A closed-loop 2×4 downlink MIMO Framework for 5G New Radio using OpenAirInterface

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***Abstract*—We present the first-of-a-kind closed-loop 2×4 MIMO implementation for the downlink of 5G Open RAN using OpenAirInterface (OAI), which is capable of transmitting up to two transmission layers. Our implementation is a fully functional 5G New Radio (5G NR) system, including the 5G Core Network (5G CN), 5G Radio Access Network (5G RAN), as well as 5G NR User Equipment (UEs). This serves as a foundational framework for further advancements in the context of emerging Open RAN (O-RAN) development. A key feature of our implementation is the enhanced Channel State Information (CSI) reporting procedure at the UE, which includes Rank Indicator (RI), Precoding Matrix Indicator (PMI), and Channel Quality Indicator (CQI). It is adjusted for the extended configuration to maximize data rates. To demonstrate the performance of our implementation, we measure the downlink data rates using *iperf3* in two scenarios: (i) fixed channels to assess two-layer data transmission and (ii) *Rice1* channels for general transmission analysis. The obtained simulation results demonstrate that, compared to the existing 2×2 MIMO configuration in the OAI, our implementation improves the data rates in almost all scenarios, especially at the high Signal-to-Noise-Ratios (SNRs).**

***Index Terms*—MIMO, 5G NR, OpenAirInterface, PDSCH**

I. Introduction

Multiple-Input Multiple-Output (MIMO) technology serves as the cornerstone of modern wireless communication systems, which allows for sending and receiving multiple data signals simultaneously over the same radio channel [1]. In the context of fifth-generation mobile networks (5G), the 3GPP has standardized closed-loop MIMO transmission schemes that support up to 8 transmission layers [2], maximizing the potential for spatial multiplexing and diversity gains. These schemes rely on parameters related to channel state information (CSI) reported by user equipment (UE), which enables the Base Station (gNB) to optimize the transmission by determining the appropriate number of transmission layers, selecting the proper modulation and coding scheme (MCS), and choosing the most effective precoding matrix.

Historically, testing innovations and conducting practical experiments in mobile cellular networks was largely exclusive to network operators and vendors, due to the proprietary nature of the systems and strict licensing restrictions. However, this landscape is evolving with the advent of open source cellular stacks and affordable Software-Defined Radio (SDR) devices. Several open source platforms now support 5G Radio Access Network (RAN) simulation and deployment, including srsRAN [3]–[6], OpenAirInterface5G (OAI 5G RAN) [6]–[8], and Open AI Cellular (OAIC) [9], [10], the latter being an expansion of srsRAN. After a thorough evaluation, we select the OAI 5G RAN [7] for our work due to its comprehensive feature set and seamless integration with the OpenAirInterface 5G Core Network (OAI 5G CN) [11].

OpenAirInterface (OAI) is an open source software project providing a 3GPP-compliant implementation of key components for both 4G and 5G RANs, as well as the OAI 5G CN. The OAI 5G RAN and OAI 5G CN were introduced and described in [12], which presented the preliminary results available at the time of publication, along with a roadmap for future development and an overview of OAI's roles in both research and industrial contexts. Subsequent practical deployment scenarios were explored in [13]–[15]. The authors of [16] attempted to implement NR MIMO functions within OAI 5G RAN and verified their implementation using the built-in rfsimulator. While they provided detailed mathematical analyses, the downlink data rate was not presented. In [17], a framework for Multi-User MIMO based on OAI was demonstrated, along with detail analyses of the system's power and energy consumption, as well as the provisional result of the uplink data rate.

Currently, the OAI 5G RAN supports up to 4 transmitting (TX) antenna at the gNB. However, its CSI reporting scheme is still limited to the 2×2 configuration. This work develops a fully functional 5G NR system based on the OAI, and extends its CSI functionality. Building upon the existing MIMO implementation, we present, a 2×4 closed-loop MIMO downlink communication scheme, in which the gNB is equipped with up to 4 TX antennas and the UE with up to 2 receiving (RX) antennas. To be specific, at the gNB, we propose and implement a simple algorithm that enables the gNB to recognize the PMI for 1 and 2 transmission layers using 4 TX antennas. We also propose a new Modulation and Coding Scheme (MCS) selection scheme based on the reported CQI. On the UE side, we derive a new RI calculation scheme, as well as a new PMI reporting procedure. Our implementation establishes a framework for developing more advanced MIMO features within OAI, which potentially leads to bigger impact on the evolution of the emerging O-RAN.

The rest of this paper is organized as follows. Section. II provides an overview of the 5G NR downlink CSI reporting process and outlines our contributions to enhancing MIMO communication capabilities provided by OAI. Section III-A details our system configuration and the evaluation setup. In Section III-B, we present and discuss the results of the data rates achieved in various scenarios. Finally Section. IV concludes the paper.

Notation: Bold face upper case letters are used for matrices. The $\mathrm{Tr}(\mathbf{X})$, $\det(\mathbf{X})$, and $\mathbf{X}^\dagger$ stand for the trace and determinant and Hermitian transpose of $\mathbf{X}$, respectively.

II. Proposed CSI Reporting Procedure for 5G NR Downlink 2×4 Closed-loop MIMO

For closed-loop transmission, transmitters adapt their data transmission according to the conditions of the wireless channel, which is termed CSI in the context of 5G NR. In order to obtain the CSI, a gNB first broadcasts a known reference signal, referred to as Channel State Information Reference Signal (CSI-RS), to its UE. The UE uses the received CSI-RS to estimate the channel and then reports the CSI parameters to the gNB. For closed-loop MIMO transmission in 5G NR, the CSI feedback generally includes three indicators: CQI, PMI, and RI. Based on the CSI feedback, the gNB schedules downlink data transmissions via the Physical Downlink Shared Channel (PDSCH), determining the number of transmission layers, the precoding matrix, and the MCS. Fig. 1 illustrates the CSI reporting process. It is worth mentioning that the CSI feedback only serves as a reference for the gNB, which is not obligated to strictly follow it. However, in our implementation, the gNB fully utilizes all three indicators - RI, PMI, and CQI - to determine number of transmission layers, precoding matrix and MCS accordingly.

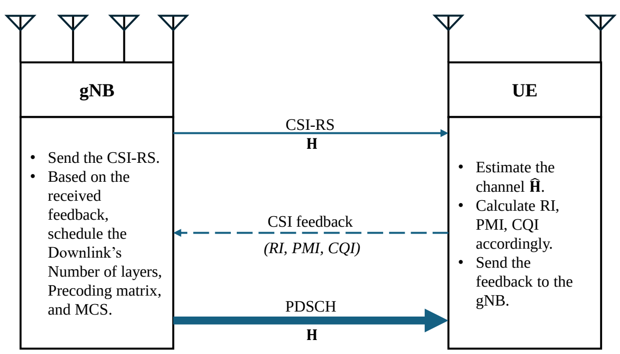

Fig. 1. A visualization of the CSI reporting procedure

A. Rank Indicator Computation

After estimating the wireless channel, the UE needs to compute and report the RI to the gNB. The RI is proportional to the rank of the wireless channel and reflects the potential for spatial multiplexing gains. In other words, the RI provides information regarding the maximum number of uncorrelated paths of the channel. This helps the gNB determine the optimal number of transmission layers based on current channel conditions. Other CSI indicators, such as PMI and CQI, are then computed based on the RI. In our setup, we provide two possible configurations: 2×4 MIMO and 1×4 MISO. Obviously, for the MISO case, the RI is always 1. On the other hand, in the MIMO case, the RI can be either 1 or 2. As mentioned previously, the current OAI's implementation only supports calculating the RI for 2×2 channels. In this work, we extend the RI calculation functionality so that the UE can calculate the RI regardless the number of TX antennas at the gNB. However, the number of the UE's RX antennas remains limited to 2, as our focus is on the gNB.

The steps to calculate the RI are summarized as follows:

- For each subcarrier, based on the CSI-RS, the UE estimates the channel, denoted by $\hat{\mathbf{H}}$. We adopt the channel estimation algorithm provided by OAI.
- Instead of directly computing the RI from $\hat{\mathbf{H}}$, the UE defines the matrix $\mathbf{M}$ as:

$$\mathbf{M} = \hat{\mathbf{H}}^\dagger \hat{\mathbf{H}} \tag{1}$$

  Note that the rank of $\mathbf{M}$ is also the rank of $\hat{\mathbf{H}}$. It is known from MIMO theory, the capacity of the corresponding channel depends of the eigenvalues of $\mathbf{M}$.
- Since the UE has 2 antennas, $\mathbf{M}$ is always a 2×2 matrix, regardless of the number of antennas at the gNB. Next, the UE calculates the following parameter:

$$\gamma = \frac{\sum_{i,j} m_{ij}^2}{\det(\mathbf{M})} = \frac{m_{11}^2 + m_{22}^2 + m_{12}^2 + m_{21}^2}{m_{11}m_{22} - m_{12}m_{21}} \tag{2}$$

  where m_{ij} denotes the (i,j)-entry of $\mathbf{M}$. Let σ_1 and σ_2 denote the eigenvalues of $\mathbf{M}$. Then, γ can be equivalently rewritten as

$$\gamma = \frac{\sum_{i,j} m_{ij}^2}{\det(\mathbf{M})} = \frac{\mathrm{Tr}(\mathbf{M}\mathbf{M}^\dagger)}{\det(\mathbf{M})} = \frac{\sigma_1^2 + \sigma_2^2}{\sigma_1 \sigma_2} = \frac{\sigma_1}{\sigma_2} + \frac{\sigma_2}{\sigma_1} \tag{3}$$

  Note that $\gamma \geq 2$.
- It is easy to see that a large value of γ implies a significant difference between σ_1 and σ_2, suggesting that $\hat{\mathbf{H}}$ is effectively rank-1 matrix. On the other hand, if σ_1 and σ_2 are of similar values, making $\hat{\mathbf{H}}$ closer to a rank-2 matrix, γ will approach 2. Thus, we define a threshold for γ, denoted by γ_{th}, to decide if the involving channel is rank-1 or rank-2.
- These steps are repeated for all subcarriers. If more subscarriers exhibit rank-2 channels than rank-1, the RI is set to 2, and vice versa.

After extensive testings, we find that $\gamma_{th} = 2.5$ yields the best performance in our considered scenarios.

B. Precoding Matrix Indicator Selection

While RI indicates the number of independent data streams the gNB can schedule, the PMI guides the BS how to multiplex these streams to optimize the rate. Specifically, PMI refers to an index that is a suggestion for the gNB to select a proper Precoding Matrix from a pre-determined codebook. Our implementation employs the Type I Single-Panel Codebook, which is described in the Sect. 5.2.2.2.1 of [2]. In this configuration, the PMI includes i_2 and i_1, which is further comprised of $i_{1,1}$, $i_{1,2}$, and $i_{1,3}$. The parameter i_2 essentially indicates a coarse estimation of the beam direction, while i_1 provides a finer estimate. In the current OAI implementation, which supports CSI functionality for only 2 TX antennas, there are four Precoding Matrices to select when RI $= 1$, and two when RI $= 2$. Hence, i_1 is not necessary and not reported.

The PMI computation becomes far more complex with 4 TX antennas at the gNB. As mentioned earlier, RI can be either 1 or 2, and the PMI depends on the value of RI. In both cases, there are 32 Precoding Matrices for the gNB to select from the codebook.

- If RI $= 1$, then i_2 and only $[i_{1,1}\ i_{1,2}]$ are reported. For 4 TX antennas, the possible values are $i_{1,1} = 0, 1, 2, ..., 7$; $i_{1,2} = 0$; and $i_2 = 0, 1, 2, 3$.
- If RI $= 2$, then i_2 and $[i_{1,1}\ i_{1,2}\ i_{1,3}]$ are reported. In this case, the values are $i_{1,1} = 0, 1, 2, ..., 7$; $i_{1,2} = 0$; $i_{1,3} = 0, 1$; and $i_2 = 0, 1$.

The process of determining the PMI (i.e. i_2 and $[i_{1,1}\ i_{1,2}\ i_{1,3}]$) and the appropriate Precoding Matrix is as follows:

- After receiving the CSI-RS, the UE selects a proper codebook based on the calculated RI.
- The UE then computes the Signal-to-Interference-and-Noise-Ratio (SINR) for each of the Precoding Matrices in the chosen codebook by summing up the received signal power and the interference and noise power across all the subcarriers. Note that, for the sake of optimizing the speed and memory consumption of the software, the OAI quantifies the calculated SINR directly into dB scale using a pre-determined lookup table. As a result, the returned values of the SINR are always integers.
- Finally, the UE chooses the PMI corresponding to the Precoding matrix that yields the highest SINR.

C. Channel Quality Indicator Selection

The final CSI parameter is the CQI, which is an integer between 0 and 15. It indicates channel quality and suggests the highest MCS suitable for the downlink transmission to achieve the required block error rate (BLER) under current channel conditions. The CQI is selected based on the maximum SINR calculated in the PMI selection step, using a lookup table that corresponds to a BLER of 0.1 or less. The lookup table for the SINR–CQI mapping is shown in Table I, which is constructed by from our extensive simulations. It is worth mentioning that in our provided table, the CQI values start from 4 as our simulation results show that the transmission is still reliable at this CQI value, even when the calculated SINR is low. Additionally, when RI $= 2$, the CQI is capped at 13, in order to guarantee the reliability of the two layers the downlink transmission.

CQI	**RI** $= 1$	**RI** $= 2$
4	SINR ≤ 2	SINR ≤ 2
5	SINR $= 3$	SINR $= 3$
6	SINR $\in \{4, 5\}$	SINR $\in \{4, 5\}$
7	SINR $\in \{6, 7\}$	SINR $\in \{6, 7\}$
8	SINR $\in \{8, 9\}$	SINR $\in \{8, 9\}$
9	SINR $= 10$	SINR $\in \{10, 11\}$
10	SINR $\in \{11, 12\}$	SINR $\in \{12, 13\}$
11	SINR $\in \{13, 14, 15\}$	SINR $\in \{14, 15\}$
12	SINR $= 16$	SINR $\in \{16, \ldots, 21\}$
13	SINR $\in \{17, 18\}$	SINR > 21
14	SINR $= 19$	
15	SINR > 19	

TABLE I
PROPOSED LOOKUP TABLE TO OBTAIN CQI FROM SINR

III. IMPLEMENTATION AND SIMULATION RESULTS

A. Implementation

A fully functional OAI 5G NR system includes the 5G CN, 5G RAN, and 5G NR UEs. The 5G CN and 5G RAN are typically run on the same host PC, however they can be configured to operate on different hosts as disaggregating is a key feature of the O-RAN architecture, to which the OAI is mainly dedicated. Using OAI's rfsimulator, UEs can be hosted either on the same or on different hosts from the 5G CN and 5G RAN. In this work we consider a single-user MIMO system but note that multiple NR UEs can be served by a single gNB.

In order to minimize transmission line delays, we select an all-in-one configuration for this work. The implemented system includes a gNB which consists of the OAI 5G CN, the OAI 5G RAN, and a UE. The OAI rfsimulator module supports various channel models. Again, to minimize the delay due to channel modeling, which could result in significantly lower calculated throughput compared to the true value, we adopted the *Rice1* model, which has just one tap. Additional taps in the channel model increase computational complexity, potentially extending the total transmission time and reducing the measured data rate.

We configure the gNB and the UE to operate on the band *n78*, which belongs to Frequency Range *FR1* and uses the Time Division duplex mode (TDD) [18]. In term of bandwidth, the system is set to utilize 106 resource blocks (RBs), with subcarrier spacing of 30 kHz, corresponding to a bandwidth of 40 MHz, including the guardband. The 5G NR frame structure is described in detail in [19].

Once the connection between the UE and the gNB is established, one can perform *iperf3* to measure the data rate between the two ends. In this work, we limited our consideration to the downlink performance on the PDSCH using the TCP protocol. The data rate of the implemented 4×2 implementation will be compared to the rate of the 2×2 configuration available within the OAI repository.

B. Results and Discussions

1) Fixed Channel: To investigate the effect of transmitting data via 2 layers, we first consider a fixed rank-2 wireless channel. The source code of the OAI rfsimulator was adjusted to fix the values of the wireless channel to a rank 2 matrix. In this way, the UE would always report an RI of 2, which makes the gNB always transmit data using 2 layers. Specifically, the 2×4 channel matrix is fixed to:

$$\mathbf{H}_{2\times 4} = \begin{bmatrix} 1 & 0.5 & 0.25 & 0.125 \\ 0.125 & 0.25 & 0.5 & 1 \end{bmatrix} \quad (4)$$

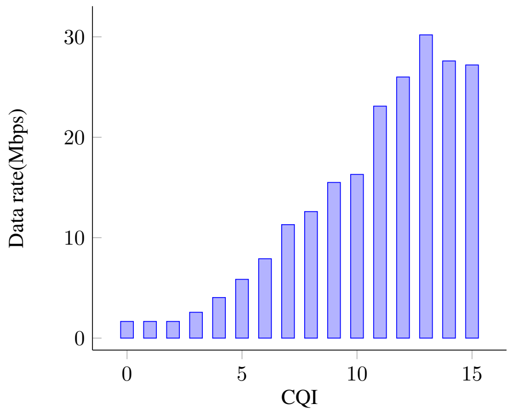

Fig. 2. Data rate versus the CQI value for noise-free transmission for the fixed channel in (4).

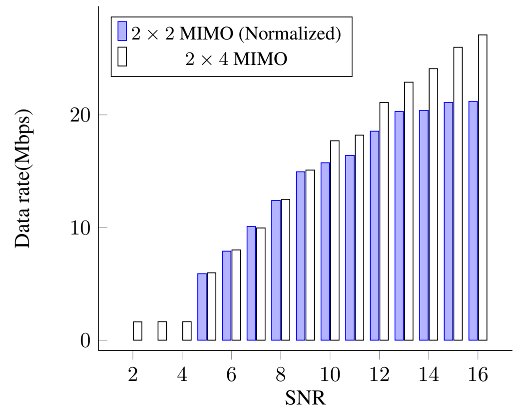

Fig. 3. Data rate versus SNR (i.e., normalized noise power) for the fixed channel in (4).

For this fixed channel, we consider two scenarios. In the first scenario, we investigate the data rate using different CQI values when the transmission is noise free. The source code of the UE is modified to report all possible CQI values. In the second one, we examine the performance of our system when additive white Gaussian noise (AWGN) is added to the received signal at the UE. The noise power is normalized relatively to the received signal power.

Fig. 2 plots the data rates for different CQI values where the transmission is noise free using the MIMO channel in 4. The CQI and MCS tables utilized are 5.2.2.1-2 and 5.1.3.1-1 from [2], respectively. According to these tables, the CQI values from 0 to 2 all result in MCS 0, resulting in the same data rate for these CQI values, as shown in Fig. 2. We can also observe that the data rate peaks at CQI 13 then declines afterward. The reason is that when the CQI increases, the coding rate and the order modulation are increased accordingly, while inter-layer interference is relatively fixed. After some point, the coding rate becomes unable to recover data reliably, leading to packet retransmissions and, consequently, a reduction in data rates. We note that this observation also holds for other $2{\times}4$ channels we experimented, which are omitted for the sake of brevity. Based on this observation, we set the maximum CQI value to 13 in Table I when $\mathrm{RI} = 2$.

Next, Fig. 3 demonstrates the data rate versus SNR (i.e. for noisy channels). It also includes the data rates for the fixed 2×2 MIMO channel given by:

$$\mathbf{H}_{2\times 2} = \begin{bmatrix} 1 & 0.5 \\ 0.5 & 1 \end{bmatrix} \quad (5)$$

We compare our 2×4 implementation to the 2×2 implementation from the original OAI 5G RAN source code [7], but the rfsimulator's source code was customized to always fix the simulated channel to 5. Comparing two systems with different numbers of antennas, it is important to remark that the OAI rfsimulator takes twice more time for the $2{\times}4$ MIMO case than the 2×2 MIMO case since performing matrix multiplications on a $2{\times}4$ channel is twice as complex as those for the 2×2 case. We also remark that *iperf3* also includes the time spent by the rfsimulator to calculating the achieved data rate. Thus, to obtain a fair comparison, we halve the data rates for the 2×2 MIMO case. We can observe from Fig. 3 that the data rate increases with SNR, which is expected.The gains of the 2×4 MIMO systems over the 2×2 counterpart are significant for high SNRs. Note also that for the 2×2 MIMO case, the data rates for the first three values associated with SNRs of 2, 3, and 4 are not shown. The reason is that in the OAI's implementation, for these low SNRs, the UE reports $\mathrm{CQI} = 0$ and the gNB automatically selects $\mathrm{MCS} = 9$, which is very high for low SNRs. Indeed, in our experiment, we see that this MCS results in a flood of re-transmissions and a high BLER. As a result, the connection between the two ends is unreliable, and the UE eventually stops working after some time.

2) Random Channel: In this subsection, we study the performance of the implemented 2×4 MIMO system using *Rice1* channel model. We also consider two scenarios, similar to the fixed channel cases described in the previous subsection. Fig. 4 plots the data rate for different CQI values for the noise-free scenario. Again, the data rates for CQI values of 0, 1, and 2 are identical since all correspond to the same MCS. On the higher end, the data rates for CQI 14 and 15 are nearly the same. This can be attributed to the fact that, at these CQI values, the transmission is sensitive to the inter-layer interference. We observe that for when $\mathrm{CQI} = 15$, re-transmissions occur slightly more often than for $\mathrm{CQI} = 14$. This explains why $\mathrm{CQI} = 15$ offers a minor improvement in data rate over $\mathrm{CQI} = 14$. It would be reasonable to assume that if the CQI was allowed to increase, the data rate would decrease for higher CQI values, similar to what was observed in the previous section.

In the final numerical experiment, we study the performance of our proposed system for noisy channels. Fig. 5 demonstrates the data rate as a function of the SNR. Notably, when $\mathrm{SNR} =$ 10 dB, (i.e. the normalized noise power is -10 dB), the data rate peaks and equals the data rate of the noise-free channel where the highest CQI is adopted (cf. Fig. 4). When compared to the 2×2 MIMO case, the 2×4 configuration consistently

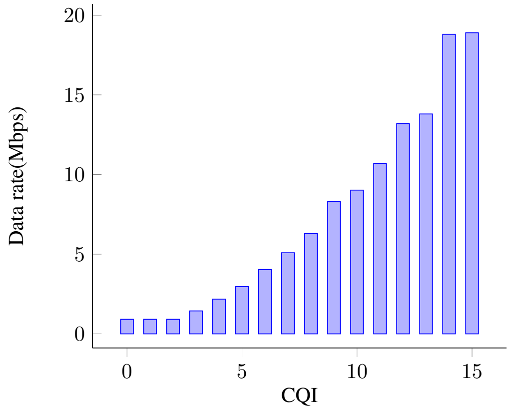

Fig. 4. Data rate versus the CQI value for noise-free transmission for the fixed channel in for the *Rice1* channel model.

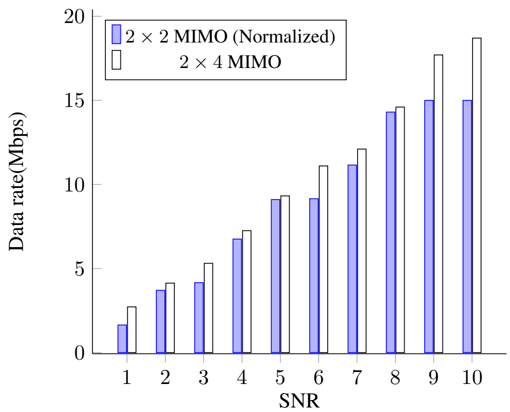

Fig. 5. Data rate versus SNR (i.e., normalized noise power) for the *Rice1* channel model.

offers an improvement in data rates, in particular at the high values of SNR.

IV. Conclusion and Future Work

In this paper, we have implemented a closed-loop 2×4 MIMO system based on the 5G RAN OAI, supporting up to 2 transmission layers using Type I codebook. Specifically, a fully functioning 5G NR system, which includes 5G CN, 5G RAN, and NR UEs was built for the first time, which serves as a framework for further extensions or optimizations. At the UE, we improved the RI calculation, extended the PMI reporting procedure to support 4 TX antennas at the gNB,, and modified the CQI reporting to maximize the data rates of 2-layer transmissions. The simulation results have shown that the implemented 2×4 MIMO system offers considerable improvements in terms of the data rates in all the considered scenarios over the 2×2 MIMO counterpart currently available on OAI, especially at the high SNRs.

For future work, our first priority is to replace the OAI rfsimulator by real-world transmission using SDR devices at both the gNB and the UE. We aim to report our results for real-world transmission in the very near future. Additionally, we plan to extend the current single-user 2×4 MIMO setup to support multi-user MIMO, which is the primary motivation for this work.

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