q. Ngo and E. G. Larsson, “Linear multihop amplify-and-forward relay channels: Error exponent and optimal number of hops,” IEEE Trans. Wireless Commun., vol. 10, no. 11, pp. 3834–3842, Nov. 2011.
[4] X. Tan et al., “Increasing indoor spectrum sharing capacity using smart reflect-array,” in IEEE Int. Conf. Commun. (ICC), Kuala Lumpur, Malaysia, May 2016, pp. 1–6.
[5] N. Rajatheva et al., “White paper on broadband connectivity in 6G,” [Online]. Available: https://arxiv.org/abs/2004.14247, 2020.
[6] M. Z. Chowdhury et al., “6G wireless communication systems: Applications, requirements, technologies, challenges, and research directions,” IEEE Open J. Commun. Soc., vol. 1, pp. 957–975, Aug. 2020.
[7] S. Kisseleff et al., “Reconfigurable intelligent surfaces for smart cities: Research challenges and opportunities,” IEEE Open J. Commun. Soc., vol. 1, pp. 1781–1797, Dec. 2020.
[8] E. Björnsson et al., “Intelligent reflecting surface versus decode-and-forward: How large surfaces are needed to beat relaying?” IEEE Wireless Commun. Lett., vol. 9, no. 2, pp. 244–248, Feb. 2020.
[9] M. Di Renzo et al., “Reconfigurable intelligent surfaces vs. relaying: Differences, similarities, and performance comparison,” IEEE Open J. Commun. Soc., vol. 1, pp. 798–807, July 2020.
[10] Z. Abdulla et al., “A hybrid relay and intelligent reflecting surface network and its ergodic performance analysis,” IEEE Wireless Commun. Lett., vol. 9, no. 10, pp. 1653–1657, Oct. 2020.
[11] ———, “Optimization of intelligent reflecting surface assisted full-duplex relay networks,” IEEE Wireless Commun. Lett., vol. 10, no. 2, pp. 363–367, Feb. 2021.
[12] J. Wang et al., “Joint beamforming and reconfigurable intelligent surface design for two-way relay networks,” IEEE Trans. Commun., To appear.
[13] X. Ying et al., “Relay aided intelligent reconfigurable surfaces: Achieving the potential without so many antennas,” [Online]. Available: https://arxiv.org/abs/2006.06644, 2020.
[14] Y. Hüdüm et al., “Hybrid RIS-empowered reflection and decode-and-forward relaying for coverage extension,” IEEE Commun. Lett., vol. 25, no. 5, pp. 1692–1696, May 2021.
[15] M. Obeid and A. Chaaban, “Joint beamforming design for multiuser MISO downlink aided by a reconfigurable intelligent surface and a relay,” [Online]. Available: https://arxiv.org/abs/2104.08417, 2021.
[16] C. Huang et al., “Deep reinforcement learning-based relay selection in intelligent reflecting surface assisted cooperative networks,” IEEE Wireless Commun. Lett., vol. 10, no. 5, pp. 1036–1040, May 2021.
[17] Z. Kang et al., “IRS-aided wireless relaying: Optimal deployment and capacity scaling,” [Online]. Available: https://arxiv.org/abs/2105.08495, 2021.
[18] C. You et al., “Wireless communication via double IRS: Channel estimation and passive beamforming designs,” IEEE Wireless Commun. Lett., vol. 10, no. 2, pp. 431–435, Feb. 2021.
[19] B. Zheng et al., “Efficient channel estimation for double-IRS aided multi-user MIMO system,” IEEE Trans. Commun., vol. 69, no. 6, pp. 3818–3832, June 2021.

[20] W. Dinkelbach, “On nonlinear fractional programming,” Management science, vol. 13, no. 7, pp. 492–498, Mar. 1967.

[21] H. Shen et al., “Secrecy rate maximization for intelligent reflecting surface assisted multi-antenna communications,” IEEE Commun. Lett., vol. 23, no. 9, pp. 1488–1492, Sep. 2019.

[22] Y. Sun et al., “Majorization-minimization algorithms in signal processing, communications, and machine learning,” IEEE Trans. Signal Process., vol. 65, no. 3, pp. 794–816, Feb. 2017.