

Distributed Space-Time Block Coding Scheme in In-band Full Duplex Relaying Networks

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Abstract—This paper proposes a cooperative scheme for in-band full duplex (IFD) in a one-way two-hop relaying system. The proposed scheme realizes collocated space-time block coding by applying both of the superposition coding at the source and the IFD mode at the relay. The achievable rate of the proposed scheme is derived for fixed relay channel gains and compared to those of the upper-bound IFD as well as existing IFD relaying schemes. Our achievable-rate results elucidate that our scheme is close to the upper-bound IFD than any other scheme.

Keywords— In-band full duplex, capacity, superposition coding

I. INTRODUCTION

Capacity analyses corresponding to duplex mode and transmission protocol with cooperative relays have been studied in [1]-[5]. Generally, the baseline assumption is half-duplex (HD), where two orthogonal times are required for signal reception and transmission at the relay node. However, with recent breakthroughs in technology, in-band full-duplex (IFD) relaying that allows simultaneous reception and transmission at the same frequency band is becoming accelerated, even for the nomadic small-size relay [6], [7] as well as for the physically isolated relay between the transmitter and receiver [8]. Since self-interference is substantially mitigated to the noise level by a combination of analog and digital interference cancellation techniques [7], it is not considered in this paper.

Authors in [2] derived the information-theoretic Ergodic capacities of spectrally efficient amplify-and-forward (AF) and decode-and-forward (DF) relaying schemes that considered implement varying degrees of broadcasting and receive collision in single-relay channel. Another DF scheme based on superposition coding (SC) [3] was proposed. However, these works focused only on HD. In [4], the fundamental capacity of an IFD/AF scheme under the influence of self-interference was derived, but a direct link between the source and the destination nodes was not considered. Recently, in [5], the information-theoretic analysis in [2] was extended to both IFD/AF and IFD/DF relaying schemes under a virtual antenna array realizing spatial diversity. Although this work [5] has shown that IFD relaying achieves higher capacity than HD relaying, however, there was no specific signal design for the IFD/DF scheme. To the best of the authors' knowledge, there may be no other existing concrete IFD/DF relaying schemes as well.

So as to actualize the collocated space-time block coding scheme to single relay channel in this paper, we propose a concrete signal design solution with a two-step combination of IFD/DF mode, space-time coding, and SC procedure. For fixed relay channel gains, we not only state the achievable rates of, the optimal HD [3], existing IFD relaying schemes, and our proposed IFD one, but also the upper-bound IFD capacity obtained from [1] in a two-hop communication system. The capacity analysis shows our proposed scheme provides the higher capacity over aforementioned schemes, and is more close to the upper-bound IFD capacity in the case when the relay node is positioned at the exact center of the source and destination nodes.

II. CHANNEL AND RELAY MODEL ASSUMPTIONS

We consider a three-node cooperative communication system as shown in Figure 1, where S is the source node, R is the relay node, and D is the destination node, where each node is configured with single antenna. R has IFD capability, while S and D all has HD capability. We assume packet-by-packet transmission at S and R . The packet transmitted by S is denoted by the complex-valued vector $\mathbf{x}$, where the k -th element is the k -th modulation symbol. We assume the different symbols are i.i.d with a zero mean, i.e. $\Xi\{x_k\}=0$ and $\Xi\{x_k x_m^*\}=\delta(k-m)$, where $\delta(\cdot)$ is the Kronecker delta.

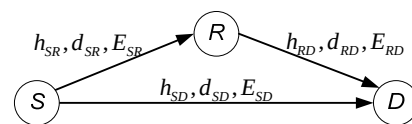


Figure 1. Schematic of fading relay channel

In an information-theoretic sense, the packet length is assumed to be sufficiently large to allow the application of long error-correcting codes to yield a practically zero probability of error. Moreover, as shown in Figure 1, the channel gain, distance, and average received signal power of S to D link are h_{SD} , d_{SD} , and E_{SD} , respectively, those of S to R link are h_{SR} , d_{SR} , and E_{SR} , and those of R to D link are h_{RD} , d_{RD} , and E_{RD} . Lastly, it is assumed as the following: All of the channel gains are constant at least for the duration of two packet lengths, and are i.i.d circularly symmetric complex Gaussian random variables with zero mean and unit variance

(i.e. $\mathcal{CN}(0,1)$) representing Rayleigh flat fading; All of the average received signal powers bag the effects of shadowing, path-loss, and transmit power.

III. SCHEME DESCRIPTIONS AND SIGNAL MODELS

A. Reference IFD/AF scheme

The signal vector $\mathbf{x}$ transmitted by S is received at D over the direct ($S \sim D$) link and at over the $S \sim R \sim D$ paths, where $A \sim B$ denotes the communication link from node A to node B . The received signal vector is given by [2], [5]

$$\begin{aligned} \mathbf{y}_D &= h_c \mathbf{x} + \mathbf{z}_c \\ &= \left(\sqrt{E_{SD}} h_{SD} + \sqrt{\frac{E_{SR} E_{RD}}{E_{SR} + N_0}} h_{SR} h_{RD} \right) \mathbf{x} \\ &\quad + \left(\frac{\sqrt{E_{RD}} h_{RD}}{\sqrt{E_{SR} + N_0}} \mathbf{z}_{SR} + \mathbf{z}_D \right), \end{aligned} \quad (1)$$

Where the scaling factor $\sqrt{\frac{E_{SR}}{E_{SR} + N_0}}$ normalizes the power of the relay signal to unity. Also, $\mathbf{z}_{SR}$ and $\mathbf{z}_D$ are additive white noise vectors whose elements are i.i.d $\mathcal{CN}(0, N_0)$ with unit variance $N_0 = 1$. It is assumed that the processing delay incurred by the relay is less than the guard interval in the cases of single carrier block transmission (SCBC) [9], [10] and orthogonal frequency division multiplexing (OFDM) transmission. In the sequel, unless mentioned otherwise, we assume the same processing delay at the relay and that all noise vectors have the same statistical properties as $\mathbf{z}_D$. Finally in (1), the variance N_0^c of the combined noise $\mathbf{z}_c$ is $1 + (E_{RD} |h_{RD}|^2 / (E_{SR} + 1))$.

B. Reference in-band IFD/DF scheme

In the reference schemes [2], [5], S broadcasts the signal vector $\mathbf{x}$. At the same time, R retransmits the decoded signal vector subjected to a time-step of τ sec so that R waits to receive a packet from S . Assuming that the received signal vector at R is correctly decoded and retransmitted, the “on-time” and “time-shifted” received signals at destination D are, respectively,

$$\mathbf{y}_D = \sqrt{E_{RD}} h_{RD} \hat{\mathbf{x}}_{-\tau} + \sqrt{E_{SD}} h_{SD} \mathbf{x} + \mathbf{z}_D, \quad (2)$$

$$\mathbf{y}_{D+\tau} = \sqrt{E_{RD}} h_{RD} \hat{\mathbf{x}} + \sqrt{E_{SD}} h_{SD} \mathbf{x}_{+\tau} + \mathbf{z}_{D+\tau}. \quad (3)$$

where $\hat{\mathbf{x}}_{-\tau}$ is the delayed decoded and modulated version of $\mathbf{x}$ at R , $\hat{\mathbf{x}}$ is the decoded and modulated version of $\mathbf{x}$ at R , and $\mathbf{x}_{+\tau}$ are the advanced versions of $\mathbf{x}$. Under the assumption of $\hat{\mathbf{x}}_{-\tau} = \mathbf{x}_{-\tau}$ and $\hat{\mathbf{x}} = \mathbf{x}$, from (2) and (3), the effective received signal of this IFD/DF scheme is

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z}$$

$$\begin{bmatrix} \mathbf{y}_D \\ \mathbf{y}_{D+\tau} \end{bmatrix} = \begin{bmatrix} \sqrt{E_{RD}} h_{RD} & \sqrt{E_{SD}} h_{SD} & 0 \\ 0 & \sqrt{E_{RD}} h_{RD} & \sqrt{E_{SD}} h_{SD} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{-\tau} \\ \mathbf{x} \\ \mathbf{x}_{+\tau} \end{bmatrix}^T + \begin{bmatrix} \mathbf{z}_D \\ \mathbf{z}_{D+\tau} \end{bmatrix} \quad (4)$$

with $\Xi\{\mathbf{z}\mathbf{z}^H\} = \mathbf{I}_2$ where $\mathbf{I}_2$ is the 2×2 identity matrix. The channel in (4) is interpreted as a vector multiple-access channel (MAC) [2].

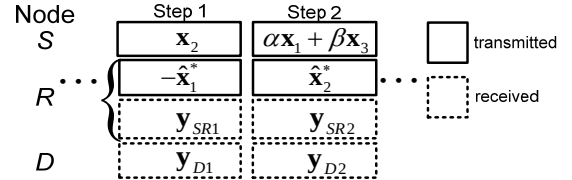


Figure 2. Structure of the proposed in-band IFD/DF scheme.

C. Proposed IFD/DF scheme

The signal design of the proposed IFD/DF scheme is shown in Figure 2 where each coding cycle is comprised of two packets (Steps 1 and 2 in the diagram), α and β are the power-division coefficients with $\alpha^2 + \beta^2 = 1$. In addition, the transmitted packets $\mathbf{x}_1$ and $\mathbf{x}_3$ in Step 2 at S are called the basic packet and the superposed packet, respectively, and each of $-\hat{\mathbf{x}}_1^*$ and $\hat{\mathbf{x}}_2^*$ that is relayed via R is independently coded with a single standard codebook.

In Step 1, S broadcasts the packet $\mathbf{x}_2$ and R transmits¹ the packet $-\hat{\mathbf{x}}_1^*$, which is obtained from the previous superposed signal vector. At the same time, R receives

$$\mathbf{y}_{SR1} = \sqrt{E_{SR}} h_{SR} \mathbf{x}_2 + \mathbf{z}_{SR1} \quad (5)$$

and decodes $\hat{\mathbf{x}}_2$, and D receives

$$\mathbf{y}_{D1} = -\sqrt{E_{RD}} h_{RD} \hat{\mathbf{x}}_1^* + \sqrt{E_{SD}} h_{SD} \mathbf{x}_2 + \mathbf{z}_1. \quad (6)$$

In Step 2, S broadcasts the SC-encoded packet $\alpha \mathbf{x}_1 + \beta \mathbf{x}_3$. Simultaneously, R transmits the packet $\hat{\mathbf{x}}_2^*$, which is obtained by decoding the signal in (5). The relay receives the signal

$$\mathbf{y}_{SR2} = \alpha \sqrt{E_{SR}} h_{SR} \mathbf{x}_1 + \beta \sqrt{E_{SR}} h_{SR} \mathbf{x}_3 + \mathbf{z}_{SR2}, \quad (7)$$

and decodes first $\hat{\mathbf{x}}_1$, and then decodes $\hat{\mathbf{x}}_3$ by subtracting $\alpha \sqrt{E_{SR}} h_{SR} \mathbf{x}_1$ from (7). The recovered $\hat{\mathbf{x}}_3$ is sent to D during Step 1 of the next encoding cycle. As for D , it receives

¹ The packet $\mathbf{x}_1$ is relayed to the destination node in order to be able to obtain the path-loss and space-time coding gains.

$$\begin{aligned} \mathbf{y}_{D2} = & \alpha \sqrt{E_{SD}} h_{SD} \mathbf{x}_1 + \beta \sqrt{E_{SD}} h_{SD} \mathbf{x}_3 \\ & + \sqrt{E_{RD}} h_{RD} \hat{\mathbf{x}}_2^* + \mathbf{z}_2, \end{aligned} \quad (8)$$

where the second component is called *inherent interference*. By assuming $\hat{\mathbf{x}}_1 = \mathbf{x}_1$, $\hat{\mathbf{x}}_2 = \mathbf{x}_2$, and $\hat{\mathbf{x}}_3 = \mathbf{x}_3$, and applying $-h_{RD} y_{D1}^* + h_{SD}^* y_{D2}$ and $\alpha h_{SD}^* y_{D1} + h_{RD} y_{D2}^*$ to (6) and (8), D finally obtains the estimated versions of $\mathbf{x}_1$ and $\mathbf{x}_2$ as

$$\begin{aligned} \tilde{\mathbf{x}}_1 = & \mathbf{x}_1 + (\beta E_{SD} |h_{SD}|^2 / \xi) \mathbf{x}_3 \\ & + (\sqrt{E_{RD}} h_{RD} \mathbf{z}_1^* + \sqrt{E_{SD}} h_{SD}^* \mathbf{z}_2) / \xi, \end{aligned} \quad (9)$$

$$\begin{aligned} \tilde{\mathbf{x}}_2 = & \mathbf{x}_2 + (\beta \sqrt{E_{SD} E_{RD}} h_{SD}^* h_{RD} / \xi) \mathbf{x}_3 \\ & + (\alpha \sqrt{E_{SD}} h_{SD}^* \mathbf{z}_1 + \sqrt{E_{RD}} h_{RD} \mathbf{z}_2) / \xi, \end{aligned} \quad (10)$$

where $\xi = \alpha E_{SD} |h_{SD}|^2 + E_{RD} |h_{RD}|^2$. Note that D is reliably able to cancel the $\mathbf{x}_3$'s component by a recursive interference cancellation starting from the strongest packet $\mathbf{x}_1$ owing to less inherent interference and noise variance in (9) than those in (10). Depending on the status of interference cancellation, the proposed scheme when there is no interference cancellation at the destination is called *P1*, and that when the components of $\mathbf{x}_3$ in (9) and (10) are cancelled is called *P2*.

IV. INFORMATION-THEORETIC ANALYSIS

A. Reference IFD schemes

From (1), the achievable rate of the IFD/AF scheme is obtained as

$$\mathfrak{R}_{IFD}^{AF} = \log_2 \left(1 + |h_c|^2 / N_0^c \right) [\text{b/s/Hz}]. \quad (11)$$

where $H_c = E_{SD} |h_{SD}|^2 + (E_{SD} E_{RD} / (E_{SR} + 1)) |h_{SR}|^2 |h_{RD}|^2$. Also, the achievable rate of the IFD/DF scheme is, from (4) and [5],

$$\mathfrak{R}_{IFD}^{DF} = \min \left\{ 0.5 \log_2 \det(\mathbf{I}_2 + \mathbf{H}\mathbf{H}^H), \mathfrak{R}_{SR} \right\}, \quad (12)$$

where $\mathfrak{R}_{SR} = \log_2(1 + E_{SR} |h_{SR}|^2)$, and $\min(x, y)$ is the minimum of x and y . It is noting worth that (4) and (12) imply that this scheme was only approached in an information-theoretic sense with mention of complicated 2×3 matrix-based equalization to cancel the MAC interference at the destination, and R may use random binning to cancel it, which is less feasible [3].

B. Proposed scheme

Let $\mathfrak{R}_1$ and $\mathfrak{R}_2$ be the transmission rates of $\mathbf{x}_1$ and $\mathbf{x}_2$ in Step 1, respectively. These rates are chosen such that the relay node R is able to reliably decode $\mathbf{x}_1$ from the SC-encoded signal vector from the previous encoding cycle. This requires

$$\mathfrak{R}_1 \leq \log_2(1 + \beta^2 \gamma_{SR}), \quad (13)$$

where $\gamma_{SR} = E_{SR} |h_{SR}|^2$ is the instantaneous signal-to-noise ratio (SNR) in the S~R link, and

$$\mathfrak{R}_2 \leq \log_2(1 + \gamma_{SR}). \quad (14)$$

For Step 2, let $\tilde{\mathfrak{R}}_1$ and $\tilde{\mathfrak{R}}_2$ be the achievable rates of $\tilde{\mathbf{x}}_1$ and $\tilde{\mathbf{x}}_2$, respectively. In order for the destination node D to reliably decode $\mathbf{x}_1$ and $\mathbf{x}_2$ from (9) and (10), $\tilde{\mathfrak{R}}_1$ and $\tilde{\mathfrak{R}}_2$ must satisfy

$$\tilde{\mathfrak{R}}_1 \leq \log_2 \left(1 + (\alpha \gamma_{SD} + \gamma_{RD})^2 / (\beta^2 \gamma_{SD}^2 + \gamma_{SD} + \gamma_{RD}) \right), \quad (15)$$

$$\tilde{\mathfrak{R}}_2 \leq \log_2 \left(1 + \frac{(\alpha \gamma_{SD} + \gamma_{RD})^2}{\beta^2 \gamma_{SD} \gamma_{RD} + \alpha^2 \gamma_{SD} + \gamma_{RD}} \right), \quad (16)$$

where the instantaneous SNRs γ_{SD} and γ_{RD} for S~D and R~D are $E_{SD} |h_{SD}|^2$ and $E_{RD} |h_{RD}|^2$, respectively. According to the note at the end of Subsection III.C, the inherent interferences $\beta^2 \gamma_{SD}^2$ and $\beta^2 \gamma_{SD} \gamma_{RD}$ in (15) and (16) are feasibly cancelled. Regarding the superimposed symbol $\mathbf{x}_1$, the resultant achievable rate of $\mathbf{x}_1$ is determined as $\mathfrak{R}_1$ when $\mathfrak{R}_1 \leq \tilde{\mathfrak{R}}_1$ because $\tilde{\mathfrak{R}}_1$ is not achievable if the S~R link is weak, while that of $\mathbf{x}_1$ is selected as $\tilde{\mathfrak{R}}_1$ when $\mathfrak{R}_1 > \tilde{\mathfrak{R}}_1$ since the final achievable rate is dependent on Step 2. Accordingly, the achievable rate corresponding to $\mathbf{x}_1$ is the minimum of $\mathfrak{R}_1$ and $\tilde{\mathfrak{R}}_1$. Similarly, the achievable rate corresponding to $\mathbf{x}_2$ is the minimum of $\mathfrak{R}_2$ and $\tilde{\mathfrak{R}}_2$ in (14) and (16). Consequently, the (sum) capacity of the proposed scheme is

$$\mathfrak{R}_{FD}^{\text{pro}} = \max_{0 \leq \alpha^* \leq 1} 0.5 \left(\begin{aligned} & \min \{ \mathfrak{R}_1, \tilde{\mathfrak{R}}_1 \} \\ & + \min \{ \mathfrak{R}_2, \tilde{\mathfrak{R}}_2 \} \end{aligned} \right), [\text{b/s/Hz}] \quad (17)$$

where the factor 0.5 indicates that transmission occurs over two time slots, and α^* is denoted as the optimal value that maximizes the capacity in (17).

C. Optimal HD scheme

By achievable rate, to show the spectral efficiency of the aforementioned IFD schemes, the achievable rate of the optimal HD scheme [3] is introduced as

$$\mathfrak{R}_{HD}^{\text{opt}} = \frac{\log_2(1 + \gamma_{SR}) \log_2(1 + \gamma_{RD})}{\log_2(1 + \gamma_{SR}) + \log_2(1 + \gamma_{RD}) - \log_2(1 + \gamma_{SD})}. \quad (18)$$

In this scheme, after S broadcasts the packet in Step 1, R

decodes it, and then transmits the uncertainty² of the destination node about the packet sent by S .

D. Upper-Bound IFD

In general, the capacity of the relay channel is not known, except for the degraded relay channel [1]. However, the upper-bound capacity for IFD can be derived by applying the maximum flow minimum cut theorem to the relay channel as suggested by Theorem 4 in [1]. The relay system in Figure 1 contains two cuts, around the source node (broadcast) ($S \sim R$, $S \sim D$) and around the destination node (multiple access) ($S \sim D$, $R \sim D$). Clearly the capacity cannot be greater than the maximum flow through either of these cuts. Accordingly, the upper-bound capacity of IFD is expressed as

$$\mathfrak{S}_{IFD}^{UB} = \max_{0 \leq \theta \leq 1} \min \left\{ \begin{aligned} &\log(1 + (1 - \theta)(\gamma_{SR} + \gamma_{SD})), \\ &\log(1 + \gamma_{SD} + \gamma_{RD} + 2\sqrt{\theta\gamma_{SD}\gamma_{RD}}) \end{aligned} \right\}, \quad (19)$$

where the first term limits the maximum information transfer from S to R and D . The second term limits the maximum information transfer from S and R to D . The codebook for each block used by S and R is assumed to be Gaussian. Please note that for the first block transmitted by the source no cooperation between S and R is possible but by assuming that $k \rightarrow \infty$ blocks are transmitted the resulting loss can be neglected.

V. NUMERICAL EVALUATION

In this evaluation, it is assumed as the following: The nodes S , R , and D are considered to lie on a line; Corresponding channel gains are dependent on the average received powers, i.e. $E\{|h_{SR}|^2\} = E\{|h_{RD}|^2\} = E\{|h_{SD}|^2\} = 1$; And noise variance $N_0 = 1$. Under this condition, when the average SNR $\bar{\gamma}_{SD} = E_{SD}$ and the distance ratio (DR) d_{SR}/d_{SD} are given, the other two average SNRs are determined as $\bar{\gamma}_{SR} = \bar{\gamma}_{SD}(d_{SD}/d_{SR})^\epsilon$ and $\bar{\gamma}_{RD} = \bar{\gamma}_{SD}(d_{SD}/(d_{SD} - d_{SR}))^\epsilon$, where $\epsilon = 3$ is the path-loss exponent.

Figures 3 and 4 plot the capacities of the proposed schemes and the reference schemes with the upper-bound IFD capacity as functions of distance ratio and $\bar{\gamma}_{SD}$, respectively. Two average SNRs are considered in Figure 3 as $\bar{\gamma}_{SD} = 0$ and 10 dB. It is shown in Figure 3 that for both SNR cases all IFD schemes outperform the optimal HD. And around DR=0.5, the capacities of the proposed P2 and the reference IFD/DF that have small capacity gap between them and are very close to the upper-bound IFD become noticeably higher than the other schemes. On the other hand, as the SNR increases, the capacity relation between P1 and reference IFD/AF has reversed due to dominant inherent interference. Moreover,

² It is corresponding to the first-step partial packet information that is not correctly decoded at the destination node in the $S \sim D$ link.

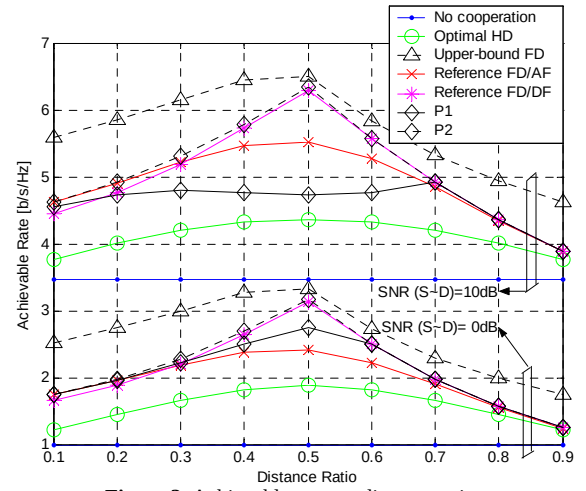


Figure 3. Achievable rate vs. distance ratio.

Figure 4 shows additionally that regardless of varying SNR, the capacity gap of P2 and reference IFD/DF scheme is almost maintained, and at higher than SNR=16 dB, even the capacity of P1 becomes worse than that of the optimal HD. From these results, it can be indicated that in terms of feasibility and spectral efficiency the proposed P2 is more effective, so that a precise inherent interference cancellation should be pre-made.

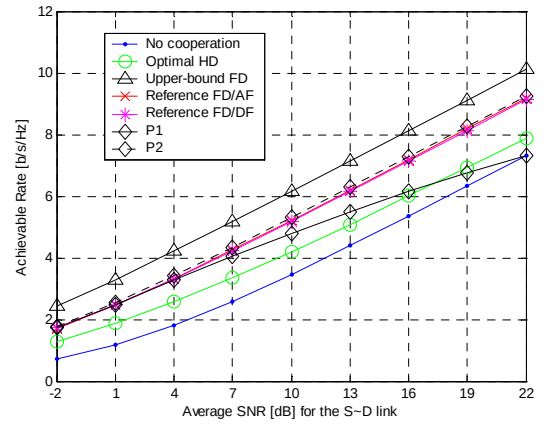


Figure 4. Achievable rate vs. average SNR for $S \sim D$ with a fixed DR of 0.3.

VI. CONCLUSION

We have proposed a feasible IFD/DF cooperative scheme based on the two-step space-time blocking and superposition coding, and compared it with both the existing IFD schemes and the upper-bound IFD. Our numerical evaluations showed that the proposed scheme is more close to the upper-bound IFD and gains more spectral efficiency than any other scheme on the assumption the inherent interference is cancelled. The analyses of reliable interference cancellation techniques will be further studied.

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