Separable MSE-based design of two-way multiple-relay cooperative MIMO networks

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Abstract—We consider the problem of jointly optimizing terminal precoder/decoders and relay forwarding matrices – on the basis of the sum mean-square-error (MSE) criterion – in multiple-input multiple-output two-way relay systems, where two multi-antenna nodes mutually exchange information via multi-antenna amplify-and-forward relays. This problem is non-convex and a local optimal solution is typically found by using iterative algorithms based on alternating optimization. We show how the constrained minimization of the sum-MSE can be relaxed to obtain two separated subproblems which, under mild conditions, admit a closed-form solution. Compared to iterative approaches, the proposed design is computationally more affordable and its performance exhibits a better scaling in the number of relays.

Index Terms—Amplify-and-forward (non-regenerative) relays, minimum-mean-square-error criterion, multiple-input multiple-output (MIMO) systems, optimization, two-way relaying.

I. INTRODUCTION

COOPERATIVE multiple-input multiple-output (MIMO) communication techniques, wherein data exchange between MIMO terminal nodes is assisted by one or multiple MIMO relays, have received a great deal of attention in the recent literature, since they assure significant performance gains in terms of coverage, reliability, and capacity [1]–[3]. Many relaying protocols operate in half-duplex mode, where two time slots are required to perform a single transmission, due to the inability of the relays to receive and transmit at the same time. To overcome the inherent halving of spectral efficiency, a possible remedy is to adopt two-way relaying (Fig. 1), which works as follows: (i) in the first slot, the two terminal nodes simultaneously transmit their signals to the relays; (ii) in the second slot, the relays precode and forward the received signals to the terminals. Since each terminal knows its own transmitted signal, the effects of self-interference can be subtracted from the received signal at the terminals, and the data of interest can be decoded.

Recently, design and performance analysis of two-way cooperative MIMO networks encompassing multiple amplify-and-forward (AF) or non-regenerative relays has been considered in several papers [4]–[9]. Compared with the single-relay case [10], the multiple-relay scenario generally leads to more challenging nonconvex constrained optimization problems, which are usually solved by burdensome iterative procedures. In [4], by adopting a weighted sum mean-squared error (MSE) or a sum-rate cost function, iterative gradient descent optimization algorithms are proposed, with transmit-power constraints imposed at the terminals and at the relays. A similar scenario is considered in [5] and [6]; in the former, the original minimum sum-MSE nonconvex optimization problem is decomposed in convex subproblems, which are iteratively solved; in the latter, an iterative procedure is proposed, based on the matrix conjugate gradient algorithm, which is shown to converge faster than conventional gradient descent methods. A similar scenario (without precoding at the terminals) is considered in [7], where minimization of a sum-MSE upper bound is considered, which leads to a convex problem, under a constraint on the total power transmitted by the relays. Some recent papers [8], [9] propose architectures for two-way relaying based on relay/antenna selection strategies.

In this paper, capitalizing on the results of [11] for a one-way scenario, we propose an optimization algorithm for two-way AF MIMO relaying networks, where terminal precoder/decoders and relay forwarding matrices are jointly derived under power constraints on the transmitted/received power at the terminals. Rather than attempting to solve it iteratively, we derive a relaxed version of the original minimum sum-MSE nonconvex optimization, which allows one to decompose it in two separate problems that admit a closed-form, albeit suboptimal, solution. We show by Monte Carlo simulation results that our approach performs comparably or better than other approaches proposed in the literature, especially for increasing values of the number of relays, and, moreover, it requires a reduced computational burden compared to iterative designs.

The paper is organized as follows. In Section II, the model of the two-way MIMO network is presented and the basic assumptions are introduced. In Section III, the proposed design is derived and discussed. Monte Carlo simulation results are reported in Section IV and conclusions are drawn in Section V.

II. NETWORK MODEL AND BASIC ASSUMPTIONS

We consider the two-way MIMO network configuration of Fig. 1, where bidirectional communication between two terminals, equipped with $N_{T,1}$ and $N_{T,2}$ antennas, respectively, is assisted by $N_{C}$ half-duplex relays, each equipped with $N_{R}$ antennas. We assume that there is no direct link between the two terminals, due to high path loss values or obstructions.
Let $s_1 \in \mathbb{C}^{N_1 \times 1}$ and $s_2 \in \mathbb{C}^{N_2 \times 1}$ denote the symbol vectors to be transmitted by terminal 1 and 2, respectively. In the first time slot, each terminal precodes its symbols with matrix $P_i \in \mathbb{C}^{N_{t,i} \times N_{s,i}}$, for $i \in \{1, 2\}$, before transmitting it to the relays, which thus receive

$$y_k = \sum_{i=1}^{2} H_{i,k}P_i s_i + w_k$$

for $k \in \{1, 2, \ldots, N_c\}$, where $H_{i,k} \in \mathbb{C}^{N_{c} \times N_{t,i}}$ is the first-hop channel matrix (from terminal $i$ to relay $k$), and $w_k \in \mathbb{C}^{N_{c}}$ models additive noise at $k$th relay. By defining $y_k \triangleq [y_{k1}^T, y_{k2}^T, \ldots, y_{kN_c}^T]^T \in \mathbb{C}^{N_{c} \times N_{c}}$, the overall signal received by the relays can be compactly written as

$$y = \sum_{i=1}^{2} H_i P_i s_i + w$$

where $H_i \triangleq [H_{i,1}^T, H_{i,2}^T, \ldots, H_{i,N_c}^T]^T \in \mathbb{C}^{N_{c} \times N_{t,i}}$ gathers all first-hop channels and $w \triangleq [w_1^T, w_2^T, \ldots, w_{N_c}^T]^T \in \mathbb{C}^{N_{c} \times N_{c}}$.

In the second time slot, the $k$th relay forwards its received signal $y_k \in \mathbb{C}^{N_{c}}$, by using the relaying matrix $F_k \in \mathbb{C}^{N_{c} \times N_{c}}$, transmitting thus $z_k = F_k y_k$. The received signal at each terminal can be written, for $i \in \{1, 2\}$, as

$$r_i = \sum_{k=1}^{N_c} G_{i,k} F_k y_k + n_i$$

where $G_{i,k} \in \mathbb{C}^{N_{r,i} \times N_{c}}$ is the second-hop channel matrix (from relay $k$ to terminal $i$), and $n_i \in \mathbb{C}^{N_{r,i}}$ is additive noise at terminal $i$. Eq. (3) can be compactly expressed as

$$r_i = G_i F y + n_i$$

by defining $G_i \triangleq [G_{i,1}, G_{i,2}, \ldots, G_{i,N_c}] \in \mathbb{C}^{N_{r,i} \times N_{c}} N_{c}$ and $F \triangleq \text{diag}(F_1, F_2, \ldots, F_{N_c})$. Moreover, by taking into account (3), vector $r_i$ can also be directly written in terms of $s_1$ and $s_2$ as

$$r_i = \sum_{j=1}^{2} C_{i,j} s_j + v_i$$

where, for $i, j \in \{1, 2\}$, $C_{i,j} \triangleq G_i F H_j P_j \in \mathbb{C}^{N_{r,i} \times N_{t,j}}$ is the dual-hop matrix from terminal $j$ to $i$, and $v_i \triangleq G_i F w + n_i \in \mathbb{C}^{N_{r,i}}$ is the equivalent noise vector at terminal $i$.

We assume customarily [8] that each terminal can estimate and subtract the self-interference deriving from its own symbols. Thus by redefining $r_i$ with a slight abuse of notation as $r_i - C_{i,i} s_i$, for $i \in \{1, 2\}$, we write explicitly

$$r_i = C_{i,2} s_2 + v_i = G_i F H_2 P_2 s_2 + v_i$$

where $i = 2$ when $i = 1$, whereas $i = 1$ when $i = 2$.

At terminal $i$, vector $r_i$ is subject to linear equalization through matrix $D_i \in \mathbb{C}^{N_{c} \times N_{r,i}}$, thus yielding a soft estimate $\hat{s}_i \triangleq D_i r_i$ of the symbols $s_i$ transmitted by terminal $i$, whose entries are then subject to minimum-distance hard decision.

In the sequel, we consider the common assumptions: (a1) $s_1$ and $s_2$ are mutually independent zero-mean circularly symmetric complex (ZMCS) random vectors, with $\mathbb{E}[s_i s_i^H] = I_{N_{s,i}}$, for $i \in \{1, 2\}$; (a2) the entries of $H_i$ and $G_i$ are independent identically distributed ZMCS Gaussian unit-variance random variables, for $i \in \{1, 2\}$; (a3) the noise vectors $w$, $n_1$, and $n_2$ are mutually independent ZMCS Gaussian random vectors, statistically independent of $\{s_i, H_i, G_i\}_{i=1}^{2}$, with $\mathbb{E}[w w^H] = \sigma_n^2 I_{N_{c}}$ and $\mathbb{E}[n_i n_i^H] = \sigma_n^2 I_{N_{r,i}}$, for $i \in \{1, 2\}$.

Full channel-state information (CSI) is assumed to be available at both the terminals and the relays. Particularly, we assume that: (i) $\{H_i\}_{i=1}^{2}$ are known at the terminals and at the relays; (ii) the $k$th second-hop channel matrices $G_{1,k}$ and $G_{2,k}$ are known only to the $k$th relay, for $k \in \{1, 2, \ldots, N_c\}$; (iii) the dual-hop channel matrix $\{C_{i,j}\}$ and the covariance matrix $K_{v,v}$, i.e.,$\mathbb{E}[v_i v_i^H] = \sigma_n^2 G_i F H_i G_i^H + I_{N_{r,i}}$, are known at the $i$th terminal, for $i \in \{1, 2\}$.

III. THE PROPOSED CLOSED-FORM DESIGN

With reference to model (6), the problem at hand is to find optimal values of $\{P_i\}_{i=1}^{2}$, $F$, and $\{D_i\}_{i=1}^{2}$ for recovering $s_1$ and $s_2$ according to a certain cost function and subject to suitable power constraints at the terminals and relays.

A common performance measure of the accuracy in recovering the symbol vector $s_i$ at terminal $i$ is the mean-square value of the error $e_i \triangleq \hat{s}_i - s_i$;

$$\text{MSE}_i \triangleq \mathbb{E}[\|e_i\|^2] = \text{tr}(K_{v,v} e_i e_i^H) \quad (7)$$

where $K_{v,v} \triangleq \mathbb{E}[v_i v_i^H]$ is the error covariance matrix, which depends on $\{P_i, F, D_i\}_{i=1}^{2}$. As a global cost function for the overall two-way transmission, we consider as in [4]–[8] the sum-MSE, defined as

$$\text{MSE}(\{P_i\}_{i=1}^{2}, \{D_i\}_{i=1}^{2}) = \text{MSE}_1 + \text{MSE}_2 \quad (8)$$

It is well-known (see, e.g., [12]) that, for fixed values of $\{P_i\}_{i=1}^{2}$ and $F$, the matrices $\{D_i\}_{i=1}^{2}$ minimizing the sum-MSE are the Wiener filters

$$D_{i,\text{mmse}} = C_{i,i}^H (C_{i,i} C_{i,i}^H + K_{v,v})^{-1} \quad (9)$$

for $i \in \{1, 2\}$. Substituting $D_{i,\text{mmse}}$ into (8) yields

$$\text{MSE}(\{P_i\}_{i=1}^{2}, F) = \sum_{i=1}^{2} \text{tr}[(I_{N_{s,i}} + C_{i,i}^H K_{v,v}^{-1} C_{i,i})^{-1}] \quad (10)$$

Hereinafter all the ensemble averages are evaluated for fixed values of the first- and second-hop channel matrices.
where it should be remembered that $C_{t,j} = G_t^* F H_t P_j$ and $K_{v,v_i} = \sigma_w^2 G_t^* F^H G_t^* + I_{N_{F,v_i}}$. It is noteworthy that the variables $P_1$, $P_2$, and $F$ are coupled in (40) and, hence, the two terms in (40) cannot be minimized independently. In this case, there are techniques (see, e.g., [9]) that minimize (40) with suitable constraints by iteratively solving a sequence of simpler problems. Herein, we pursue a completely different approach that consists of relaxing the problem so as to render the minimization of the two terms in (40) separable.

As a first step, we observe that minimizing (40) is complicated by the presence of $K_{v,v_i}^{-1}$ which depends non-trivially on $F$. By invoking [11] Lemma 1 we consider instead minimization of the following lower bound:

$$
\text{MSE}_{\text{min}}(\{P_i\}_{i=1}^2, F) = \sum_{i=1}^2 \text{tr}[I_{N_{s,i}} + \sigma_w^{-2} C_{t,j}^H C_{t,j}]^{-1}]
$$

Suitable constraints must be set to avoid trivial solutions in minimizing (41). It is customary to impose power constraints to limit the average transmit power at the terminals:

$$
E[\|\|P_i s_i\|^2] = \text{tr}(P_i P_i^H) \leq P_{T,i} > 0
$$

for $i \in \{1, 2\}$. In order to limit $F$, as in [11], [13], [14], we impose a constraint on the average power received at the terminals in the second time slot, i.e., with reference to (4), we attempt to limit, for $i \in \{1, 2\}$, the following quantities:

$$
E[\|G_i F y\|^2] = \text{tr}(G_i F K_{v,v_i} F^H G_i^H)
$$

where $K_{v,v_i} \triangleq E[yy^H] = \sum_{i=1}^2 H_i P_i P_i^H H_i^* + \sigma_w^2 I_{N_{F,v_i}}$ is the covariance matrix of $y$. To simplify the constraint, as in [11], we exploit the following chain of inequalities:

$$
\text{tr}(G_i F K_{v,v_i} F^H G_i^H) \leq \text{tr}(G_i F F^H G_i^H) \text{tr}(K_{v,v_i})
$$

$$
= \text{tr}(G_i F F^H G_i^H) \sum_{i=1}^2 \text{tr}(H_i P_i P_i^H H_i^*) + \sigma_w^2 N_{C,N_R}
$$

$$
\leq \text{tr}(G_i F F^H G_i^H) \sum_{i=1}^2 \text{tr}(H_i H_i^*) \text{tr}(P_i P_i^H) + \sigma_w^2 N_{C,N_R}
$$

$$
\leq \text{tr}(G_i F F^H G_i^H) \sum_{i=1}^2 \text{tr}(P_i P_i^H) + \sigma_w^2 N_{C,N_R}
$$

$$
\leq \text{tr}(G_i F F^H G_i^H) N_{C,N_R} \left( \sum_{i=1}^2 N_{T,i} P_{T,i} + \sigma_w^2 \right)
$$

where the last approximate inequality holds noting that, for fixed values of $N_{T,i}$, by the law of large numbers one has $H_i^* H_i/N_{C,N_R} \rightarrow I_{N_{F,v_i}}$, almost surely as $N_{C,N_R}$ gets large. Therefore, if we impose $\text{tr}(G_i F F^H G_i^H) \leq \tilde{P}_{R,i} > 0$, we get

$$
\text{tr}(G_i F K_{v,v_i} F^H G_i^H) \leq \tilde{P}_{R,i} N_{C,N_R} \left( \sum_{i=1}^2 N_{T,i} P_{T,i} + \sigma_w^2 \right).
$$

As in [11], such a choice allows one to considerably simplify the derivation of the optimal solution. In summary, the minimization problem to be solved can be expressed as

$$
\min_{\{P_i\}_{i=1}^2, F} \sum_{i=1}^2 \text{tr}[I_{N_{s,i}} + \sigma_w^{-2} C_{t,j}^H C_{t,j}]^{-1}]
$$

s.t. \begin{align*}
\text{tr}(P_i P_i^H) & \leq P_{T,i} & i \in \{1, 2\}.
\end{align*}

(16)

In order to find a closed-form solution of (16), we introduce $B_t = G_t F \in \mathbb{C}^{N_{t,i} \times N_{C,N_R}}$, with $i \in \{1, 2\}$, and rewrite (16) explicitly as

$$
\min_{\{P_i\}_{i=1}^2, \{B_t\}_{i=1}^2} \sum_{i=1}^2 \text{tr}[I_{N_{s,i}} + \sigma_w^{-2} P_i^H B_t^H B_t P_i]^{-1}]
$$

s.t. \begin{align*}
\text{tr}(P_i P_i^H) & \leq P_{T,i} & i \in \{1, 2\}.
\end{align*}

(17)

Remarkably, the cost function is the sum of two terms: the former one depends only on the variables $\{P_1, B_2\}$, whereas the latter one involves only the variables $\{P_2, B_1\}$. Therefore, (17) can be decomposed in two problems involving $\{P_1, B_2\}$ and $\{P_2, B_1\}$ separately, which can be solved in parallel. Such a property has two main advantages: (i) it allows to obtain a closed-form solution; (ii) it entails a lower computational complexity. Capitalizing on such a decomposition, the solution of (17) can be characterized by the following theorem.

**Theorem 1:** Assume that: (a4) $P_j \in \mathbb{C}^{N_{t,i} \times N_{s,j}}$ is full-column rank, i.e., rank($P_j$) = $N_{S,j} \leq N_{T,i}$, $i \in \{1, 2\}$; (a5) $B_t H_i \in \mathbb{C}^{N_{t,i} \times N_{F,v_i}}$ is full-column rank, i.e., rank($B_t H_i$) = $N_{t,i} \leq N_{T,i}$, for $i \in \{1, 2\}$. Moreover, let $H_i = U_{h,i} \Lambda_{h,i} V_{h,i}^H$ denote the singular value decomposition (SVD) of $H_i$, where $U_{h,i} \in \mathbb{C}^{N_{C,N_R} \times N_{C,N_R}}$ and $V_{h,i} \in \mathbb{C}^{N_{h,i} \times N_{F,v_i}}$ are the unitary matrices of left(right) singular vectors, and $\Lambda_{h,i} \in \mathbb{C}^{N_{C,N_R} \times N_{C,N_R}}$ is the rectangular diagonal matrix of the corresponding singular values arranged in increasing order. Then, the solution of (17) has the following general form:

$$
P_i = V_{h,i,\text{right}} \Omega_i
$$

$$
B_2 = Q_2 \Delta_{L,\text{right}}^H
$$

where $V_{h,i,\text{right}}$ contains the $N_{S,i}$ rightmost columns of $V_{h,i}$, $U_{h,i,\text{right}}$ contains the $N_{S,i}$ rightmost columns of $U_{h,i}$, the diagonal matrices $\Omega_i \in \mathbb{R}^{N_{s,j} \times N_{s,j}}$ and $\Delta_{L,\text{right}} \in \mathbb{R}^{N_{F,v_i} \times N_{F,v_i}}$ will be specified soon after, and $Q_2 \in \mathbb{C}^{N_{t,i} \times N_{S,j}}$ is an arbitrary semi-unitary matrix, i.e., $Q_2^H Q_2 = I_{N_{s,j}}$.

**Proof:** See [11] Appendix II.

**Remark 1:** (a4) implies that $N_{S,i} \leq N_{T,j}$, $i \in \{1, 2\}$.

**Remark 2:** (a5) implies that $N_{T,1} = N_{T,2}$ and, hence, in the following we set $N_T \triangleq N_{T,1} = N_{T,2}$.

Theorem 1 allows one to rewrite the optimization problem
in a simpler scalar form:

\[
\begin{aligned}
\min_{\{z_{i,\ell}, w_{i,\ell}\}_{\ell=1}^{N_S,i}} & \sum_{i=1}^{2} \sum_{\ell=1}^{N_S,i} \frac{1}{n_{i,\ell}} \sigma_n^{2} + \frac{1}{\lambda_i(H_i)} z_{i,\ell} w_{i,\ell} \\
\text{s.t.} & \\
& \sum_{\ell=1}^{N_S,i} z_{i,\ell} \leq P_{T,i}, \\
& \sum_{\ell=1}^{N_S,i} w_{i,\ell} \leq \tilde{\Omega}_k, \\
& w_{i,\ell}, z_{i,\ell} > 0 \quad \forall \ell \in \{1, 2, \ldots, N_S,i\}
\end{aligned}
\]  

(20)

with \(z_{i,\ell}\) and \(w_{i,\ell}\) representing the \(\ell\)th squared diagonal entry of \(\Omega_i\) and \(\Delta_i\), respectively, whereas \(\lambda_i(H_i)\) denotes the \(\ell\)th nonzero singular value of \(H_i\), for \(\ell \in \{1, 2, \ldots, N_T\}\). Similarly to (17), problem (20) can be decomposed into two separate problems involving disjoint subsets of variables.

It can be shown, with straightforward manipulations, that the objective function in (20) is convex if and only if

\[
z_{i,\ell} w_{i,\ell} \geq \frac{\sigma_n^2}{\lambda_i(H_i)} \quad \forall \ell \in \{1, 2, \ldots, N_S,i\}, \quad \text{with } i \in \{1, 2\}. \tag{21}
\]

To calculate the relaying matrices, let us partition solution (19) as \(B_i = [B_{i,1}, B_{i,2}, \ldots, B_{i,N_S,i}]\), with \(B_{i,k} \in \mathbb{C}^{N_T \times N_k}\) and \(i \in \{1, 2\}\). Defining \(G_k \triangleq [G_{1,k}^T, G_{2,k}^T]^T \in \mathbb{C}^{2N_T \times N_k}\) and \(B_k \triangleq [B_{1,k}^T, B_{2,k}^T]^T \in \mathbb{C}^{2N_T \times N_k}\), assuming that \(G_k\) is full-row rank, i.e., \(\text{rank}(G_k) = 2N_T \leq N_R\), with \(k \in \{1, 2, \ldots, N_C\}\), the \(k\)th relay can construct its own relaying matrix by solving the matrix equation \(G_k F_k = B_k\), whose minimum-norm solution (15) is given by

\[
F_k = G_k^\dagger B_k \tag{22}
\]

where the superscript \(\dagger\) denotes the Moore-Penrose inverse.

A step-by-step description of the proposed design algorithm is reported in Tab. I. The convex optimization in step 3) can be efficiently carried out using standard techniques, such as the interior-point methods. Moreover, an approximate closed-form solution can be obtained by generalizing the derivations of (11). Finally, similarly to (11), the advantage of having a closed-form design would allow one to perform a theoretical performance analysis in rather simple terms. In particular, it can be proven that the proposed system can achieve a diversity order that increases linearly with the number \(N_C\) of relays.

### IV. Simulation Results

In this section, to assess the performance of the considered design, we present the results of Monte Carlo computer simulations, aimed at evaluating the average (with respect to channel realizations) symbol-error probability (ASEP) of the proposed cooperative two-way MIMO system. We consider a network encompassing two terminals equipped with \(N_T = 2\) antennas, and transmitting QPSK symbols with \(N_S,1 = N_S,2 = 2\). The \(N_C\) relays are equipped with \(N_R = 4\) antennas. We also assume that \(P_{T,1} = P_{T,2} = P_k = P\), for all \(k \in \{1, 2, \ldots, N_C\}\), where \(P_k\) represents the average transmitted power at the \(k\)th relay, and set \(\sigma_n^2 = \sigma_n^2 = 1\). Consequently, we define SNR \(\triangleq P\), which measures the per-antenna link quality of both the first- and second-hop transmissions. The ASEP is evaluated by carrying out \(10^3\) independent Monte Carlo trials, with each run using independent sets of channel realizations and noise, and an independent record of \(10^3\) source symbols.

In Figs. 2-4, we report the ASEP for different values of the number \(N_C \in \{2, 3, 4\}\) of relays. We compare the performances of our closed-form design (labeled as “Proposed”) to those of the iterative technique proposed in [5] employing different number of iterations, ranging in \(\{1, 2, 5, 10\}\). It is worthwhile to note that both the strategies under comparison require the same amount of CSI. Furthermore, since the method of [5] imposes different power constraints on the design of the relaying matrices, our solutions for \(\{F_k\}_{k=1}^{N_C}\)
are properly scaled so as to ensure that the average power transmitted by each relay is the same for both methods. Results in Fig. 2 for $N_r = 2$ relays show that the proposed closed-form design, based on the solution of the relaxed problem (17), exhibits performances comparable with the iterative solution of [5] in the considered range of SNR values only when the latter employs more than 5 iterations. Figs. 3 and 4 show that, as the number of relays increases, the proposed method clearly outperforms the method of [5] even when the latter employs the maximum number of iterations. The benefits of the proposed approach are even more interesting if we take into account that the method of [5], due to its iterative nature, is not separable and generally involves a larger computational complexity in comparison to our design.

V. CONCLUSIONS

We tackled the joint sum-MSE design of terminal precoder/decoders and relay forwarding matrices for AF MIMO two-way relay systems. We showed that a relaxed version of such a problem can be separated into two simpler ones, which can be solved in closed-form in parallel. Compared to iterative methods, the proposed approach exhibits a performance gain for increasing number of relays and a reduced computational complexity.

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