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Feedback Design in Multiuser MIMO Systems Using Quantization Splitting and Hybrid Instantaneous/Statistical Channel Information

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Abstract: In the design of next generation multiuser communication systems, multiple antenna transmission is an essential part providing spatial multiplexing gain and allowing efficient use of resources. A major limiting factor in the resource allocation is the amount of channel state information (CSI) available at the transmitter, particularly in multiuser systems where the feedback from each user terminal must be limited. To this effect we propose two independent approaches for an efficient representation of the channel in multiuser MIMO systems.

In the first approach, channel quantization is considered where the total number of feedback bits is limited. A resource allocation scheme is proposed where the available rate is split between the scheduling phase, where all users feed back a coarse CSI quantization, and the precoding phase where the selected receivers refine their CSI. The optimum splitting of the available feedback rate provides a large increase in performance and even simple heuristic splitting gives a noticeable advantage.

In the second approach, we exploit a combination of instantaneous and statistical channel information. For spatially correlated Rayleigh and Ricean channels, it is shown that the CSI to large extent can be represented by the channel norm when the long-term channel statistics are known. Within a minimum mean square error (MMSE) estimation framework, feedback of a few bits of the quantized channel norm is sufficient to perform efficient resource allocation and achieve performance close to that of full CSI.

Keywords: Mobile communication, Array signal processing, Feedback design.

1. Introduction

The increasing need for fast and reliable wireless communication links opens the discussion about systems with multiple antennas located both at the transmitter and the receiver, so called multiple-input multiple-output (MIMO) systems. Integration of multiple antennas leads to great gains in capacity referred to as *spatial multiplexing gain*, and it has been shown in [1] that MIMO systems have the ability to reach higher transmission rates than one-sided array links. In multiuser configurations, the multiple base station antennas can be used to allow multiple terminals to share the same bandwidth, by virtue of a Spatial Division Multiple Access (SDMA) protocol. Further capacity improvements due to *multiuser diversity* are attainable through judicious scheduling of users. This leads to so-called multiuser MIMO (MU-MIMO) schemes which rely on a combination of user scheduling (whereby a group of co-channel users is selected by the scheduling protocol) and precoding, whereby a matrix of transmitted beams is designed so as to best serve the selected users in a way which minimizes inter-user interference [2].

On the downlink, in order to completely exploit these two gains (multiuser diversity and user multiplexing gain), full channel state information (CSI) is required at the base station. The amount of feedback, from the mobiles to the base station, needed to achieve full CSI at the transmitter is however prohibitive in many realistic scenarios (e.g., OFDMA, mobility scenarios). To deal with this problem, many researchers have recently turned on the issue of efficiently representing the CSI such that the base can operate with reduced CSI while preserving the MU-MIMO related gains. Herein, the channel is modelled as block-fading; that is, the channel is constant for a block of time slots and then updated independently. Hence, feedback can be sent in the beginning of a block to optimize the block throughput.

Several approaches have been put forward [3] including main strategies: i) Efficient quantizing of the channel vectors at the user side, and ii) exploitation of meaningful channel statistics to complement partial instantaneous channel fading information.

In this paper, we report results drawn from a collaborative effort with the EU-funded project COOPCOM. Two techniques, belonging to each category mentioned above, are described. The techniques are mostly independent and thus the systems gains (here feedback reduction gains) can be cumulated. In the first approach, we assume a quantization algorithm where the fixed total number of quantization bits is allowed to be distributed judiciously between the scheduling and the precoding stages. In the second approach we assume that some channel statistics (related to the antenna correlation matrix) are known at the transmitter as it can be estimated at the receiver and fed back using negligible long-term overhead, or estimated at the reverse link.

2. MU-MIMO based on Zero-Forcing

Most approaches to multiuser MIMO transmission under partial or full CSI have centered on linear precoding, which is much simpler than nonlinear processing (required for implementing the optimal dirty-paper coding scheme, for example), this simplicity coming at the cost of a tolerable performance loss [4]. These approaches fall under two categories: orthogonal random beamforming (ORBF) and zero-forcing beamforming (ZFBF).

The ORBF category, introduced in [5], consists of generating a number of random orthonormal beams and transmitting on each of them to the user with the corresponding highest signal-to-interference-and-noise ratio (SINR); thus, each user only needs to feed back its SINR and the index of the optimal beam instead of its entire channel information. However, this approach is only efficient when the number of users is large. Several publications have been devoted to improving the scheme for finite number of users and to analyze the effect of quantizing the SINR feedback.

When ZFBF is used, the fed back CSI is used to schedule an appropriate set of users for transmission and design a zero-forcing (ZF) precoding channel matrix, which eliminates the inter-user interference when full CSI is available. The scheduler can be designed to maximize the channel throughput, provide fairness between users, or balance these contradictive goals as in the case of the proportional fair scheduler [6]. The principle is the same for the case of limited feedback, but the zero-forcing condition needs to be relaxed in the sense of accepting some amount of inter-user interference.

Herein, the feedback design of multiuser MIMO systems with ZFBF will be discussed. The resource allocation can be divided into two stages: user selection and precoding design. In Section 3, it will be shown that the performance can be increased by splitting the total number of feedback bits between these stages such that the selected users get a larger portion. This exploits the idea that user selection requires less accurate CSI description compared with precoding/beamforming design. This simple, but important, principle leads to a general feedback design framework that can be exploited in many systems based on quantized feedback. In Section 4, a second approach is presented to deal with the case of correlated channels. It will be shown that the quantized channel norm when combined with the knowledge of the channel statistics constitutes a good design for the feedback channel, in correlated Rayleigh and Ricean fading systems. The channel statistics can be combined with the feedback in a minimum mean square error (MMSE) estimation framework that provides an efficient estimation of the user channel vector. Simulations show that only a few bits of feedback per user are required to achieve a performance close to that of full CSI.

3. Two Stage Approach to Feedback Design with Rate Splitting

In order to provide the transmitter with full CSI in a multiuser MIMO system, a large number of channel coefficients, corresponding to the product of the number transmit antennas and total number of receive antennas, needs to be fed back with a sufficiently high precision. The scheduling typically consists of two steps: finding the optimal set of users and designing the precoding matrix. The main idea of the feedback design described in this section is that much feedback can be saved in the first step of user selection. We propose to split the available feedback rate among these two tasks in order to maximize the attainable system performance.

In the first scheduling stage, all users feed back a coarsely quantized version of its channel vector. This information is utilized for user selection and then, in the second scheduling stage, the selected users send back refinements of their quantized channel state information. Hence, not all users will end up feeding back their channel with similar accuracy. This principle makes sense for several reasons; for example, only a few bits are required to remove a weak receiver from the user selection and less CSI is required to find a set of strong and spatially separated users than designing an efficient zero-forcing matrix.

Let B_{total} denote the total number of bits available for feedback (i.e., the total feedback "rate" across all users), and let α be chosen from the set [0,1] to denote the splitting factor between the two stages of the scheme. Thus, $B_1 = \alpha \cdot B_{\text{total}}$ and $B_2 = (1\text{-}\alpha)\cdot B_{\text{total}}$ bits will be dedicated to the scheduling and precoding matrix design stages, respectively. These rates are split equally among the users involved. Hence, if the total number of users is K and the number of selected users is N, then each user gets B_1/K bits to quantize its channel in the former stage and each selected user gets an additional B_2/N bits to refine the quantization in the latter stage.

The performance of a communication system can be optimized by choosing the right splitting factor α. The performance behavior with respect to α and its optimization have been investigated in [7] based on information theoretic arguments, for the case with two transmit antennas and 30 single-antenna users. The sum rate, as a function of the SNR, is shown in Figure 1 when B_{total}=120 and α is chosen in different ways. The two extremes α=0 (randomly selected users) and α=1 (all feedback takes place in the first stage, no refinement) is compared with the optimal value of α and an approximation determined using simple heuristics. The figure confirms the gain of using a two stage feedback design, since it combines the low SNR advantage of α=1 and high SNR advantage of α=0. The heuristic choice of α achieves an SNR gain of 5 dB for high SNR, although it performs slightly worse than the optimal α found by exhaustive search.

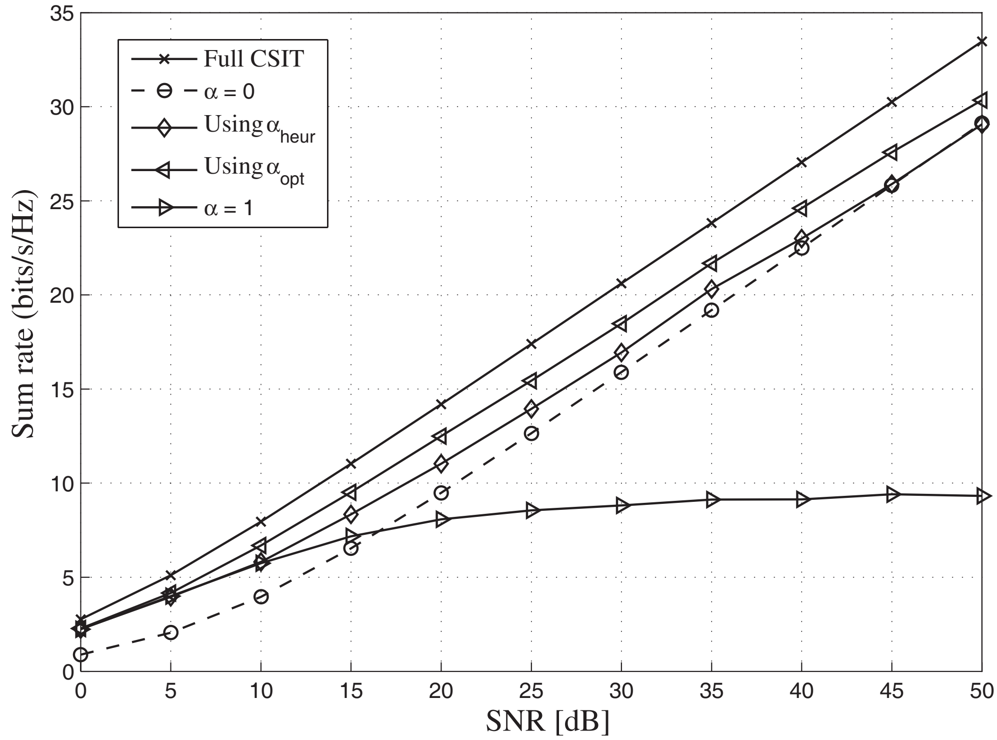

Figure 1: The sum rate for different values of the splitting factor α is compared in a broadcast MIMO channel with a two-antenna transmitter, 30 single-antenna receivers and a total number of feedback bits of 120.

4. Acquiring partial CSI using quantized channel norm feedback

Consider a macro-cellular environment where the base station is elevated (e.g., placed on the top of a building) and thereby exposed to limited local scattering, while the users are surrounded by rich local scattering (e.g., buildings, vehicles, trees, etc.). As discussed in [8], it is often necessary in such environments to model the communication channel by correlated Rayleigh and Ricean fading—that is, there are a few dominating spatial dimensions. Hence, before any information has been fed back, the transmitter has a statistical feeling about which spatial directions that are beneficial to each user.

When only a few bits of feedback are available for improving the scheduling and resource allocation, some compact representation of the current channel realization is needed. In spatially correlated environments, it has been proposed in [9,10] to feed back the quantized squared norm of the channel matrix. The idea is that partial channel state information is achieved by combining the channel norm with channel statistics. Interestingly, the channel norm, which in itself is direction independent, contributes substantial directional information when combined with the statistics; the higher the channel norm, the more accurate directional information. The intuition behind this is illustrated in Figure 2(a) and 2(b) for the Rayleigh and Ricean case, respectively.

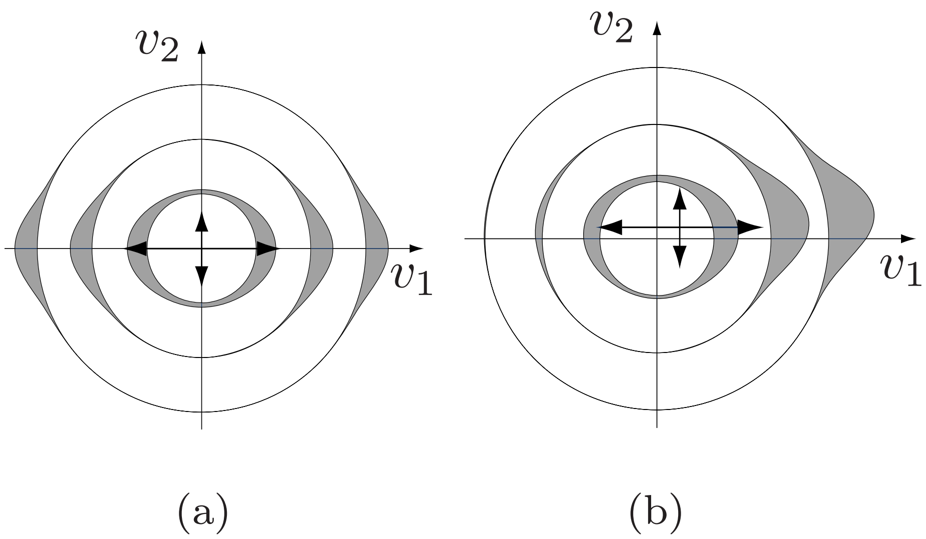

Figure 2: Illustration of the spatial channel information given by different norms (SNRs) in the two-dimensional real-valued case, with v_1 having larger variance than v_2. The norm specifies the distance from the center of coordinates to the realization (i.e., which circle it is on). The shaded area shows how the probability mass is distributed over the circle. The inner arrows indicate the standard deviation in each direction, and their crossing the mean value. The probability mass becomes more focused for higher SNRs.

4.1 MMSE estimation framework for zero-forcing beamforming systems

As described in the previous section, the feedback information of a ZFBF system can be used to improve the user selection and precoder design. The channel norm fits very nicely to this purpose, since the SINR for an arbitrary precoder can be estimated in a reliable way using an MMSE framework. For the case of Rayleigh fading channels, closed-form expressions for the MMSE estimators (and the associated MSEs) have been proposed in [9]. These are suitable for both analysis and efficient real time implementation. Ricean fading channels complicate the derivations due to the asymmetry introduced by a non-zero mean component, but it is possible to express the MMSE estimates in terms of modified Bessel functions. The expressions are readily updated with the rapidly changing channel norm information with modest complexity, as shown in [9].

Asymptotically, in the channel norm, the relative estimation error tends to zero, and the performance approaches that of maximum ratio transmission (MRT) with full CSI. This property has an important impact also on realistic communication scenarios; when a scheduler is used to, in some sense, maximize the channel throughput, users will be scheduled when their channel realizations are particularly strong.

System simulations confirm that in time division multiple access (TDMA) wide area systems, the performance of the MMSE framework with channel norm feedback is close to that of full CSI. There is also a significant performance increase over the ORBF approach of opportunistic beamforming, which requires a comparable amount of feedback but does not take the channel statistics into account. Herein, simulation results will be shown for both Rayleigh and Ricean fading in a system with four transmit antennas and multiple single-antenna users. The channel norm feedback is assumed to be perfect and exact, but quantization will be considered in the next section. In Figure 3, the cumulative distribution functions (CDFs) of the cell throughput are illustrated for a Rayleigh fading system with different number users. In Figure 4, the CDFs of the cell throughput are illustrated for a Ricean fading system with different K-factors (representing an increasing line-of-sight component). The CDF gives the probability that the throughput is smaller or equal to a specific value. Hence, high average performance is represented by a curve far to the right in the figures, while the robustness is described by the steepness. It is evident that the proposed system gives a performance that is close to optimal, while opportunistic beamforming gives a much worse performance.

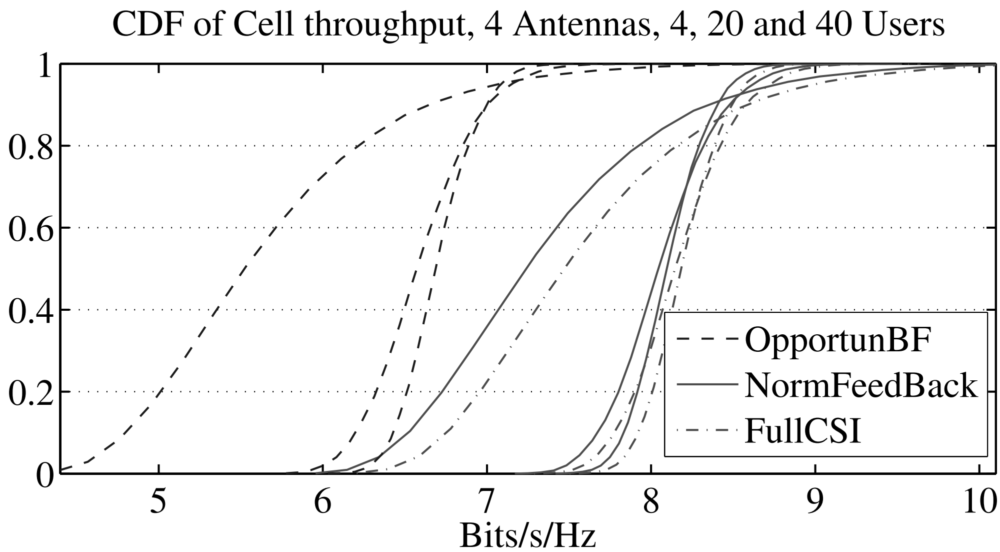

Figure 3: The CDF (over scenarios) of the average cell throughput for a cell with 4 transmit antennas and Rayleigh fading channels. The throughput of opportunistic beamforming is compared with the proposed scheme with channel norm feedback. The throughput of MRT is displayed as reference. The CDFs are plotted for 4, 20 and 40 cell users (increasing performance).

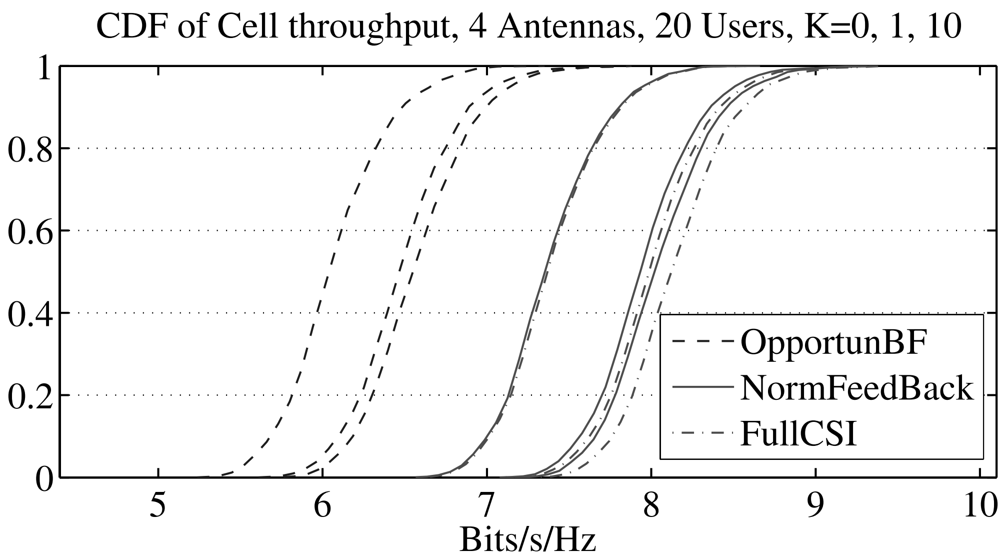

Figure 4: The CDF (over scenarios) of the average cell throughput for a cell with 20 users, 4 transmit antennas and Ricean fading channels. The throughput of opportunistic beamforming is compared with the proposed scheme with channel norm feedback. The throughput of MRT is displayed as reference. The CDFs are plotted for the Ricean K-factors K = 0, K = 1 and K = 10 (decreasing performance).

4.2 Quantization of the channel norm

The MMSE framework described above have considered feedback of the exact channel norm, but this assumption can be relaxed to case of quantized feedback with just a minor loss in performance. The Rayleigh fading MIMO case is treated in [11], where closed-form expressions similar to those in [9] are given for the MMSE estimators and the associated MSEs.

The effect of the feedback quantization on the system performance is shown in the following simulation where the throughput of opportunistic beamforming and the proposed channel norm supported zero-forcing beamforming with exact feedback is compared with the proposed scheme using 0, 1, 3, or 5 bits of feedback per user. In Figure 5, the CDFs of the cell throughput are illustrated for a Rayleigh fading system with an eight-antenna base station and 32 four-antenna users. It is clear that just single feedback bit is required per user to achieve 50% the gain of unquantized channel norm feedback, while 98% of the feedback gain is achieved using 5 feedback bits.

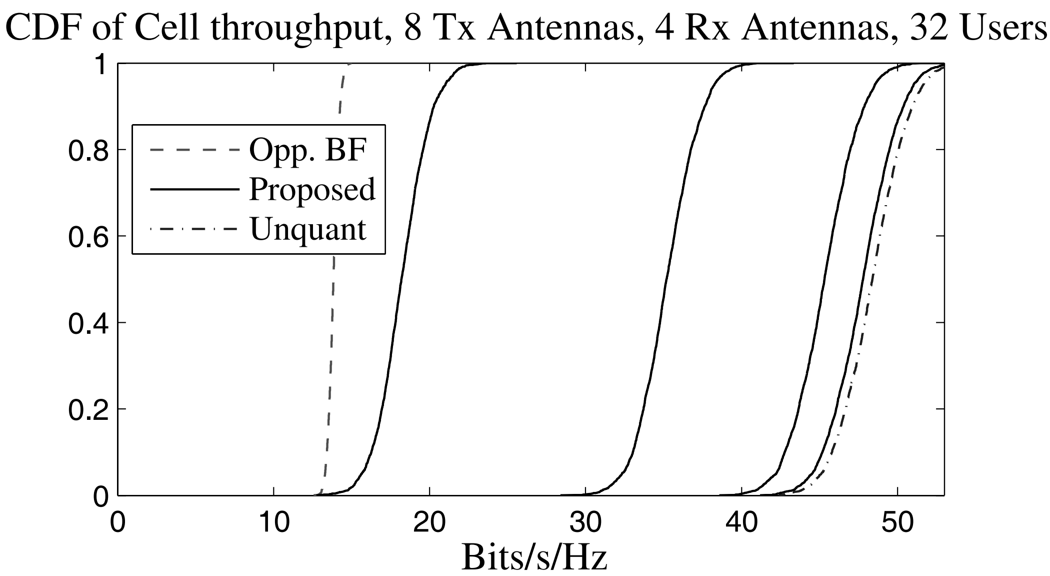

Figure 5: The CDF (over scenarios) of the average cell throughput for a cell with an eight-antenna base station and 32 four-antenna users. The throughput of opportunistic beamforming and channel norm supported zero-forcing beamforming with exact feedback is compared with the latter scheme using 0, 1, 3, or 5 bits of feedback per user (increasing performance).

5. Conclusions

Integration of multiple antennas at the transmitter and receiver leads to great gains in capacity relative to single-antenna systems, which drastically can improve the performance of next generation multiuser communication systems. In MU-MIMO, a major limiting factor is the amount of CSI to be fed back to the transmitter, since only the channel statistics and a limited number of feedback bits is typically available in practice per resource slot (time slot, frequency slot). Hence, the feedback design will be a critical point for the performance of the resource allocation.

In this paper, systems based on zero-forcing beamforming have been discussed. A general two-stage feedback design framework has been described, where the scheduling is divided into two stages: finding the optimal set of users and designing the precoding matrix. The scheduling performance was shown to depend on the splitting of the feedback bits between these two stages; sufficiently many bits should be fed back to aid the user selection, while the remaining bits are used to refine the feedback of selected users to improve the precoding matrix design. The quasi-optimal splitting factor is derived, and in this case the channel performance is drastically improved. In fact, even a simple heuristic approach gives a noticeable gain.

It has also been shown that the combination of long-term channel statistics and instantaneous quantized channel norm feedback provides sufficient information at the transmitter for efficient scheduling and precoding in wide area scenarios. The information is merged in the conditional statistics which is used to estimate the signal strength, as a function of the precoder, in an MMSE estimation framework. Asymptotic results show that for strong channel norm realizations the channel is almost fully determined, with a relative estimation error tending to zero. Hence, in systems with channel dependent scheduling where only users with strong channels are scheduled, only a few feedback bits describing the norm of the channel is required to provide similar performance as the case with perfect CSI. In practice these two methods can be cumulated, by splitting the quantization bits for the channel norm across the scheduling and the precoding stages.

When it comes to future work, the derivation of the optimal splitting factor, as well as the optimal quantization of the channel norm, are still open problems.

Acknowledgement

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