Selective Excitation of Characteristic Modes on an Electrically Large Antenna for MIMO Applications

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Abstract—**The selective excitation of individual characteristic modes for MIMO applications on an electrically large antenna structure is investigated. The characteristic mode analysis yields that a large number of modes is significant and thus basically suited for use in a multi-mode antenna. In order to find appropriate excitation arrangements for the individual characteristic modes, they are grouped according to their symmetry properties. It is found that characteristic currents belonging to the same group are correlated and thus cannot be excited separately, resulting in a reduced set of uncorrelated antenna ports.**

Index Terms—**Multiple-input multiple-output (MIMO), multi-mode antenna, characteristic modes, correlation.**

I. Introduction

Multiple-input multiple-output (MIMO) has become a fundamental technique in modern wireless communication systems. In order to enable MIMO in spatially restricted applications such as modern mobile devices, multi-mode antennas have attracted a lot of attention in recent years [1], [2]. Instead of using several antennas located spatially apart, a single antenna structure is employed on which characteristic modes are excited.

Due to their orthogonality properties, the characteristic modes are most suitable for MIMO applications, offering pattern and polarization diversity. Therefore, by selectively exciting individual characteristic modes, uncorrelated antenna ports are realized.

Mostly, multi-mode antennas based on the theory of characteristic modes have been reported for applications where the antenna structure is of electrically small to intermediate size, e.g. a current smartphone chassis in typical LTE frequency bands, utilizing just a few characteristic modes [3], [4]. However, as the need for higher data rates steadily grows, future techniques, such as massive MIMO, could make use of considerably greater numbers of characteristic modes [5], which generally are supported by electrically large antenna structures.

Therefore, the selective excitation of characteristic modes and its limitations on an electrically large antenna structure are investigated in this paper. To this purpose, section II summarizes the basic properties of the characteristic modes. In section III, general aspects of the selective excitation of characteristic modes are explained. In sections IV and V, the modal analysis and modal excitation of an electrically large antenna structure are conducted. Section VI gives a short summary of the results.

II. Theory of Characteristic Modes

The characteristic modes of an arbitrary perfectly electrically conducting (PEC) structure form a basis set of characteristic surface current densities and corresponding characteristic electromagnetic fields for the expansion of the total radiated or scattered electromagnetic fields of the structure [6]. They are described by real eigenvalues λ_n and real eigenvectors (eigencurrents) $\mathbf{I}_n$ which are computed using the following generalized eigenvalue equation [7]:

$$\mathbf{X}\mathbf{I}_n = \lambda_n \mathbf{R}\mathbf{I}_n. \tag{1}$$

The real symmetric matrices $\mathbf{R}$ and $\mathbf{X}$ are, respectively, the real and imaginary part of the complex impedance matrix $\mathbf{Z}$ of the structure. This impedance matrix is determined by means of the method of moments (MoM) [8].

The eigenvectors of different characteristic modes are orthogonal to each other with respect to the impedance matrix. The orthogonality relationships of the characteristic modes are summarized as follows [9]

$$\mathbf{I}_m^H \mathbf{Z}\mathbf{I}_n = (1 + j\lambda_n)\,\delta_{mn} \tag{2}$$

$$\mathbf{I}_m^H \mathbf{R}\mathbf{I}_n = \delta_{mn} \tag{3}$$

$$\mathbf{I}_m^H \mathbf{X}\mathbf{I}_n = \lambda_n \delta_{mn} \tag{4}$$

where δ_{mn} is the Kronecker delta and ^{H} means conjugate transpose. From these relationships, it can be derived that the characteristic electromagnetic fields radiated by the characteristic surface current densities on the structure are orthogonal to each other in the far field.

If the structure is excited by an arbitrary incident electric field, the resulting total surface current density can be expressed as a weighted sum of the characteristic current densities [9]. When the method of moments is applied, the total surface current density is represented by the total current vector $\mathbf{I}$ and the excitation (e.g. by a plane wave) by the MoM-excitation vector $\mathbf{V}^i$:

$$\mathbf{I} = \sum_n \alpha_n \mathbf{I}_n = \sum_n \frac{\mathbf{I}_n^H \mathbf{V}^i}{1 + j\lambda_n} \mathbf{I}_n \tag{5}$$

where α_n is the modal weighting coefficient of the n-th characteristic mode. The scalar product $\mathbf{I}_n^H \mathbf{V}^i$ is called modal excitation coefficient [10]. It is a measure for the similarity between the n-th eigencurrent and the excitation. Only if the two vectors are correlated, i.e. the scalar product is unequal

to zero, the mode will contribute to the total current and is said to be excited. In addition, (5) shows that for a mode to contribute significantly to the total current, its eigenvalue must be close to zero or, in other words, its modal significance [10]

$$\text{MS}_n = \left| \frac{1}{1 + j\lambda_n} \right| \tag{6}$$

needs to be close to one.

In [11], the normalized modal weighting coefficient b_n is introduced which is defined as the modal weighting coefficient α_n normalized by the total radiated power P_{rad} of the driven antenna structure:

$$b_n = \frac{\alpha_n}{\sqrt{P_{\text{rad}}}}. \tag{7}$$

It is equal to the correlation coefficient between the total excited surface current density and the n-th characteristic surface current density and is thus easier to interpret than α_n.

III. Selective Excitation of Characteristic Modes

In order to effectively excite a specific characteristic mode, its modal weighting coefficient in (5) must be maximized. This is accomplished if

1) the eigenvalue is zero and
2) the modal excitation coefficient is maximized.

In a first step, only those modes with eigenvalues close to zero are taken into account (significant modes) in order to ensure that the first criterion is approximately met. In the next step, the excitation (a set of discrete feed ports) has to be designed adequately to maximize the modal excitation coefficient [10]. If electrically large antenna structures are considered, the first criterion is typically fulfilled by a large number of modes so that the main task is to find appropriate excitations for those modes.

An obvious choice in order to maximize the modal excitation coefficient would be to make the excitation vector $\mathbf{V}^i$ collinear to the eigenvector $\mathbf{I}_n$. In general, this would result in a dense excitation vector representing an antenna structure covered by a large amount of discrete feed ports which would be practically unfeasible.

In practice, it is desired to use as few feed ports as possible in order to excite a specific characteristic mode. This is mostly due to the complexity of the resulting feed network (matching networks, couplers etc.; cf. [12], [13]). Therefore, the excitation vector representing the feed ports in the MoM has usually only very few entries [14]. A common approach is to place voltage sources where maxima of the characteristic surface current density occur [15].

For MIMO applications, several significant characteristic modes are employed in order to make use of the diversity offered by the orthogonality relationships in (2) to (4) [1]. Besides the above-mentioned criteria for the excitation of a single characteristic mode, it has to be ensured that the chosen excitation does not excite other significant modes which are supposed to be used for MIMO. In other words,
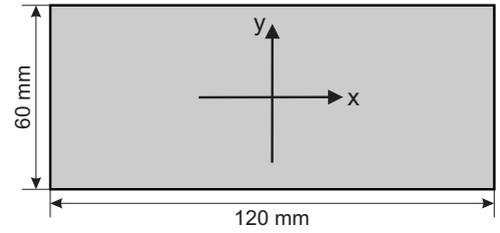
Fig. 1. Rectangular PEC plate and coordinate system.
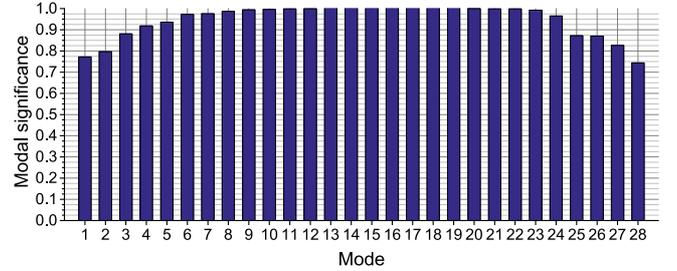
Fig. 2. Modal significances of rectangular PEC plate at 7.25 GHz.

the excitation vector has to be designed in such a way that it is correlated with the desired eigenvector, but orthogonal to all other eigenvectors.

However, the theory of characteristic modes does not guarantee that the eigenvectors themselves are orthogonal to each other, as the eigenvector correlation coefficient

$$\rho_{mn} = \frac{\mathbf{I}_m^H \mathbf{I}_n}{\|\mathbf{I}_m\| \, \|\mathbf{I}_n\|}, \tag{8}$$

where $\|\cdot\|$ denotes the Euclidean norm, is not necessarily zero. If for example the m-th and the n-th eigenvector were correlated, i.e. not orthogonal to each other, the excitation vector specifically designed for the n-th eigenvector could in principle also excite the m-th eigenvector. Likewise, the excitation vector specifically designed for the m-th eigenvector could also potentially excite the n-th eigenvector. Therefore, both excitation vectors would be correlated as well, i.e. they would excite the same modes, thus reducing MIMO performance due to port correlation [16].

Hence, when dealing with a large number of significant characteristic modes for MIMO, it is purposeful to examine the eigenvector correlations in order to design appropriate excitations.

IV. Characteristic Mode Analysis of Electrically Large Rectangular Plate

In this section, a rectangular PEC plate of dimensions $120\,\text{mm} \times 60\,\text{mm}$ is used as a simple model for the chassis of a typical modern mobile device (Fig. 1). The characteristic mode analysis is conducted at 7.25 GHz where the plate appears electrically large.

Characteristic modes with a modal significance greater than $1/\sqrt{2}$ (eigenvalue between 1 and −1) are considered

(a) Mode 1.　(b) Mode 2.

(c) Mode 3.　(d) Mode 5.
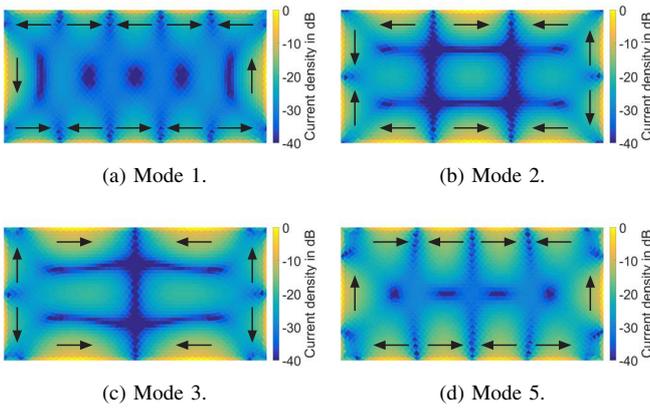
Fig. 3. Normalized surface current densities of four significant characteristic modes of rectangular PEC plate at 7.25 GHz.

TABLE I
GROUPING OF SIGNIFICANT MODES ACCORDING TO PARITY OF NUMBER OF CURRENT MAXIMA ALONG PLATE EDGES

Group	Modes	Long edge	Short edge
1	3, 8, 14, 18, 22, 24, 27	Even	Even
2	5, 9, 11, 16, 19, 25, 28	Even	Odd
3	2, 4, 6, 13, 15, 21, 23	Odd	Even
4	1, 7, 10, 12, 17, 20, 26	Odd	Odd

TABLE II
GROUPING OF SIGNIFICANT MODES ACCORDING TO RELATIVE CURRENT DIRECTIONS ALONG OPPOSITE PLATE EDGES

Group	Modes	Long edge	Short edge
1	3, 8, 14, 18, 22, 24, 27	Common	Common
2	5, 9, 11, 16, 19, 25, 28	Differential	Common
3	2, 4, 6, 13, 15, 21, 23	Common	Differential
4	1, 7, 10, 12, 17, 20, 26	Differential	Differential

TABLE III
GROUPING OF SIGNIFICANT MODES ACCORDING TO THEIR SYMMETRY PROPERTIES

Group	Modes	Symmetry
1	3, 8, 14, 18, 22, 24, 27	Reflection at x-axis Reflection at y-axis Point symmetry
2	5, 9, 11, 16, 19, 25, 28	Reflection at y-axis
3	2, 4, 6, 13, 15, 21, 23	Reflection at x-axis
4	1, 7, 10, 12, 17, 20, 26	Point symmetry

significant, i.e. they may be used for radiation. The characteristic mode analysis yields that 28 modes fulfill this criterion at 7.25 GHz. Their modal significances are shown in Fig. 2. These significant modes are focused on throughout the rest of the paper.

To gain a better understanding of the significant characteristic modes, their surface current densities need to be inspected. In Fig. 3, the surface current densities of four different modes at 7.25 GHz are displayed. The principal current directions are denoted by arrows. At first sight, the modes exhibit rather complex current distributions. In particular, the current densities have several local maxima where voltage sources could be placed in order to excite the modes, as explained in section III.

A. Grouping of Characteristic Modes

It is thus purposeful to sort the modes according to the distribution of their current maxima. Since the maxima typically occur at the plate edges, the characteristic modes can be sorted according to the number of current maxima along the edges. Modes may have an even or odd number of current maxima along the long and the short edge of the plate, respectively. For example, mode 2 in Fig. 3(b) has an odd number of current maxima (three) along the long edge of the plate and an even number (two) along the short edge. The grouping of the significant modes according to the parity of their number of current maxima along the edges is summarized in Table I.

According to this grouping, both mode 1 and mode 2 may be excited by a voltage source at the center of the lower long edge. The grouping of Table I is apparently not

sufficient in order to find rules for the selective excitation of the characteristic modes. However, proper inspection of the modes yields that the currents of mode 1 at the upper and lower long edge flow in opposite directions (180° out of phase) and the currents of mode 2 flow in the same direction (in phase). Mode 1 may thus be denoted a differential mode with respect to the long edges, whereas mode 2 is a common mode with respect to the long edges. Similar observations can be made with respect to the short edges so that the modes can also be sorted according to their relative current directions along opposite edges. This grouping is listed in Table II.

The two groupings yield the same four mode groups. Taken together, they give sufficient information on how to excite the characteristic modes of a specific group. For example, mode 1 (group 4) may be excited by voltage sources placed at the center of the lower and upper long edge, respectively, and driven differentially (180° out of phase). This way, the modes of groups 1 and 2 will ideally not be excited as they have current nulls at those positions and the modes of group 3 will not be excited because they have to be fed in phase. Alternatively, the modes of group 4 may be excited by voltage sources placed at the center of the left and right short edge, respectively, and driven differentially.

Further inspection of the characteristic surface current densities yields that the groups defined in Tables I and II in fact represent the symmetry properties of the characteristic modes. With regard to the coordinate system introduced in Fig. 1, mode 1 (Fig. 3(a)) possesses point symmetry around the coordinate origin, mode 2 (Fig. 3(b)) possesses reflection symmetry with respect to the x-axis, mode 5 (Fig. 3(d)) possesses reflection symmetry with respect to the y-axis and mode 3 (Fig. 3(c)) possesses all three kinds of the aforementioned symmetries. The grouping according to the symmetry of the
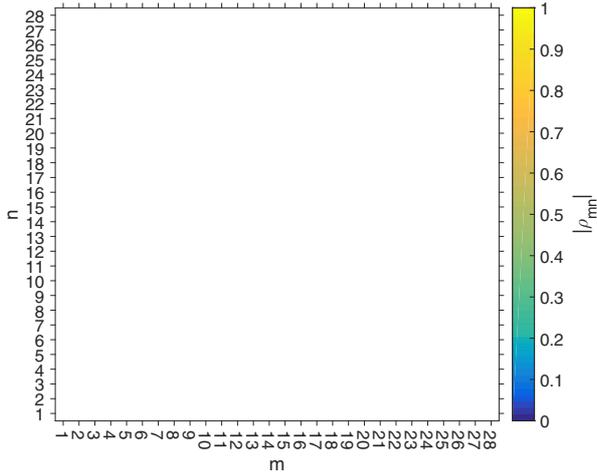
Fig. 4. Eigenvector correlation coefficients of rectangular PEC plate at 7.25 GHz.

Fig. 5. Voltage source locations and feed directions on rectangular PEC plate.

TABLE IV
PORT ARRANGEMENT CORRESPONDING TO FIG. 5

Antenna port	Voltage sources	Mode group to be excited
1 ●	1, 2, 3, 4	1
2 ●	5, 6	2
3 ●	7, 8	3
4 ●	7, 8	4

characteristic modes is summarized in Table III. This kind of grouping is more fundamental than the two ones previously introduced.

B. Correlation of Characteristic Modes

In the previous subsection, the significant characteristic modes have been grouped according to their symmetry properties. These properties give hints on how to excite the modes belonging to the same group. However, there are still seven modes per group. The question arises how to excite individual modes within the same group.

It is now purposeful to examine the eigenvector correlation as introduced in section III in order to gain further insight into the relationships between the modes of the same group. The eigenvector correlation coefficients of the 28 significant modes calculated using (8) are depicted in Fig. 4. As an example, the color plot shows that mode 1 has a non-negligible correlation coefficient with modes 7, 10, 12, 17, 20 and 26. These are exactly the modes of group 4. All other correlation coefficients are close to zero. From Fig. 4 it can be deduced that modes belonging to the same group in Table III are correlated whereas modes belonging to different groups are approximately orthogonal to each other.

Therefore, as explained in section III, if an excitation is designed for a single mode, this excitation will potentially be able to excite all the modes of the corresponding group. In such a scenario, although there are 28 significant characteristic modes with orthogonal far fields, only four uncorrelated antenna ports may be realized due to the characteristic current correlation.

V. EXCITATION OF ELECTRICALLY LARGE RECTANGULAR PLATE

Based on the modal analysis and the mode grouping in the previous section, the excitation of the significant characteristic modes is further investigated. To this end, voltage sources, implemented as gap sources in the MoM [14], are placed on the structure. Tables I, II and III are utilized to find appropriate port locations and excitation phases. Several such voltage sources may then be excited simultaneously in order to form one antenna port.

From the symmetry properties of the characteristic modes it is deduced that the excitation vectors should possess the same symmetry properties in order to be correlated with the eigenvectors of the desired group and orthogonal to the eigenvectors of the other groups. In other words, the arrangement of the antenna ports will reflect the symmetry of the characteristic modes which are to be excited.

On this basis, one possible approach to the placement and excitation of the voltage sources is shown in Fig. 5. The voltage sources, depicted as the black dots, are placed at the edges of the rectangular plate. In order to represent the symmetry of the characteristic modes, certain voltage sources have to be driven simultaneously. These groups of voltage sources are called antenna ports. Here, the voltage sources 1, 2, 3 and 4 form the antenna port 1. They are arranged and driven in such a way that they possess the same symmetry as the modes of group 1 (cf. Fig. 3(c)) and thus potentially excite only these modes. In the same manner, the other antenna ports are defined under the constraint to use as few voltage sources as possible. As the remaining characteristic modes have current maxima at two or all four edge centers (cf. 3(a), (b) and (d)), they can potentially be excited by antenna ports consisting of only two voltage sources as shown in Fig. 5. The antenna ports 3 and 4 use the same voltage sources (7 and 8), but with different feed directions. The assignment of the voltage sources to the antenna ports and the groups of the characteristic modes they are supposed to excite is summarized in Table IV.

In order to analyze which characteristic modes are excited by the antenna ports, the normalized modal weighting
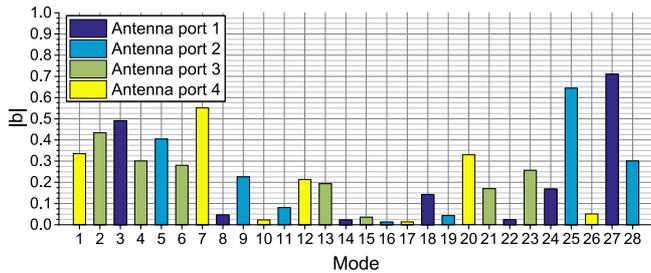
Fig. 6. Normalized modal weighting coefficients of rectangular PEC plate excited according to Table IV at 7.25 GHz.
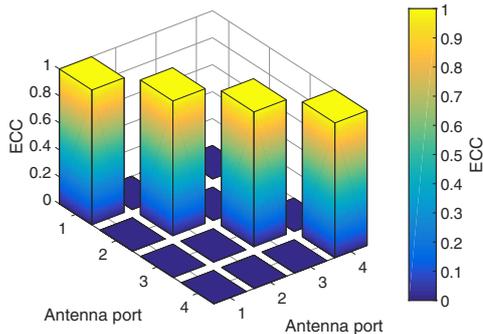
Fig. 7. Envelope correlation coefficients (ECC) of antenna ports according to Table IV at 7.25 GHz.

coefficients in (7) are used. Their absolute values are plotted in Fig. 6. Every mode is excited by only one antenna port or, in other words, every port excites a different subset of significant characteristic modes which means that the antenna ports are uncorrelated. This is confirmed by Fig. 7 which depicts the envelope correlation coefficients (ECC) calculated using the total radiated electromagnetic fields [11]. Moreover, the excited subsets are exactly the mode groups identified in section IV-A and thus all 28 significant characteristic modes are already in use, leaving no further degree of freedom to realize a fifth uncorrelated antenna port. These observations demonstrate the basic principle that, if there is a group of correlated characteristic modes, these modes will potentially be excited jointly by the same excitation.

VI. Conclusion

Electrically large antenna structures exhibit a large number of significant characteristic modes which, due to their orthogonality properties, offer great diversity potential for MIMO applications. However, as the characteristic currents themselves may be correlated, the excitation of individual modes is restricted. The example considered in this paper shows that, out of the 28 inherently orthogonal characteristic modes, four sets of modes remain that can be excited individually, thus drastically reducing the number of viable uncorrelated antenna ports and consequently the diversity potential.

The grouping of the characteristic modes has shown that the correlation of the characteristic currents seems to be related to their symmetry properties. Further research needs to be conducted in order to gain deeper insight into this relationship and corroborate the observations made in this paper. Future work will focus on a thorough theoretical analysis, backed by simulations and measurements of antenna structures with different, in particular more complex, symmetry properties.

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