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Superimposed Radio Resource Sharing for Improving Uplink Spectrum Efficiency

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***Abstract*—IMT-Advanced is expected to provide much higher cell spectrum efficiency than current cellular systems. In order to improve the uplink cell spectrum efficiency of cellular systems, a superimposed radio resource sharing (SRRS) method is proposed in this paper through fully exploiting near-far effect and channel differences of multiple user equipments (UE) in the cellular system. Simulations are performed and verify the effectiveness of the proposed method. Simulation results show that the uplink cell spectrum efficiency can be greatly improved compared with the existing scheme.**

***Index Terms*—Cellular, superimposed radio resource sharing, uplink, power**

I. INTRODUCTION

IMT-Advanced is expected to provide about three times higher cell spectrum efficiency than LTE [1]. In order to achieve such a high cell spectrum efficiency, sophisticated techniques are required especially for the uplink transmission due to the hardware complexity and power limitations of UE. One promising scheme to solve this problem is uplink multi-user multi-input multi-output (MU-MIMO) [2], in which multiple UEs simultaneously transmit their data to BS collaboratively in the same time and frequency by exploiting the spatial freedom. But the achievable multiplexing gain of UL MU-MIMO is limited by the number of antennas of BS. In addition to MU-MIMO, a new superimposed radio resource sharing method is presented in this paper, in which also the same time and frequency resource is shared by superimposed multiple UEs' signals, and then capture effect and SIC (Successive Interference Cancellation) [3] are exploited to detect signals that have different power levels.

So far some papers concerning capture effect using terminals transmitting at predefined different power levels are proposed and analyzed in AWGN channel, which is called power-level division multiple access (PDMA) [4], [5]. However, generally in cellular system, the received signal powers of different UEs at BS are quite not balanced due to different frequency selectivities of their fading channels, different path loss that is well known as near-far effect and different shadowing they undergo. Furthermore, when the inter-cell interference power control is employed, the cell-edge UE has to be forced to reduce its transmission power, resulting in the received power further unbalanced. In the proposed method, such received power diverseness is exploited for introducing new dimensional multiplexing in uplink transmissions.

Hereinafter we define UE-layer as an UE group, in which each UE has similar received signal power at BS. Following the unique scheduling scheme, UEs belonging to different UE-layers can be allowed to transmit data simultaneously in the same time and frequency resource. To separate the superposed signals from multiple UEs, BS is built with SIC which utilizes the received power profile of UE. Through this way, the signals of all UEs can be detected one-by-one sequentially. As a result, the power dimension multiplexing can be achieved at BS by exploiting channel diverseness. It is noted that the proposed multiplexing scheme can be easily combined with MU-MIMO to further gain the uplink cell throughput.

The paper is organized as follows: section II describes the system model with SRRS for single and multiple-antenna BS respectively. Section III presents the user scheduling algorithm for SRRS. Section IV elaborates the transmitting processing of UE and the receiving processing of BS. Section V provides the performance evaluation results. Section VI discusses some considerations for the application of the proposed method. Finally section VII concludes this paper.

II. SRRS SYSTEM MODEL

A. *Single Antenna BS*

Let us assume there are total N UEs to transmit data in a cell, and the physical resource block (PRB, hereafter) means a frequency-time resource block for multi-carrier system. Then the single antenna BS can support the proposed SRRS method for single antenna UE and one UE is allowed in each UE-layer. The general system model of SRRS for single antenna case is shown in Figure 1.

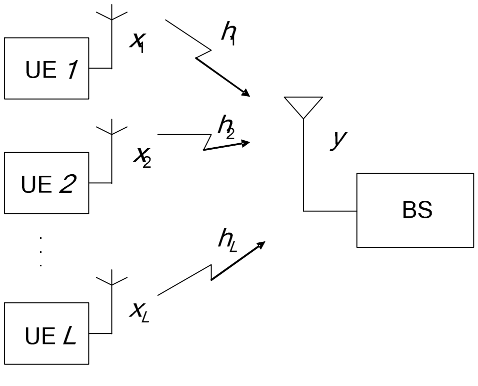

Fig. 1. Single antenna BS

Consider the number of UE-layers is L ($L \leq N$) and then the received signal at BS is expressed as,

$$y = \sum_{l=1}^{L} h_l x_l + n \qquad (1)$$

where h_l denotes the channel response of UE in l^{th} UE-layer to BS, x_l denotes the data symbol transmitted by this UE and n is the Gaussian noise. At first BS will detect the signal of UE with the strongest signal power in all UE-layers while regarding other signals as interferences. After the strongest signal is detected, BS can perform interference cancellation to remove its effect, which will enable the detection of the UE with the second strongest signal power. In this way, all signals from L UE-layers can be decoded successively.

To be specific, assuming L is equal to 2, U1 is the higher power UE and U2 is the paired UE on the same PRB with lower power, then firstly capture effect is exploited to detect the signal of U1 directly. The corresponding SINR of U1 is written as,

$$SINR_{U1} = \frac{P_{s\_U1}}{P_{s\_U2} + P_n} \qquad (2)$$

where $P_{\text{s\_U1}}$, $P_{\text{s\_U2}}$ is the received signal power of U1 and U2 respectively and P_{n} is the noise power.

If the value of $SINR_{\text{U1}}$ is high enough, x_{U1} can be successful decoded by using channel response which is derived from orthogonally transmitted pilot signals from U1. And then interference cancellation can remove the detected UE, i.e. U1, from the superposed signals y:

$$y - \hat{h}_{U1} * x_{U1} = \hat{h}_{U2} * x_{U2} + n + S_r \qquad (3)$$

where $\hat{h}_{U1}, \hat{h}_{U2}$ are the channel estimations, x_{U1}, x_{U2} are the transmitting signals and S_{r} is the interference resulting from U1 due to interference cancellation remaining error.

At this moment the signal of U2 can be detected, but now the corresponding SINR of U2 should be,

$$SINR_{U2} = \frac{P_{s\_U2}}{P_{sr} + P_n} \qquad (4)$$

where P_{sr} is the power of S_{r} in (3), which is related to $P_{\text{s\_U1}}$.

While for the traditional case, only one UE (e.g., U1) is scheduled for one PRB, so the SINR of U1 here is,

$$SINR_{U1} = \frac{P_{s\_U1}}{P_n} \qquad (5)$$

Obviously, the SINR of each user (both U1 and U2) in the couple is lower compared to the traditional situation, as shown in (2), (4) and (5) respectively, whereas we're able to get two streams transmitted by two UEs in one PRB. Because these two factors affect to the channel capacity, the uplink cell throughput of SRRS is evaluated by simulations in section V, where it can be seen that the performance will be improved by using SRRS in the uplink transmissions.

B. *Multi-antenna BS*

It can be easily extended to multi-antenna BS combined with MU-MIMO, which can support SRRS of either single antenna or multi-antenna UE and now one UE-layer can have multiple UEs. The system model of multi-antenna BS with SRRS is illustrated in Figure 2.

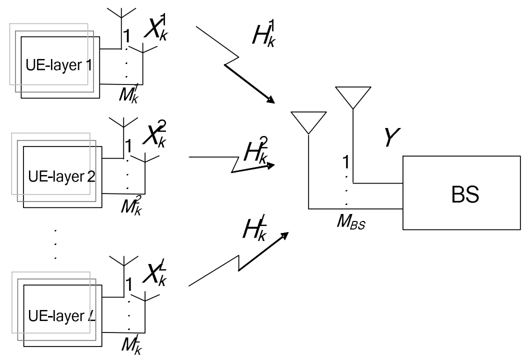

Fig. 2. Multi-antenna BS

Assuming BS has M_{BS} receiving antennas, the k^{th} UE in the l^{th} UE-layer has M_k^l transmitting antennas, the total number of UE-layer is L and the number of UEs in the l^{th} UE-layer is V_l, the received signal at BS is,

$$\begin{aligned} Y &= \sum_{k=1}^{V_1} H_k^1 X_k^1 + \sum_{k=1}^{V_2} H_k^2 X_k^2 + \ldots + \sum_{k=1}^{V_L} H_k^L X_k^L + N \\ &= \sum_{l=1}^{L} \sum_{k=1}^{V_l} H_k^l X_k^l + N \end{aligned} \qquad (6)$$

where $Y = [y_1, y_2, \ldots, y_{M_{BS}}]^T$ denote the received signals, H_k^l is a $M_{BS} \times M_k^l$ matrix denoting the MIMO channels from the k^{th} UE to BS, $X_k^l = [x_1, x_2, \ldots, x_{M_k^l}]^T$ denote the data symbols transmitted by the k^{th} UE in the l^{th} UE-layer and $N = [n_1, n_2, \ldots n_{M_{BS}}]^T$ are the Gaussian noises at BS.

If all UEs transmit independent data streams on each of their transmitting antennas, in order to support the SRRS method, the maximum number of streams from each UE-layer is supposed to be equal to or less than the number of receiving antennas of BS, i.e., the following constraint should be satisfied for each UE-layer:

$$\sum_k M_k^l \le M_{BS} \quad (l = 1, \cdots, L) \qquad (7)$$

For example, if all UEs have only one antenna and BS is equipped with two antennas, four UEs at most can be grouped to share one PRB in the uplink. Provided that U1 and U2 belong to the strong UE-layer while U3 and U4 fall into the weak UE-layer, the formula (6) becomes to be,

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} h_{13} & h_{14} \\ h_{23} & h_{24} \end{pmatrix} \begin{pmatrix} x_3 \\ x_4 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \qquad (8)$$

BS can separate their signals by MIMO detection within both strong and weak UE-layer, which can perform well because of the balanced signals residing in the same layer, and SIC between different UE-layers.

III. PF SCHEDULING ALGORITHM FOR SRRS

The proportional fair (PF) based scheduling algorithm which can be applied to this SRRS method is presented in this section.

As for the first step, BS should detect the signal powers via pilot signals orthogonally transmitted by all N UEs, so as to estimate the instantaneous transmittable rate of each UE.

The metric of the k^{th} UE for competing PRB in traditional PF scheduling algorithm [6] is expressed as,

$$\Pi_{PF}(k) = \frac{r_k}{\overline{R}_k} \tag{9}$$

where r_k is the instantaneous transmission rate of the k^{th} UE on this PRB and $\overline{R}_k$ is the average throughput for the k^{th} UE in a past window and updated every TTI.

After calculating the metrics of all UEs, BS performs PRB allocation following the criteria as,

$$UE = \arg\max_{k\in[1,N]}\left(\Pi_{PF}(k)\right) \tag{10}$$

BS will allocate PRB to the UE which has the maximum metric.

Similarly, when multiple UEs want to share a PRB, a proper metric should be defined for these UEs for the PRB competition. For example, one such a metric is shown in (11):

$$\Pi_{PF\_reuse}(U) = \sum_{k=1}^{U} \frac{r_k}{\overline{R}_k} \tag{11}$$

where U is the number of UEs to share the PRB, note that here r_k is also the instantaneous transmission rate of the k^{th} UE but must be determined with the interferences caused by other UEs scheduled in the same PRB. So with (11), the traditional PF criteria (10) can be expressed as,

$$UE = \arg\max\left(\Pi_{PF\_reuse}(1)\right) \tag{12}$$

Then the criteria for BS to allocate PRB with SRRS is,

$$UE(s) = \arg\max\left(\max\left(\Pi_{PF\_reuse}(i)\right)\right) \quad (\mathrm{i} = 1,\cdots,U_{\max}) \tag{13}$$

where $U_{\max}$ is the supportable maximum number of UEs sharing the same PRB. Formula (13) shows that in order to allocate a PRB, BS should:

- Find the maximum metric when only 1 UE is allowed to transmit in the PRB
- Find the maximum metrics when 2 to $U_{\max}$ UEs are allowed to share the PRB respectively
- Find the maximum one among the above $U_{\max}$ metrics and allocate PRB to the corresponding UEs

For example, as for the aforementioned instance of single antenna UE and 2-antenna BS in section II, $U_{\max}$ in (13) is 4, which is greater than $U_{\max}$ being 2 in the traditional MU-MIMO. So this proposed method will achieve a better performance because of the increased freedom of scheduling.

IV. TRANSMISSION AND RECEIVING PROCESSING

The presented method can be flexibly combined with SC-FDMA or OFDM for uplink. In the following the transmission and receiving processing are elaborated for single antenna UE and BS respectively. The extension to multi-antenna case is straightforward. For simplicity in this paper we take two UE-layers for example, and the general system architecture is illustrated in Figure 3. In fact, through simulations it is found that assigning more UE-layers is not very cost-effective compared with two layers.

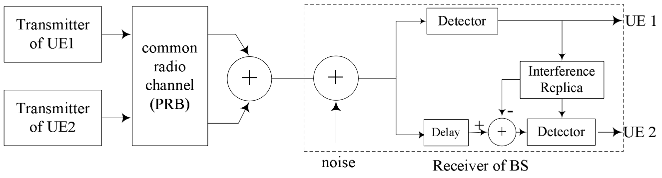

Fig. 3. System architecture of 2 UE-layers

For transmission processing, the structure of transmitter is shown in Figure 4. Note that the M-point DFT block is only needed for SC-FDMA.

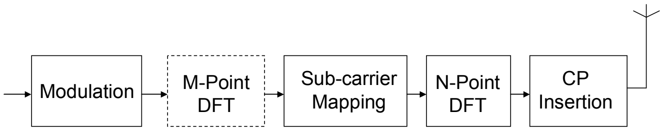

Fig. 4. Transmitter structure

It is noted that the sub-carrier mapping of PRB should be localized instead of distributed so as to facilitate the SRRS.

While for receiving processing, the structures of receiver are shown in Figure 5 and Figure 6 for SC-FDMA and OFDM respectively. As also illustrated in Figure 3, the interference cancellation processing is needed to remove the detected signal of UE in the stronger UE-layer (e.g., UE1) from the received superposed signals. Obviously, channel estimation accuracy of UE1 will affect the detection performance of UE2 in the weaker UE-layer, so orthogonal pilot transmissions from both UEs are assumed in this paper, and the degree of accuracy can be satisfied as a result of the pilot signals with high SNR of UE1 without interference from UE2. After removing the replica signal of stronger UE-layer, signal in the weaker UE-layer can be detected sequentially.

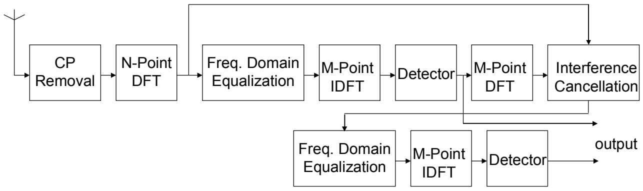

Fig. 5. Receiver structure for SC-FDMA

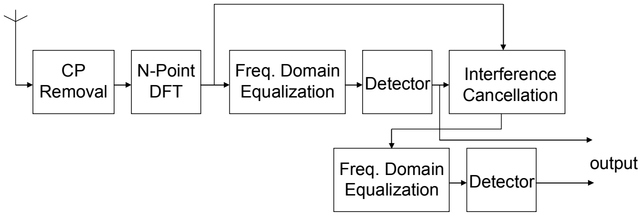

Fig. 6. Receiver structure for OFDM

V. SIMULATIONS RESULTS

Simulations are performed to compare the uplink cell throughput of the traditional method with the proposed SRRS method. Table I gives the major parameter settings in the simulations. For simplicity, the number of UE-layers is restricted to 2.

TABLE I SYSTEM PARAMETERS

Parameters		Assumptions
Transmission bandwidth		5 MHz
PRB bandwidth		180 kHz (12 sub-carriers)
FFT size		512
Sub-frame (TTI) length		1 ms
UE transmission power		21 dBm
Noise figure of BS		5 dB
Thermal noise density		-174 dBm/Hz
Distance-dependent path loss		128.1 + 37.6log10(R) dB
Lognormal shadowing	Standard deviation	8 dB
	Correlation distance	50 m
Channel model		Six-ray TU channel model
Maximum Doppler Frequency		5.5 Hz
Scheduling algorithm		Frequency-domain channel-dependent PF
Traffic model		Full buffer traffic
Modulation and coding scheme		QPSK : 1/3, 1/2, 2/3, 3/4 16QAM : 1/2, 2/3, 3/4, 4/5 64QAM : 2/3, 3/4
Channel estimation		Non-ideal
Target BLER		0.1
UE distribution		Uniform
Min. distance between UE and BS		>= 50 m

Without loss of generality here we only simulate and give the results of single antenna configurations for both BS and UE, to find out whether this method can actually improve the performance. The EESM method [7] is used for the effective SINR computation. In SIC, channel estimation error is modeled as a Gaussian variable with variance set according to SINR as shown in [8]. Formula (13) is used as the scheduling criterion to select UEs for each PRB. It is noted that pilot signaling overhead is not considered in this paper.

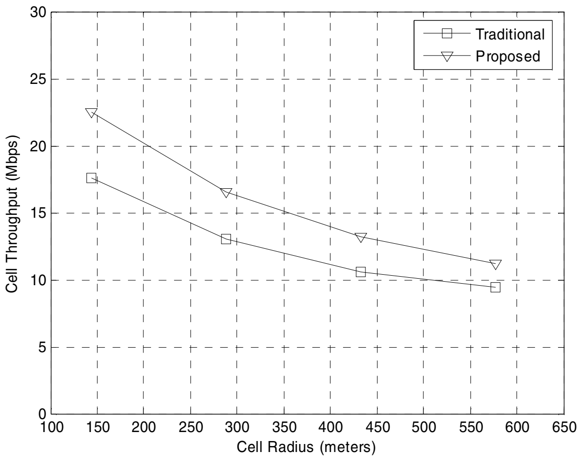

Fig. 7. Uplink cell throughput vs. cell radius

Figure 7 shows the uplink cell throughput comparison between the traditional method and SRRS, in respect to cell radius, when the UE number is 20 per cell. It can be seen that the uplink cell throughput can be significantly improved. This performance gain comes from two streams multiplexed in one PRB, although the transmission rate of each stream is somewhat decreased, as compared to the traditional case that supports only one single stream.

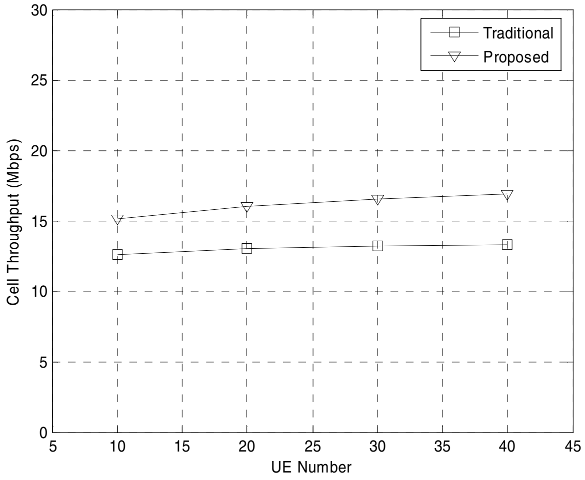

Fig. 8. Uplink cell throughput vs. number of UEs

Figure 8 shows the uplink cell throughput comparison in respect to the number of UEs per cell. We arrive at the same conclusion that it can gain the performance. Moreover, as the UE number increases, we shall have more freedom to choose UE pairing during the scheduling, therefore, this method can work better as shown in Figure 8.

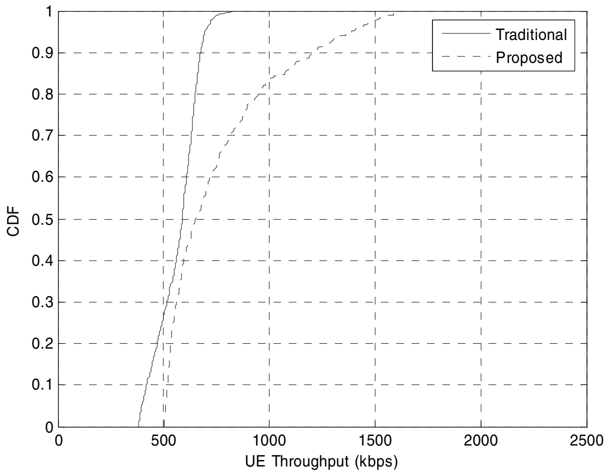

Fig. 9. CDF curve of UE throughput

Figure 9 shows the CDF of UE throughput. It can be seen that the performance of cell-edge UE throughput can be improved, since the cell-edge UE will have more chances to be scheduled as the one from the weaker UE-layer in the UE-paring, as opposed to the traditional method. On the other hand, a higher peak data rate can also be achieved, for the cell-center UE with high SINR in the stronger UE-layer.

It is not illustrated here but should be pointed out that adding more parallel streams in one PRB can not obtain obvious improvement any longer, compared with two UE-layers multiplexing. A simple explanation is that: assuming $r(k)$ denotes the average spectrum efficiency with k UEs to share a PRB, obviously, $r(k)$ is a decreasing function as discussed in section II, and then if $0.5 < r(2)/r(1) < 1$, the performance will be improved when two UEs are paired for SRRS, compared with one UE occupying the whole PRB, however, when the number of scheduled UE increases to 3, the condition is changed to $2/3 < r(3)/r(2) < 1$; this constraint becomes harder to meet. Furthermore, as the number of UE-layers increase, the complexity of scheduling algorithm will increase a lot, as well as more delay of signal decoding which is caused by more operations of SIC. Therefore, considering the tradeoff between complexity and performance, it can be said that setting two UE-layers is suitable for the application of this method.

VI. DISCUSSIONS

In this section, uplink reference signal arrangement and transmission power control for SRRS are discussed in brief.

For the uplink sounding reference signal (SRS), it is preferred to utilize frequency division multiplexing (FDM) between SRSs of UEs from different UE-layers, and code division multiplexing (CDM) between SRSs from different UEs in the same UE-layer or different antennas of the same UE. The reason is that the channel diversity and frequency selectivity in a wide frequency band will destroy the orthogonality of the SRS sequences, like Zadoff-Chu sequences used in LTE [9], and thus will result in the poor estimation quality for the weak UE-layers if CDM is used for different UE-layers. While for the latter case, CDM can be utilized here without such problem because of balanced received signal powers.

For the uplink demodulation reference signals (DMRS), it is preferred to utilize CDM between DMRSs for all cases. The reason is that generally the frequency channel response over one PRB (localized) is flat, and thus the orthogonality of the reference signal sequences can still be kept. Therefore, CDM is preferred to save the radio resource compared to FDM between DMRSs.

After the scheduling has finished, in order to meet the power requirements of two paired UEs more precisely, a fast closed loop transmitting power control can be used. For example, let us assume that the scheduler has chosen U1, U2 as a couple to share the same PRB with the transmitting power P_1, P_2 respectively. For both U1 and U2, the power adjustment is allowed within the range $[P_{\min}, P_{\max}]$ considering the BLER performance and coding and modulation scheme. On one hand, from U1's standpoint, P_2 ought to satisfy the SINR requirement of U1, i.e.,

$$P_2 \le \min\big(f(P_1), P_{\max}\big) \qquad (14)$$

where the increasing function $f(\cdot)$ can be tabled offline in practice. On the other hand, considering U2 ought still to be decoded despite suffering from the remaining error interference after performing SIC, the constraint of the transmitting power of U1 and U2 is,

$$P_2 \ge \max\big(g(P_1), P_{\min}\big) \qquad (15)$$

where the increasing function $g(\cdot)$ is supposed to be computed considering the adopted channel estimation and interference cancellation algorithms in practice. P_1, P_2 should be set with appropriate margin and adjusted fast enough according to the radio channel status to fit the power property (14), (15) to guarantee that this method can work efficiently, i.e., not to cause unacceptable interference to each other in the pairing. Taking into account the Doppler Effect, in case that BS can track the power variations caused by channel fluctuation, this method is more suitable for slow-fading channel, e.g., for low mobility UE or femto-cell environment.

VII. CONCLUSION

A SRRS (superimposed radio resource sharing) method is proposed in this paper in order to further improve the uplink cell spectrum efficiency for future IMT-Advanced system. Through the proposed method, the same time and frequency resource is shared by multiple UEs with different received signal power levels. The method can be combined with any MU-MIMO schemes, and achieve additional multiplexing gain which can exceed the limitation of antenna number on BS. With proper scheduling algorithm to select UE pairing, simulation results have shown that the uplink cell spectrum efficiency can be significantly improved compared with existing method.

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