Capacity and Robustness of Single- and Dual-Polarized MIMO Systems in Office and Industrial Indoor Environments

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***Abstract*— A study on the suitability of multiple-input multiple-output (MIMO) architectures employing either single- or dual-polarization antennas is presented, with the purpose of identifying not only which architecture provides better average capacity performance, but also which is more robust for avoiding low channel rank. It is expected that systems with high robustness will be required for MIMO in demanding industrial applications. A measurement campaign employing dual-polarized 8x8 patch arrays at 2.4 and 5.2 GHz is analyzed, where measurements were performed in two very distinct indoor scenarios: an office building and an industrial environment. For both environments the performance of three 4x4 subsystems (dual-polarized, vertical-polarized and horizontal-polarized) are compared in terms of the average capacities attained by these systems and their eigenvalue distributions. Average capacities are found to be only marginally different, indicating little advantage of dual-polarized elements for average performance. However, an eigenvalue analysis indicates that the dual-polarized system is most robust for full-rank MIMO communications, by providing orthogonal channels with more equal gain.**

I. INTRODUCTION

Although multipath signals in wireless systems have traditionally been considered wasteful and/or harmful to system performance, studies done in [1, 2], have shown that multipath propagation can increase the capacity of a wireless communication system, provided multiple antennas are used at the transmitter and receiver. Multiple-input multiple-output (MIMO) systems employ multiple antennas at both the transmitter and the receiver allowing parallel spatial data pipes to be created within the same physical channel, resulting in increased capacity and improved spectral efficiency [3].

Increased use of wireless technologies in homes and businesses has resulted in high interest in MIMO architectures for indoor environments. The motivation for our new study in this area is twofold. On one hand, most previous indoor studies have been conducted in office environments and none (to the author's knowledge) in industrial environments, thus limiting to some extent the generality of the previous findings. On the other hand, it is expected that industrial applications will be more demanding [4], requiring a high degree robustness against factors such as low MIMO channel rank. Our purpose, therefore, is to compare the office and industrial indoor environments, not only in terms of average performance, but also in terms of the ability of MIMO systems to be robust in diverse propagation environments.

This paper presents the results of investigations that were conducted in an office and an industrial environment, based on wideband measurements recorded at 2.4 and 5.2 GHz using a dual-polarized (dual-pol) antenna system. Dual-pol elements are interesting from the standpoint of robustness, since they provide two orthogonal channels even in a keyhole (or rank-1) MIMO channel. Also, dual-pol elements can provide more compact antenna designs by allowing pairs of elements to be co-located [5, 6]. The main drawback of dual-pol elements is possible reduced average receive power when cross-pol scattering is limited.

II. MEASUREMENT CAMPAIGN

A. Measurement System and Data Processing

The experimental wideband 8×8 channel sounder used in the measurement campaign is as explained in [7]. The measurements were done at 2.4 and 5.2 GHz in both environments, using a dual-polarized linear patch array at both the transmitter and receiver, shown schematically in Fig. 1.

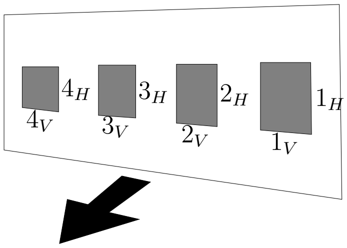

Fig. 1. Dual-polarized patch array employed for measurements. Each element has ports to excite linear vertical (V) and horizontal (H) polarization.

At each location described below, 20 channel snapshots were recorded with 200 ms between snapshots. Although the measurement system is capable of probing channels with 80 MHz of instantaneous bandwidth, only 30 MHz of bandwidth was used in this study, consistent with the limited operation of the narrowband patch elements.

B. Measurement Locations

The measurements in the industrial environment were carried out at the Heavy Machinery Lab (HML). As shown in Fig. 2, the transmitter (TX) was placed at the entrance of the room and the receiver (RX) was placed at 6 different locations within the room.

The HML environment is mainly comprised of brick walls, concrete floors, wooden doors (except for the entrance which consists of a glass door) and fluorescent lights. The equipment in the lab comprises machinery, a Gaussian cage and metallic work benches with rubber surfaces.

The office measurements were carried out at the Carl and Emily Fuchs Institute of Microelectronics (CEFIM). As shown in Fig. 3, the TX was placed at a single fixed position in the corridor and the RX was placed at 11 different office and laboratory locations.

The CEFIM environment typically consists of “drywall” partitioning, carpeted floors, wooden doors and fluorescent lights. The corridors are lined with laminated posters, metallic bins and chairs. All rooms contain furniture, white boards, air conditioners, steel air vents, computer equipment and large windows covering the width of the room.

In the HML, two RX orientations were considered (0^0 and 90^0 relative to TX), and in CEFIM, two TX orientations were considered (0^0 and 90^0 relative to RX). These two orientations are referred to as Set A and B, respectively. HML and CEFIM are buildings at the University of Pretoria and both the 2.4 GHz and 5.2 GHz measurements were done at the same positions.

C. Channel Normalization and Capacity

Since the measurements were taken using dual-polarized antennas at the receiver and transmitter, the 8×8 channel matrix is represented as

$$\mathbf{H} = \begin{bmatrix} \mathbf{H_{VV}} & \mathbf{H_{HV}} \\ \mathbf{H_{VH}} & \mathbf{H_{HH}} \end{bmatrix} \tag{1}$$

where $\mathbf{H_{IJ}}$ is a subchannel matrix consisting of the polarization *I* and *J* at the RX and TX, respectively. For the purpose of analyzing systems employing different polarizations, 4×4 subsets are extracted from the full 8×8 channel matrix. The response of a V-pol or H-pol system is given directly by $\mathbf{H_{VV}}$ and $\mathbf{H_{HH}}$, which use antenna elements $\{1_V, 2_V, 3_V, 4_V\}$ or $\{1_H, 2_H, 3_H, 4_H\}$, respectively. The dual-pol system is analyzed using the outer elements, or $\{1_H, 1_V, 4_H, 4_V\}$.

In order to preserve changes in received power with position, channels are normalized to ensure unit average single-input single-output (SISO) gain for the complete environment (but not for each location). The normalization is computed as $\tilde{\mathbf{H}}^{(m,n)} = \alpha^{-1/2}\mathbf{H}^{(m,n)}$ with

$$\alpha = \frac{1}{N_r N_t N_f N_l}\sum_{n=1}^{N_l}\sum_{m=1}^{N_f}\left(\left\|\mathbf{H}_{\mathbf{VV}}^{(m,n)}\right\|_F^2 + \left\|\mathbf{H}_{\mathbf{HH}}^{(m,n)}\right\|_F^2\right)/2 \tag{2}$$

where $\mathbf{H}^{(m,n)}$ and $\tilde{\mathbf{H}}^{(m,n)}$ are the measured and normalized channel matrices for the mth frequency bin at location n, $\|\cdot\|_F$ is Frobenius norm, and N_r, N_t, N_f and N_l are the number of receivers, transmitters, frequency bins, and locations, respectively.

Uninformed transmit channel capacity is computed as [1]

$$C = \log_2 \det\left[\mathbf{I} + \frac{\rho}{N_t}\tilde{\mathbf{H}}\tilde{\mathbf{H}}^H\right], \tag{3}$$

where $\mathbf{I}$ is the identity matrix, ρ is the assumed average SISO signal-to-noise ratio (SNR), $\tilde{\mathbf{H}}$ is the normalized channel matrix and $\{\cdot\}^H$ is the conjugate matrix transpose. The eigenvalues of the channel are computed as the squares of the singular values of $\tilde{\mathbf{H}}$. A reference SNR of 20 dB was chosen for the computations.

III. RESULTS

The average capacities for all locations in the HML and CEFIM environments are given in Tables I and II, respectively, indicating that none of the systems capture the ideal capacity of a 4×4 i.i.d. Gaussian channel (27 bits/s/Hz), but rather only provide 45% to 70% of this maximum value. For the single V-pol and H-pol cases, the reduced capacity indicates limited multipath and higher spatial correlation. Although the dual-pol array increases the conditioning of the channel (as we will show later), the capacity level is not significantly different from the single-pol cases due to the reduced receive power, resulting from the weak cross-pol subchannels. In other words, when using dual-polarization, the increase in rank and the reduction in power appear to approximately cancel.

The main difference in capacity performance of HML versus CEFIM (as depicted in Fig. 4 and Fig. 5) is the frequency dependence. For HML, 5.2 GHz has the better performance, while for CEFIM, 2.4 GHz has better performance. This could partially be explained due to the different nature of propagation in the two environments: in CEFIM, transmission through walls should be important, while in HML, large metal machines and partitions would only support reflective mechanisms.

TABLE I

AVERAGE CAPACITIES IN HML WITH RESPECT TO ANTENNA POLARIZATION AND ORIENTATION, AND CARRIER FREQUENCY

		2.4GHz [b/s/Hz]	5.2GHz [b/s/Hz]
Dual-Pol	Set A	15.0	17.1
	Set B	16.9	17.9
V-Pol	Set A	14.3	13.9
	Set B	14.4	14.9
H-Pol	Set A	15.0	16.6
	Set B	17.0	18.9

TABLE II

AVERAGE CAPACITIES IN CEFIM WITH RESPECT TO ANTENNA POLARIZATION AND ORIENTATION, AND CARRIER FREQUENCY

		2.4GHz [b/s/Hz]	5.2GHz [b/s/Hz]
Dual-Pol	Set A	18.1	14.8
	Set B	18.0	15.0
V-Pol	Set A	16.7	12.6
	Set B	16.2	11.8
H-Pol	Set A	18.9	16.0
	Set B	18.0	16.1

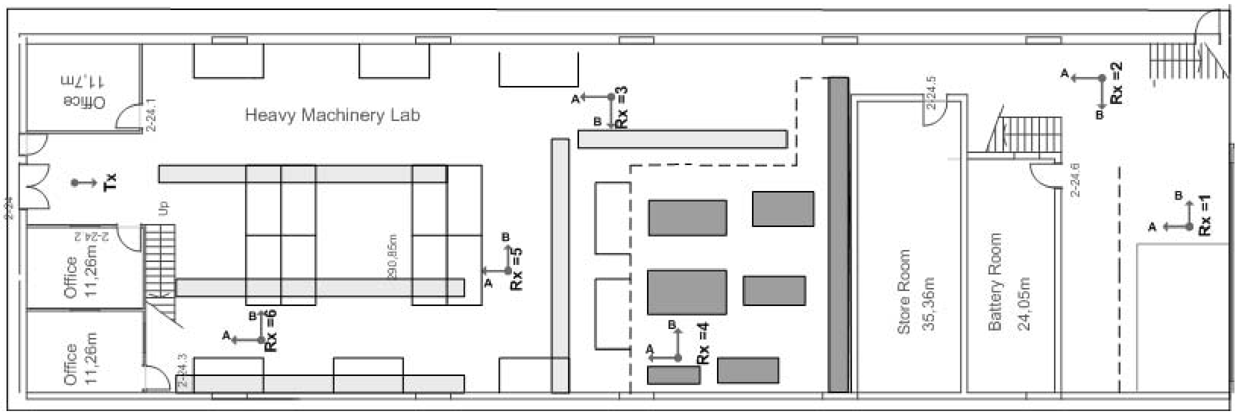

Fig. 2. The HML layout showing the transmitter and receiver. Rx=n refers to the locations where the receiver was placed. Arrows show the orientation of the arrays for the different cases.

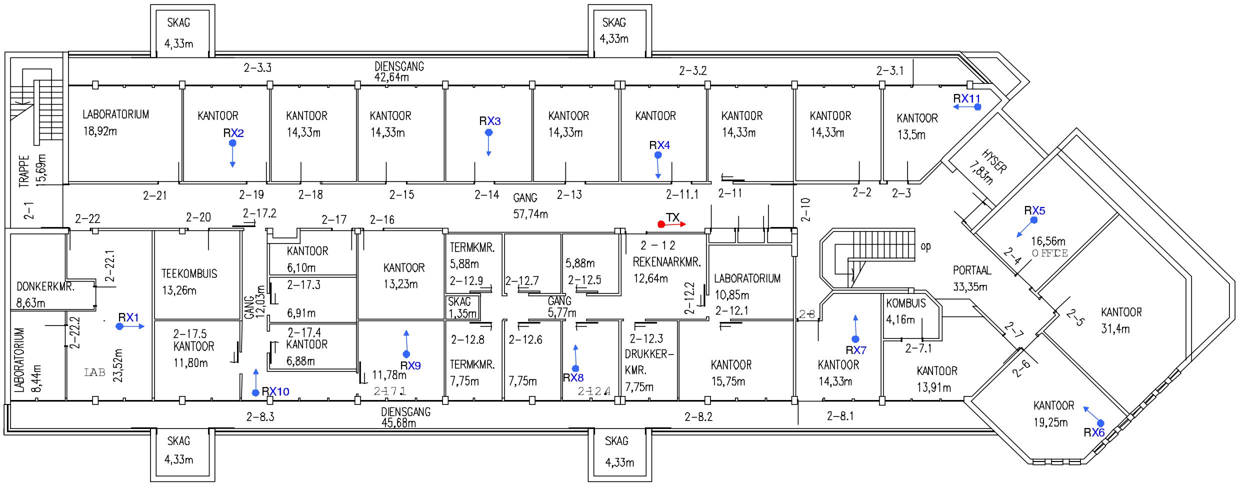

Fig. 3. The CEFIM layout showing the transmitter and receiver. Rx=n refers to the locations where the receiver was placed.

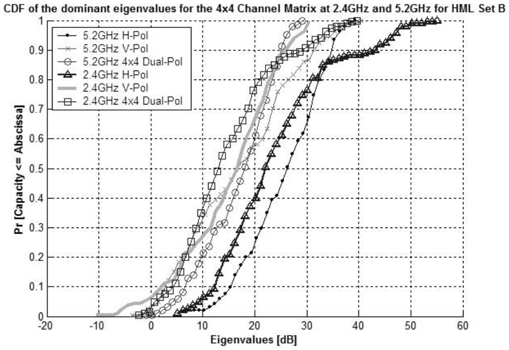

Fig. 4. The CDF of the eigenvalues of 2.4 GHz vs. 5.2 GHz for HML Set B.

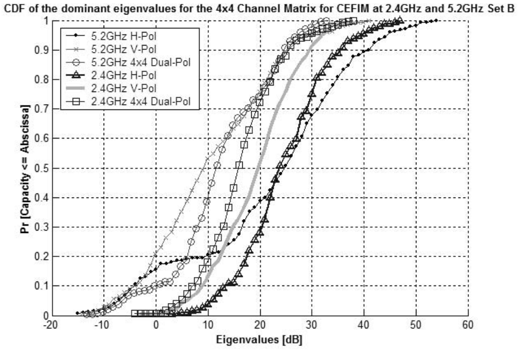

Fig. 5. The CDF of the eigenvalues of 2.4 GHz vs. 5.2 GHz for CEFIM Set B.

A. *Performance Analysis of Antenna Polarization*

Average capacity values for HML in Table I suggest that the systems can be ranked in order of decreasing performance as H-pol, dual-pol, and V-pol. The same ranking is also found for CEFIM in Table II. These differences can be attributed to the fact that H-pol has a wider azimuthal pattern than V-pol, leading to a higher average channel gain. However, the differences in the capacity for the two environments are not sufficient to support the conclusion that one system performs better than the others.

To further analyze the systems, the eigenvalue distributions were obtained as depicted in Figures 6-9. Only the first

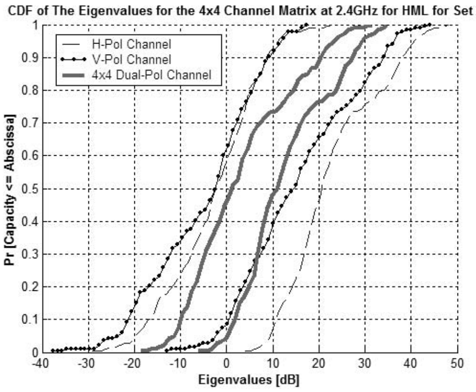

Fig. 6. The dominant eigenvalues for the dual- and single-polarized systems in HML at 2.4 GHz for Set A.

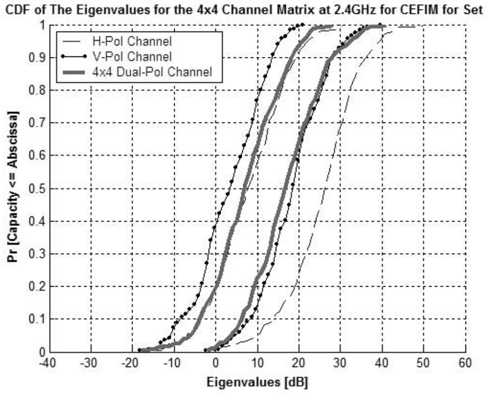

Fig. 7. The dominant eigenvalues for the dual- and single-polarized systems in CEFIM at 2.4 GHz for Set A.

two eigenvalues are shown, since the other eigenvalues are quite weak and do not significantly contribute to the capacity. Similar distributions were obtained for the others scenarios (not shown).

It is evident in the figures that the dual-pol system suffers a power loss relative to the single-pol systems. This is also apparent from the 10% and 50% CDF levels of the first eigenvalue, as shown in Table III. This power loss is to be expected, because most indoor environments exhibit depolarization ratios (defined here as the ratio of the average receive power of same-pol to cross-pol) on the order of 3 to 10 dB. However, if the reduced power level is a problem, it is anticipated that a real communications system could employ power control to overcome this loss.

Our second objective is to determine which system is more robust with respect to different types of propagation channels, which is especially important for industrial applications. In our present context, we define a robust MIMO system as one that can provide at least two parallel subchannels that have almost equal quality (equal gain) almost all of the time. To study this idea concretely, we compute the ratio of the first two channel eigenvalues in dB, which we refer to as the "eigenvalue spacing." Note that in the results that follow, lower eigenvalue spacing is better, indicating more similar channel gains.

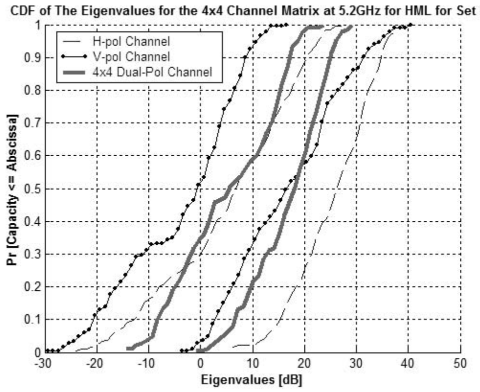

Fig. 8. The dominant eigenvalues for the dual- and single-polarized systems in HML at 5.2 GHz for Set B.

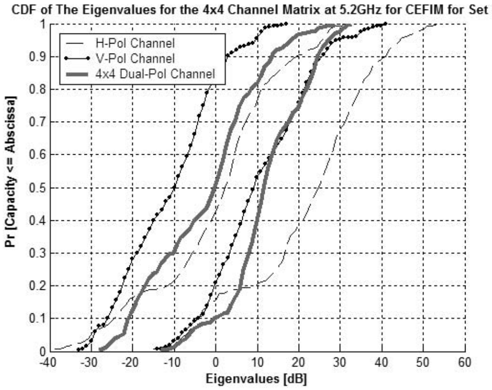

Fig. 9. The dominant eigenvalues for the dual- and single-polarized systems in CEFIM at 5.2 GHz for Set B.

CDFs of the eigenvalue spacing for the different antenna systems are plotted in Fig. 10 and Fig. 11 for the two environments at 2.4 GHz and Fig. 12 and Fig. 13 for the same environments at 5.2 GHz. In each CDF, the 50% level indicates roughly which system has lower spacing on average, and the 90% level indicates which system has lower spacing most of the time, since only 10% of the cases would have higher (worse) eigenvalue spacing.

The 50% and 90% levels are tabulated in Table IV, showing that the dual-pol system offers a 10-20 dB improvement in eigenvalue spacing both on average and for low outage level. This result suggests that dual polarization is more robust with respect to the operating environment, as long as the somewhat

TABLE III
THE 10% AND 50% LEVELS FOR THE DOMINANT EIGENVALUE FOR HML AND CEFIM AT 2.4 GHZ AND 5.2 GHZ

		2.4GHz Set A		5.2GHz Set B	
		10% [dB]	50% [dB]	10% [dB]	50% [dB]
Dual-Pol	HML	3	11	7	18
	CEFIM	6	17	0	11
V-Pol	HML	1	15	3	16
	CEFIM	9	19	-4	9
H-Pol	HML	11	21	15	26
	CEFIM	14	26	-4	25

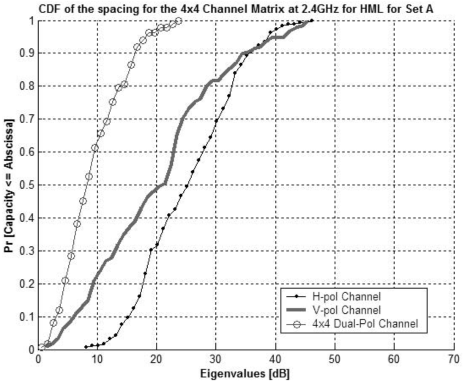

Fig. 10. The spacing between the eigenvalues for the dual- and single-polarized systems in HML at 2.4 GHz for Set A.

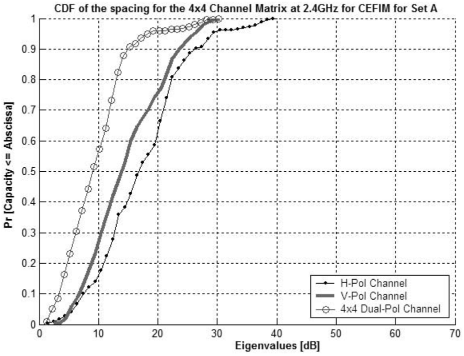

Fig. 11. The spacing between the eigenvalues for the dual- and single-polarized systems in CEFIM at 2.4 GHz for Set A.

reduced average power can be tolerated.

IV. CONCLUSION

In this work, the performance of a dual-pol MIMO system in an office and industrial environment was analyzed. The average capacities were found to be between 45% and 70% of the ideal maximum, indicating somewhat reduced channel quality compared to an ideal i.i.d. Gaussian channel.

Regarding average capacity, the dual-pol system did not offer any advantages over single-pol, in contrast to results reported in [6]. This could possibly be attributed to the fact that the dual-pol system exhibits a power loss relative to the single-pol system, basically offsetting the increased capacity from improved channel conditioning.

TABLE IV
THE 50% AND 90% LEVELS OF THE SPACING BETWEEN THE FIRST TWO EIGENVALUES FOR HML AND CEFIM AT 2.4 GHZ AND 5.2 GHZ

		2.4GHz Set A		5.2GHz Set B	
		50% [dB]	90% [dB]	50% [dB]	90% [dB]
Dual-Pol	HML	8	16	9	19
	CEFIM	9	15	14	25
V-Pol	HML	20	35	18	32
	CEFIM	14	24	19	40
H-Pol	HML	25	36	16	34
	CEFIM	17	26	21	29

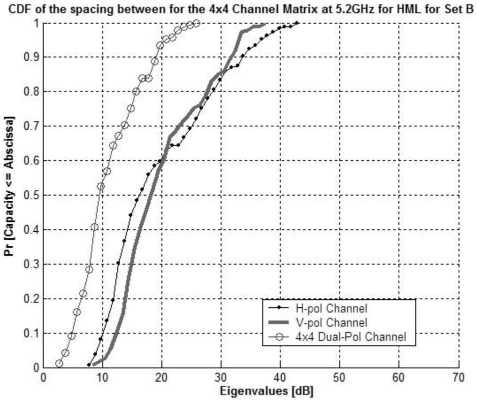

Fig. 12. The spacing between the eigenvalues for the dual- and single-polarized systems in HML at 5.2 GHz for Set B.

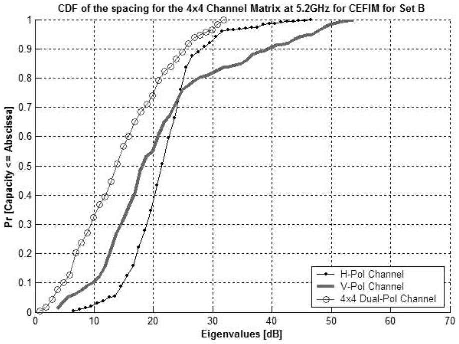

Fig. 13. The spacing between the eigenvalues for the dual- and single-polarized systems in CEFIM at 5.2 GHz for Set B.

The robustness of single- versus dual-pol systems with respect to changing environment was studied by looking at the eigenvalue spacing of the first two channel eigenvalues. Results indicate 10-20 dB reduction in the spacing when dual polarization is employed, suggesting that dual polarization is a good candidate for demanding industrial applications.

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