A study on multi-RIS for multi-user distributed MIMO systems

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***Abstract*—This paper presents a preliminary analysis on the impact of Reconfigurable Intelligent Surfaces (RISs) for the realization of multi-user Distributed multiple input multiple output (DMIMO) systems, where the distributed units are actually RISs. Assuming no direct link between the multi-antenna Access Point (AP) and the users, we design the joint transmit beamforming from the AP to the set of RISs associated to each user, performed via RIS phase shift shaping. In order to comply with the semi-passive nature of RISs, the phase shifts are computed via a Genetic Algorithm (GA), where the optimization is based on the Signal-to-Leakage-and-Noise-Ratio (SLNR) precoding scheme. Numerical results confirm that this GA implementation significantly outperforms the common Maximum Ratio Beamforming (MRB) approach in terms of interference suppression and sum-rate, but at the price of a significant increase in computational complexity. Our solution justify the interest of a multi-RIS system for spatial multiplexing, and opens to several further research directions.**

***Index Terms*—Reconfigurable intelligent surfaces, multi-user MIMO, distributed MIMO, Beyond 5G.**

I. Introduction

The exploitation of Reconfigurable Intelligent Surfaces (RISs) in wireless networks [1] makes it possible to alter the wireless channel to favor signal propagation and improve the connection of those devices that would otherwise struggle to obtain a link with the mobile network [2]. RISs (or metasurfaces) are in fact semi-passive devices, which can be configured to modify the reflection angle of the incident signal, among other possible functions. They are one of the key technologies for beyond 5G networks [3]. In this paper we propose a novel implementation of a multiple RISs system.

Previous works investigated the adoption of multi-RISs system. In [4], authors analysed a multi-hop transmission with RISs to serve users in locations particularly difficult to reach, while in [5] the authors simulated a multi-RISs-aided system to further increase the richness of the environment, supporting the communication between a source and a destination. A multi-RISs system for capacity improvement has been presented in [6] for single user scenario, while authors in [7] studied a double-RISs system with a hybrid beamforming for a multi-user scenario.

Differently from previous works, the aim of our solution is to resort on an arbitrary number of RISs to serve multiple users in parallel, thus to achieve high-throughput in Space Division Multiple Access (SDMA) networks, thanks to different spatial channels. Furthermore, we propose a novel approach based on Genetic Algorithm (GA), which was already proven effective in another study related to RIS for the design of multi-pair RIS-aided communications [8]. In particular, our framework emulates a distributed MIMO (DMIMO) scenario [9], where the Distributed Units (DUs) are replaced by RISs, as represented in Fig. 1. Our work is inspired by Cell-Free MIMO [10], a popular technology in the recent years, which can be seen as a special case of DMIMO. The convenience of this configuration is to exploit the spatial diversity of the distributed nodes to decrease correlation between the spatial channels, to effectively serve more users in the same time and frequency resources. Optimal design parameters are computed relying on an adaptation of the GA, for (the inter-RIS and) inter-user interference suppression, based on a metric borrowed and adapted from a SDMA precoding technique, namely Signal-to-Leakage-Plus-Noise (SLNR) ratio [11]. Our technique permits to optimize the phase shifts of each RIS independently from the others, thus enabling parallel computations. Furthermore, our analysis is based on the latest 3GPP 3-D channel model simulator [12], considering the richness of the wireless channel and a variety of configurations.

In the current version of the work, we do not characterize analytically the SINR statistics, due to the challenging task of adapting the approach adopted in [5], for a multi-RIS aided SISO setting, to our setting. This is subject of ongoing work.

The work is articulated as follows: Section II introduces system and channel model. Section III contains detail on system design and its performance assessment, along with a sketch of the adaptation of a GA to our framework. Numerical results are reported and discussed in Section IV, while Section V summarizes our findings and concludes the work.

II. System model

For a RIS-aided communications, where the RIS consists of N elements, the received signal in a Single Input Single Output (SISO) system is:

$$y = \sum_{n=1}^{N} \left(g_n \beta_n h_n^{\mathrm{RIS}} x \right) + h^{\mathrm{AP}} x + w, \tag{1}$$

where h_n^{RIS} and g_n are the (Access Point) AP-RIS channel response and RIS-UE (User Equipment) channel response,

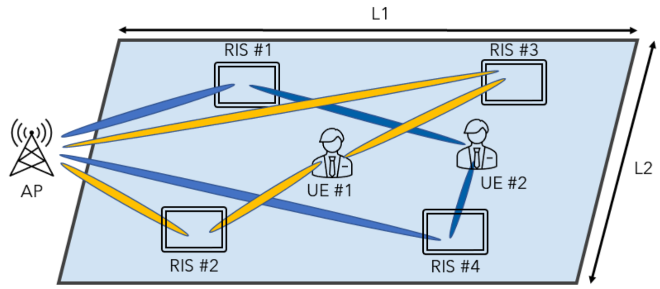

Fig. 1. Multi-user multi-RIS DMIMO system.

respectively. h^{AP} represents the AP-UE channel, $\beta_n = e^{j\phi_n}$ is the RIS n-th element coefficient, with ϕ_n its associated phase shift[1], and w is the complex zero-mean additive white Gaussian noise with variance σ_k^2.

We consider a DMIMO system with M_{RIS} RIS units, equally spaced along the border of a given area, each of them composed of N elements, and with K single-antenna users (i.e. $N_r = 1$). The AP is equipped with an antenna array of $N_t = N_{ty} \times N_{tz}$ elements. The end-to-end channel $\mathbf{H}_k^{\mathrm{tot}}$ from the AP to user $k \in [1 \dots K]$, aided by a subset of the overall number of available RISs $\mathcal{M}_{\mathrm{RIS}} = \{1, \dots, M_{\mathrm{RIS}}\}$, say $\mathcal{R}_k \subseteq \mathcal{M}_{\mathrm{RIS}}$, can be therefore written as:

$$\mathbf{H}_k^{\mathrm{tot}} = \mathbf{H}_k^{\mathrm{AP}} + \sum_{r \in \mathcal{R}_k} \mathbf{G}_{r,k} \mathbf{\Theta}_r \mathbf{H}_r^{\mathrm{RIS}} \tag{2}$$

where:

- $\mathbf{H}_k^{\mathrm{AP}}$ is the $N_r \times N_t$ channel matrix for the link between user k and the AP.
- $\mathbf{\Theta}_r$ is a diagonal matrix of size N, containing phase elements of the r-th RIS, $r \in \mathcal{R}_k$.
- $\mathbf{G}_{r,k}$ $N_r \times N$ channel matrix between RIS r and user k.
- $\mathbf{H}_r^{\mathrm{RIS}}$ $N \times N_t$ channel matrix for RIS r and the AP.

We focus on a scenario where the path between the AP and the UE is severely blocked by obstacles, i.e. $\mathbf{H}_k^{\mathrm{AP}} = \mathbf{0}$. In this preliminary study we postulate the absence of the AP-UE link to focus on the sole impact of multiple RIS exploitation. The more general scenario where the direct path is available for an arbitrary subset of users or all of them is subject of ongoing investigation.

The path loss $\mathrm{PL}_{\mathrm{RIS}}$ on the resulting RIS-aided link, from the AP to user k, can be computed as [13][2]

$$\mathrm{PL}_{\mathrm{RIS}} = \frac{256\pi^4}{\lambda^4} N^2 \frac{d_{t,e}^2 d_{e,r}^2}{G_{t,e} G_{e,r}} \epsilon_p \tag{3}$$

where $d_{t,e}$ and $d_{e,r}$ are the RIS element distances from AP to RIS and from RIS to UE, respectively, and ϵ_p is the element efficiency. $G_{t,e}$ and $G_{e,r}$ are the RIS element directional gains from AP to RIS and from RIS to UE, respectively, and they depend on the RIS element pattern as reported in [15]:

$$F(\theta_r, \phi_r) = \begin{cases} cos(\theta_r)^3 & \theta_r \in [0, \pi/2], \phi_r \in [0, 2\pi] \\ 0 & \theta_r \in (\pi/2, \pi], \phi_r \in [0, 2\pi] \end{cases} \tag{4}$$

with θ_r the elevation and, respectively, ϕ_r the azimuth angle of the RIS r. The received SNR in dB at user k from RIS r is

$$\mathrm{SNR}_{r,k}^{\mathrm{RIS}} = P_i + G_t + G_r + \mathrm{PL}_{\mathrm{RIS}} - P_w \quad [dB] \tag{5}$$

where $P_r = P_t / M_{\mathrm{RIS}}$ is the AP transmitted power[3] toward RIS r, G_t is the antenna gain of the transmitter (AP), and G_r is the antenna gain of the receiver (UE). P_w is the noise power and $P_w = F + 10\log_{10}(k_B T B)$.

In our work the channel matrices $\mathbf{G}$ and $\mathbf{H}^{\mathrm{RIS}}$ are generated with the latest 3GPP 3-D channel model [12], where the propagation path is characterized by a number of clusters distributed over the area, which group the rays generated by the scattering environment. A thorough description and tutorial on this channel model implementation can be found in [16]. For a LOS link, the channel is the result of both LOS $\mathbf{H}^{\mathrm{LOS}}$ and NLOS $\mathbf{H}^{\mathrm{NLOS}}$ contributions:

$$\mathbf{H} = \sqrt{1/(K_R+1)}\mathbf{H}^{\mathrm{NLOS}} + \sqrt{K_R/(K_R+1)}\mathbf{H}^{\mathrm{LOS}} \tag{6}$$

where K_R is the Rician factor, and $\mathbf{H}^{\mathrm{NLOS}}$ is the result of the sum of the scatterers contributions:

$$\mathbf{H}^{\mathrm{NLOS}} = \sum_{n=1}^{N_{\mathrm{cl}}} \sum_{m=1}^{M_{\mathrm{ray}}} \sqrt{\frac{P_n}{M_{\mathrm{ray}}}} \, \mathbf{\Gamma}_{n,m} \tag{7}$$

where P_n is the power scattered from the corresponding cluster, and $\mathbf{\Gamma}_{n,m}$ is the m ray of cluster n channel response, encompassing the effects of the antenna array response and of the radiation power pattern. The actual channel quality experienced by the user will then depend on the overall channel simulation parameters.

III. DMIMO WITH MULTI-RIS SYSTEM

In this section we present the techniques implemented to spatially serve multiple users in a multi-RIS system. The first subsection describes the beam steering approach at the AP, while the second and third subsections describe two different beamforming solution for the RIS. The latter is the one we specifically designed for SDMA.

A. Beam steering at the transmitter side

The joint processing of both the AP-RIS and RIS-UE channels for beamforming can be a complex task. In order to simplify the system we decided to apply a beam steering technique at the AP side, to direct each beam toward a different RIS. To perform the beamsteering we assume, without loss of generality, that the AP knows the angular directions of the RISs; this is indeed realistic, since RISs placement can be considered static (or at least non variable over relatively

[1]We remark that our study is focused on phase control only.

[2]A planned extension of our investigation includes also the adoption of more refined, measurements-based PL models provided in [14].

[3]For sake of simplicity, we only analyze the case of uniform transmit power splitting among the available RISs.

long time periods). The effectiveness of this strategy will then depend on the strength of the LOS link relative to the other signal paths. The (length-N_t) beamsteering vector $\mathbf{v}_r$ toward RIS r can be computed as:

$$\mathbf{v}_r = \frac{1}{\sqrt{N_t}} e^{-j2\pi d(\sin(\theta_r)\sin(\phi_r)n_y + \cos(\theta_r)n_z)/\lambda} \tag{8}$$

with $n_y = [0, \ldots, N_{ty}]$ and $n_z = [0, \ldots, N_{tz}]$ the transmitter antenna element indexes along the y-axis and z-axis respectively, and $d = \lambda/2$ the inter-element spacing. After applying this beamforming vector, the equivalent channel between the AP and the RIS r $\mathbf{h}_r^{eq}$, is a $N \times 1$ vector given by:

$$\mathbf{h}_r^{eq} = \mathbf{H}_r^{\mathrm{RIS}} \mathbf{v}_r. \tag{9}$$

B. Maximum Ratio Beamforming (MRB)

In order to maximize the signal power received by the user, a beamforming technique can be applied by the suitable tuning of the RIS phase shifts. In case of a single RIS, and assuming that the link between the AP and the UE is severely disrupted (blocked), the optimal solution is to match the phase shift of the RIS element θ_n with the phase shift resulting from the AP-RIS link and RIS-UE link ([17], [18]):

$$\theta_n = -\arg(g_r) - \arg(h_n). \tag{10}$$

In our scenario, this beamforming technique, namely Maximum Ratio Beamforming (MRB), could lead to high interference between the users, due to the spatial correlation among them. A beamforming technique with good interference management capabilities must be then designed and adopted.

C. SLNR-based Genetic Algorithm

Multi-user communications literature offers many alternative precoding techniques to tackle the interference suppression in MIMO systems, such as the SLNR precoder scheme, widely adopted for SDMA. It aims at minimizing the *leakage* [19], defined as the interference caused by a fixed user to all the remaining ones. With reference to a generic multi-user system, let us consider the channel matrix of the i-th user $\mathbf{H}_i$ with size $[N_r \times N_t]$ and the precoding matrix of the k-th user $\mathbf{P}_k$ with size $[N_t \times L]$, where L is the number of data streams per user. In this framework, the *leakage* generated by user k can be expressed as:

$$\textstyle\sum_{i=1,\, i\neq k}^{K} \|\mathbf{H}_i \mathbf{P}_k\|_F^2 \tag{11}$$

where $\|\cdot\|_F^2$ is the Frobenius norm. The metric to be maximized by the chosen precoder is the so called SLNR, i.e. the ratio between the useful signal power for user k and the noise σ_k^2 plus the corresponding *leakage*:

$$\mathrm{SLNR}_k = \frac{\|\mathbf{H}_k \mathbf{P}_k\|_F^2}{N_r \sigma_k^2 + \|\widetilde{\mathbf{H}}_k \mathbf{P}_k\|_F^2} \tag{12}$$

where:

$$\widetilde{\mathbf{H}}_k = [\mathbf{H}_1 \ \cdots \ \mathbf{H}_{k-1} \ \mathbf{H}_{k+1} \ \cdots \ \mathbf{H}_K]^{\mathsf{T}} \tag{13}$$

is an extended $N_r(K-1) \times N_t$ channel matrix that only excludes the *leaking* user k. It is shown in [20] and [11] that the expression of the optimal precoder under a SLNR-based criterion is linked to the solution of the generalized eigenvalue problem. In a multi-RIS framework, the SLNR expression for user k and RIS r can be adapted as

$$\mathrm{SLNR}_{r,k}^{\mathrm{RIS}} = \frac{\|\mathbf{G}_{r,k} \boldsymbol{\Theta}_r (\mathbf{H}_r^{\mathrm{RIS}} \mathbf{p}_r)\|_F^2}{\sigma_k^2 + \|\widetilde{\mathbf{G}}_{r,k} \boldsymbol{\Theta}_r (\mathbf{H}_r^{\mathrm{RIS}} \mathbf{p}_r)\|_F^2} \tag{14}$$

where:

$$\widetilde{\mathbf{G}}_{r,k} = [\mathbf{G}_{r,1} \ \cdots \ \mathbf{G}_{r,k-1} \ \mathbf{G}_{r,k+1} \ \cdots \ \mathbf{G}_{r,K}]^{\mathsf{T}} \tag{15}$$

is an extended $N_r(K-1) \times N$ channel matrix that only excludes user k for RIS r. In (14) $\mathbf{p}_r$ is a single column vector since we are considering $L = 1$. However, the SLNR-based scheme requires both amplitude and phase tuning of the antenna elements. This is in contrast with the semi-passive RISs we are considering in our system. Moreover, actual RISs adopt antenna elements with 1-bit or 2-bit phase resolution (4-bit resolution RISs have been considered in [21]). For this reason, we restrict the solution to be found in the search space composed by phase matrices with phase shifts in the set $\{0, \pi/2, \pi, 3\pi/2\}$. Given these considerations, the SLNR cannot be directly adopted here, but we design an iterative optimization approach based on the Genetic Algorithm, where SLNR is the optimization metric. Thus, we can still take advantage of the SLNR definition to tune the RIS independently for each user, but satisfy the constraints given by the nature of the RISs, to estimate a capacity bound for this systems.

In particular, given a population of phase matrix candidates (chromosomes analog in our setting), the cost of each chromosome is the SLNR computed with that matrix, and a fitness measure is assigned. Then, the GA must update the present population to get a new generation, through two characteristic operations:

- Crossover: recombination of chromosomes by splitting parents (chromosomes from the actual generation) at a random crossover point, and then creating children (chromosomes of the successive generation) by exchanging tails. The chromosomes with an higher fitness value will be chosen for crossover with an higher probability.
- Random mutation: local random modification of a gene of the chromosome, preventing falling in local minima. If it is applied too often, GA becomes equivalent to a random search.

The population of the new generation will be then composed by new chromosomes obtained with these operations, and a certain number of *elite* chromosomes, i.e. those with the best fitting metric from the previous generation. The new cost for each chromosome in the new population is recomputed, and the algorithm is iterated until a stopping point (e.g. maximum number of generations) is reached. Although convergence of a GA is not guaranteed, it is still a powerful tool and proved effective in tuning RIS phases for interference suppression. Moreover, we try to improve the starting condition of this algorithm by forcing the initial population to contain one matrix given by the MRB and one given by the SLNR

TABLE I
GA PARAMETERS.

PARAMETER	VALUE
Population size (# chromosomes)	10
Chromosome size (# genes)	N
Generation count limit (# iterations)	100
Elitism (# chromosomes kept at each generation)	2
Random mutation probability	0.1
Crossover probability	1

precoding, suitably quantized and normalized. A summary of the main parameters of the GA is reported in Table I. The use of GA is demanding from a complexity point of view, and could not be easily implementable in real systems. An exception could be represented by slow varying channels, where mobility is not a concern. Since we are more interested in investigating the capabilities of this system, than the actual implementation, we temporarily neglect complexity issues. Moreover, the assumed perfect channel knowledge is one of the main open problems for RIS-aided communications [22], [23]. We leave the analysis of these problems for future studies.

D. User-RIS assignment

Since the multi-user capabilities are obtained by exploiting different RISs, an important aspect is the assignment of the users to the RISs. The main constraint is that each user must be assigned to at least one RIS. A possible solution is to sequentially assign a user the RIS with the maximum channel quality, until all the RISs have been assigned. However, spatial correlation among users could degrade the effectiveness of this assignment. More sophisticated solutions (e.g. taking into account the *leakage*) could be considered, but this step could lead to a further increase in the overall complexity, therefore it is postponed for future investigations.

E. System performance assessment

The Signal-to-Interference-Plus-Noise-Ratio (SINR) at a certain user k can be computed as the sum of the contributions of the RISs assigned to user k, divided by the the noise power plus the sum of the interference caused by all the other RISs, serving different users:

$$\mathrm{SINR}_k^{(\mathcal{R}_k)} = \frac{\sum_{r\in\mathcal{R}_k} \left|\mathbf{G}_{r,k}\boldsymbol{\Theta}_r(\mathbf{H}_r^{\mathrm{RIS}}\mathbf{v}_r)\right|^2}{N_r\sigma_k^2 + \sum_{j\in\overline{\mathcal{R}}_k} \left|\mathbf{G}_{j,k}\boldsymbol{\Theta}_j(\mathbf{H}_j^{\mathrm{RIS}}\mathbf{v}_j)\right|^2} \quad (16)$$

where $\overline{\mathcal{R}}_k$ is the complementary set of $\mathcal{R}_k$ on $\mathcal{M}_{\mathrm{RIS}}$. The capacity given by a multi-RIS system serving one user can be computed as,

$$C_{\mathrm{MR}} = B\log_2\left(1+\mathrm{SINR}_k^{(\mathcal{M}_{\mathrm{RIS}})}\right) \quad (17)$$

where B is the bandwidth, while the sum-rate in a multi-user multi-RIS system is given by

$$R_{\mathrm{MU-MR}} = \sum_{k=1}^{K} B\log_2\left(1+\mathrm{SINR}_k^{(\mathcal{R}_k)}\right). \quad (18)$$

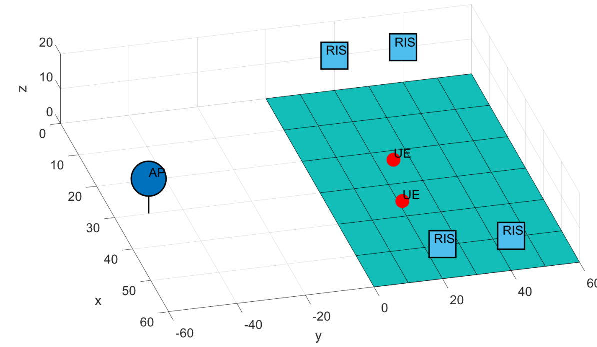

Fig. 2. System instance with 2 users, 4 RISs and AP-distance 50 m from the area of interest.

TABLE II
MAIN SIMULATION PARAMETERS.

PARAMETER	VALUE
Carrier frequency f_c	28 GHz
Bandwidth B	20 MHz
Noise figure F	7 dB
Maximum TX power P_t	47 dBm
Area dimension (rectangular) $L_1 \times L_2$	60 m $\times$ 60 m
AP distance from area	$[0,\ldots,300]$ m
Number of users K	$\{1,2,3,4,6,8,10,12\}$
Number of RIS per user	from 1 up to 4
Polarization pol	single
Total elements per RIS N	100
Total antennas per AP N_t	32
Total antennas per UE N_r	1

IV. RESULTS AND DISCUSSION

The main design parameters can be found in Table II. Fig. 2 is an instance of the system we are considering, where 4 RISs are equi-spaced along two edges of the considered rectangular area, the positions of 2 users are randomly generated, and the AP is set at a distance of 50 m from the area where users can be placed.

We later exploit different configurations, where many different numbers of users are considered, while user spatial coordinates are independently and uniformly distributed over the area.

Fig. 3 depicts the Cumulative Distribution Function (CDF) of the users SINR for different combinations of users and/or RISs. The number of RISs is always equal or larger than the number of users to be served. It can be seen how increasing the number of users leads to a smaller SINR value for the single user, due to the power splitting among them and the rising of inter-user interference. For $K = 2$, the two implemented techniques have similar performance, but GA guarantees a more uniform SINR behaviour, while with MRB some users are more disadvantaged than others. However, already from $K = 4$ the interference disrupts the transmission quality for MRB, whereas GA proves indeed effective in interference reduction. Finally, for $K = 8$, GA significantly outperforms MRB (about 10 dB).

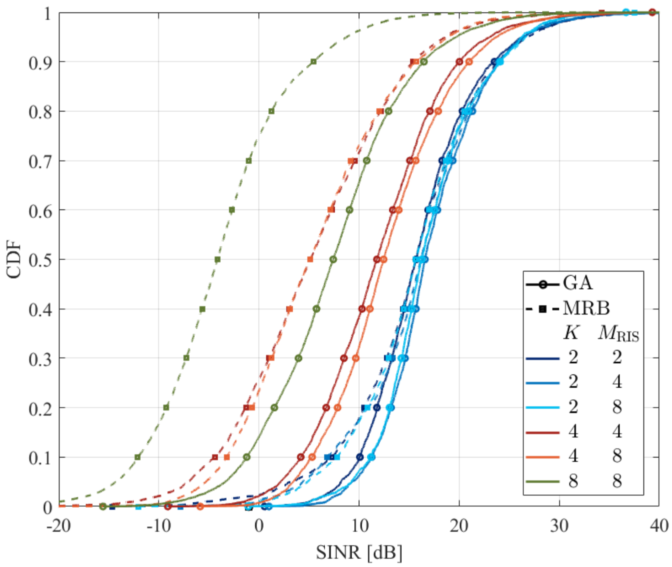

Fig. 3. CDF of users SINR with AP distance of 50 m.

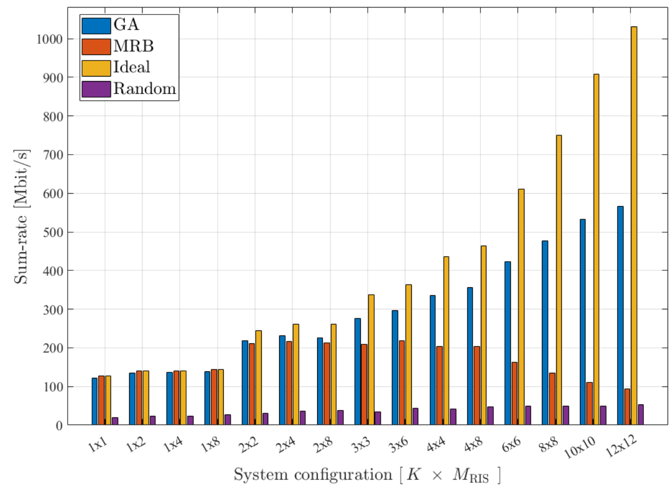

Fig. 4. Sum-rate performance with AP distance of 50 m.

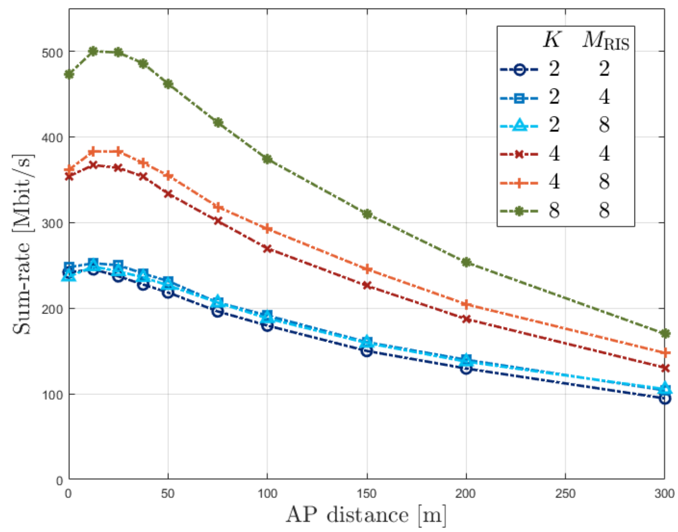

Fig. 5. Sum-rate with respect to the AP distance from area with GA.

In Fig. 4, a larger set of parameter configurations are compared, in terms of the sum-rate. Moreover, we report also the results for an ideal interference-free case ("Ideal"), as a benchmark, and the results from a random RIS phase shifts assignment ("Random"). As for the previous figure, GA algorithm shows great improvements relative to the MRB for $K = 4$ and $K = 8$. As expected, interference is still reducing the maximum achievable rate, but GA can counteract it pretty well. Another interesting aspect is that having more RISs for each user has some benefits only for larger number of users. There are two main reasons for this; first of all, deploying a larger number of RISs implies both transmit power splitting and an increased beamforming complexity, therefore reducing the link budget; on the other hand, RIS assignment could produce some mismatch, so once we assign the first RIS to each user, the remaining ones could have not very good channel qualities. An idea could then be to just assign one RIS to a user and leave the remaining RISs unused, thus increasing the power per RIS. Nevertheless, the collected results show that the overall capacity can be improved by serving more users in parallel with multiple RIS, even if increasing the number of users beyond a certain value (e.g. $K = 8$) could not be a viable solution for this scenario.

In Fig. 5 we compare the effect of different AP distances from the area, for a given subset of previously analyzed UE-RIS configurations. As expected, sum-rate decreases as distance increases, but a maximum value of the sum-rate is observed when the AP is about 25 meters far from the area. This behavior is caused by the angular spread of the field radiation pattern of the transmitter, whereby gain is higher when the receiver angular direction is closer to the direction perpendicular to the planar antenna array. Thus, when the AP moves far from the area, the RISs angular spread is narrower, causing an initial increase of the performance, soon overtaken by the overall distance impact. We remark that this holds when the AP is directly facing towards the area, but not in presence of a generic tilting. Nonetheless, blockage of the direct path AP-UE somewhat implies that the considered framework assumes the AP not to be very close to the area.

V. Conclusions

In this paper we proposed an approach for RIS exploitation in DMIMO wireless networks. In particular, we designed a low-cost multi-RIS system able to improve network capacity through SDMA, even in scenarios where there is no direct link between the users and the AP. With a large number of antennas and RIS elements, effective interference-suppressing techniques can be used to serve multiple users in parallel. GA optimization is exploited to jointly shape the phase matrices for each RIS, mitigate the inter-user interference on a leakage-based criterion. A realistic 2-bit resolution has been considered for phase control of the antenna elements.

Our system design strategy proves effective for interference suppression and outperforms a MRB scheme, at the price of a non-negligible computational complexity, whose possible reduction, along with the management of further issues like the RIS-user association optimization, will be tackled in future work.

ACKNOWLEDGMENT

Riccardo Tuninato acknowledges support from TIM S.p.A. through the PhD scholarship.

Computational resources were also provided by HPC@POLITO, a project of Academic Computing within the Department of Control and Computer Engineering at the Politecnico di Torino (http://www.hpc.polito.it).

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