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Effective Degree-of-Freedom of a Compact Six-Port MIMO Antenna

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***Abstract*—In this paper, we confirm that angle and polarization diversities are indeed the dominant diversity mechanisms of a recently proposed compact six-port MIMO antenna array, as it exhibits similar effective degree-of-freedom (EDOF) performance as that of the ideal array with co-located antenna elements evaluated in propagation scenarios with different angular spreads. Furthermore, the same approach can also be applied to determine the relative contributions of different diversity mechanisms to the EDOF performance of a given array.**

I. INTRODUCTION

Recently, a compact co-located six-port antenna has been experimentally verified to offer six degrees-of-freedom (DOFs) in a rich scattering environment [1]. The experiment was performed in a 6×6 MIMO setup using the compact six-port array at the receive (RX) end and a larger six-port array at the transmit (TX) end. Both these arrays have previously been reported in [2], where the antenna elements of both arrays are designed to yield the desired radiation pattern characteristics of the fundamental electric (E) and magnetic (M) dipoles.

The TX antenna array is designed for reference purpose using standard antenna elements, occupying a cubic volume of $(0.75\lambda)^3$ (λ denotes the wavelength). On the other hand, in order to demonstrate that six DOFs are attainable using the co-located six-port E/M dipole array [3], electrically smaller antenna elements are used in the compact RX array. Occupying a cubic volume of $(0.24\lambda)^3$, the phase centers of the three electric dipoles of the RX array are essentially co-located at the center of the array structure, whereas the magnetic dipoles are placed at about 0.1λ away from the array center. Using the two arrays, six effective DOFs (EDOFs) [4] are attained from the measured 6×6 MIMO channels in a non-line-of-sight (NLOS) scenario with rich multi-path propagation.

The achieved compactness of the six-port RX array implementation is a substantial improvement in comparison to existing designs in the literature. In fact, it approaches the analytical limit obtained in [5], where the dimension of the 12-element MIMO cube needs to be about $(0.2\lambda)^3$ in order to obtain six DOFs, if the mutual coupling is taken into account. Nevertheless, unlike the ideal E/M dipole array, which is in theory infinitely small, the compact array is implemented within a finite volume. Furthermore, as described above, the phase centers of the elements in the compact array do not exactly coincide, *i.e.*, there is finite spacing between the ports. Consequently, it is conceivable that space diversity that is not present in the ideal array can to some extent contribute to the EDOF performance of the compact array. If the space diversity is found to be significant in the compact array, the claim in [1] that the measured six EDOFs are primarily the result of angle and polarization diversities no longer holds. In other words, the fabricated compact array must correctly replicate the diversity characteristics of the ideal co-located E/M dipole array.

Therefore, in this paper, we analyze the underlying diversity mechanisms of the compact array, in order to determine potential contribution from space diversity in the achieved DOF performance. For this purpose, we use the EDOF metric to evaluate the compact array when the array is subjected to a wide range of angular spreads in the channel. This is because arrays with only polarization and angle diversities can provide at best two EDOFs when the angular spread becomes very small, and hence it follows that space diversity is necessarily present if higher EDOF is obtained in such a scenario.

It should be noted that the same evaluation approach can be used to determine the underlying diversity mechanisms of an arbitrary array, particularly the relative importance of angle and polarization diversities versus space diversity in facilitating the EDOF performance of the array.

II. DIVERSITY MECHANISMS OF THE COMPACT ARRAY

To study the diversity mechanism of the compact six-port array, we employ the Kronecker channel model. In particular, the channel for evaluating a given array is defined by $\mathbf{H} = \mathbf{R}^{1/2}\mathbf{H}_{\text{IID}}$, where $\mathbf{R}$ denotes the correlation matrix of the array. Here, we have assumed that the array of interest is at the RX end. The correlation matrix $\mathbf{R}$ of the array-under-test can be obtained using the measured radiation patterns of its antenna elements together with the assumed propagation channel. In this study, we use a 3D Gaussian distribution to describe the angular power spectrum (APS) of the propagation channel. In addition to compare the compact array and the ideal E/M dipole array, we also evaluate the EDOF performance of the larger reference six-port TX array. This is because the larger spacing between the phase centers of the antenna elements (of about 0.5λ) in the reference array is expected to offer a higher DOF through space diversity.

In Fig. 1, we obtain the eigenvalues γ_k of $\mathbf{R}$ for the ideal, compact and reference arrays when the Gaussian APS is of

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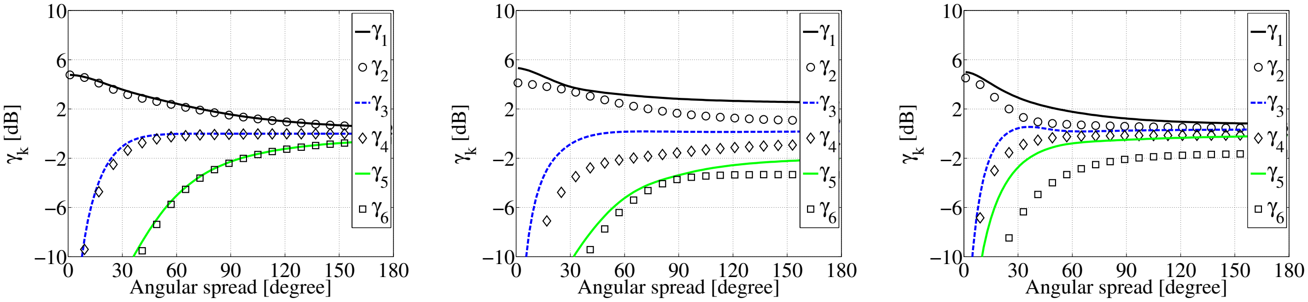

(a) Eigenvalue of $\mathbf{R}_{\text{ideal}}$ (b) Eigenvalue of $\mathbf{R}_{\text{compact}}$ (c) Eigenvalue of $\mathbf{R}_{\text{ref}}$

Fig. 1. Eigenvalues of six-port arrays given the 3D Gaussian APS with different angular spreads.

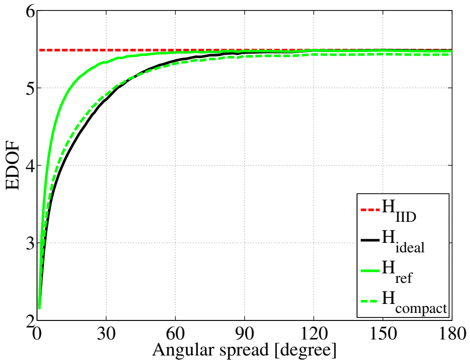

Fig. 2. EDOF of $\mathbf{H}_{\text{ideal}}$, $\mathbf{H}_{\text{compact}}$ and $\mathbf{H}_{\text{ref}}$.

different angular spreads. The six eigenvalues are normalized by their mean magnitude in order to highlight the spread among them. It is noted that a similar plot as in Fig. 1(a) has also been presented in [6].

For larger angular spreads, the eigenvalues of the ideal and compact arrays appear in three pairs, with two eigenvalues of similar magnitudes in each pair. The slight discrepancy in the case of the compact array as compared to the ideal array is the result of non-ideal realization of the E/M dipole patterns in the compact array. On the other hand, the eigenvalues of the reference array do not share this trend at larger angular spreads, due to additional contributions from space diversity. However, for all three arrays, the gain imbalance among the eigenvalues is reduced as the angular spread is increased, indicating better orthogonality and DOF in the MIMO channel. It can also be observed that the gain imbalance is the smallest for the reference array, which points to the benefit of space diversity in array design.

For very small angular spreads, only two eigenvalues can be effectively utilized in all cases. However, the eigenvalues of the reference array fall off at a slower rate than those of the other two arrays when the angular spread reduces. This is due to space diversity resulting from the relatively large spacing between the element phase centers.

The impact of space diversity can be further observed from the EDOF performance of the corresponding channels $\mathbf{H}_{\text{ideal}}$, $\mathbf{H}_{\text{compact}}$ and $\mathbf{H}_{\text{ref}}$ in Fig. 2, for a reference SNR of 20 dB. The performance of the IID Rayleigh channel $\mathbf{H}_{\text{IID}}$ is also given. According to the result, the EDOFs of all three arrays converge to that of the IID channel in the case of large angular spreads. However, it is noted that the reference array achieves better performance than the ideal E/M dipole array in the case of small angular spreads. This is due to space diversity, which is exploited to improve the performance of the reference array as angle and polarization diversities become less effective at small angular spreads. On the other hand, the compact array shares a similar performance as that of the ideal E/M dipole array. Therefore, we conclude that the achieved EDOF performance using the compact array is only attributed to angle and polarization diversities.

III. CONCLUSIONS

In this work, we show that the six DOFs that are achieved by a compact co-located array in a previous experiment are the result of angle and polarization diversities, as in the case of an ideal E/M dipole array. A further confirmation is obtained in that when a larger array from the same previous experiment is studied, space diversity is found to contribute significantly to its EDOF performance. This finding also indicates that space diversity should be exploited whenever possible in array design, in order to complement angle and polarization diversities and to maximize the EDOF performance.

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