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Characteristic Mode Inspired Advanced Multiple Antennas

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***Abstract*— This article, as part of the special issue on Characteristic Modes (CM), updates the recent progress in developing advanced multiple antenna systems based on CM analysis (CMA). The multiple antennas include the antenna arrays of multiple radiating elements fed by one single signal port and arrays of multiple antennas fed by multiple signal ports simultaneously and combinations thereof. The challenges, opportunities and how CMA assists for the design of antenna elements, multiple antennas, and antenna arrays are addressed, including physical insights and dedicated advanced CMA methods. Two types of advanced multiple antenna systems inspired by the CMs are discussed as examples. One is about the multi-mode multi-port antenna (M^{3}PA). The other one is about the CMA-enabled metasurface antenna (metantenna). Both can serve as unit cells of massive multiple input multiple output antennas.**

***Index Terms*— antenna arrays, antenna ports, Characteristic Modes, MIMO, multiantenna systems.**

I. INTRODUCTION

THE use of multiple antennas is a key enabling factor in wireless communication systems in order to cope with ever more demanding applications such as ultra-high data-rate communications, navigation, and localization.

Despite the great benefits provided by multiantenna systems, there are still several challenges which may be encountered during the design process. These can be categorized into the challenges at three different levels: element level, inter-element level, and array level. At the element level, the challenge is to deal with the design of a single antenna element. Important parameters for the overall design at this level are, for instance, the control of the radiation pattern and polarization, the antenna size, and the impedance bandwidth. These issues are discussed e.g. in [1]–[3] and as well as in [47] a related paper of this special issue. At the inter-element level the interaction of two or more antenna elements in close proximity, particularly in terms of mutual coupling is explored [7]–[10]. In the case of multiport antennas, the coupling and correlation of the antenna ports are of utmost importance [11]–[13]. At the array level, finally, the implementation of multiantenna techniques such as beamforming, direction-of-arrival estimation or spatial multiplexing is carried out [14]–[19].

As will be demonstrated throughout this article, characteristic modes are used to aid the design process at all three levels. They enable a thorough and systematic analysis of typical multiantenna problems and thus provide new insight. Based on this, design guidelines can be derived in order to tackle these problems more intuitively and more efficiently, even allowing the introduction of completely new design methods for multiantenna systems.

II. APPLICATION OF CHARACTERISTIC MODES TO MULTIPLE-ANTENNA SYSTEMS

The characteristic modes have become attractive for enabling a more thorough analysis of antenna problems and thus facilitating a more systematic design. These statements particularly apply to multiantenna systems. The characteristic modes are useful for tackling the diverse challenges encountered on the different levels of multiantenna design, as will be shown in this section.

A. *Element Level*

At the element level, the characteristic modes are basically employed in the same way as in single-antenna systems. A characteristic mode analysis is conducted to identify the significant modes for radiation which may then be manipulated in order to control the desired antenna parameters.

One of the most prominent applications is the control of the radiation pattern. Due to the concept of pattern multiplication, the single-element pattern has a considerable impact on the overall array performance. The use of characteristic modes facilitates a more sophisticated pattern control. For example, in [1] the antenna is shaped in such a way that it offers two characteristic modes with omnidirectional radiation patterns. The dimensions of the antenna are adjusted so that the two modes have different resonance frequencies. This way, the antenna enables broadband operation in terms of input impedance by exciting the two modes simultaneously. Additionally, a stable omnidirectional radiation pattern is achieved over the desired frequency range.

Similarly, the polarization of an antenna element can be controlled. Characteristic modes offering different types of linear polarization can be selectively excited by appropriately placed

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feed points on the antenna element. These feed points can also be excited simultaneously in order to enable circular polarization, realizing a polarization-reconfigurable antenna element [2]. Again, the simultaneous excitation of modes at different resonance frequencies can be exploited in order to enable broadband operation in terms of polarization as well as input impedance [3].

Another related research topic which should be mentioned is the design of orbital angular momentum (OAM) antennas. Here, characteristic modes are used to control the phase pattern. Higher-order OAM modes are constructed purposefully by selecting suitable characteristic modes [4]–[6].

B. *Inter-Element Level*

Now that antenna elements with desired properties are available, the next step is to place them in close proximity to facilitate the design of compact arrays. The mutual coupling between antenna elements arises as a critical problem in such constellations. Again, the characteristic modes are used for both the analysis of mutual coupling and the design of countermeasures.

The analysis of mutual coupling consists of a modal analysis of typically two antenna elements in close proximity [7]–[10]. The principal task is to identify those modes which are responsible for the coupling. This way, deeper insight into the principal coupling mechanisms is gained. To this end, mutual modal admittances [7]–[9] or related equivalent-circuit concepts [10], [20] are particularly convenient tools. The mutual admittance matrix of the antenna ports can be expanded in terms of modal admittance matrices, i.e., admittance matrices per characteristic mode. This way, the influence of individual modes on the mutual coupling can be analyzed. It should be noted, however, that more modes have to be taken into account compared to a common modal analysis as mutual coupling does not only rely on radiation mechanisms due to significant modes, but also on reactive coupling due to higher-order modes [9].

Having identified the principal coupling mechanisms, countermeasures can be employed. For example, inductive loading by means of slots cut into the antenna element [7], discrete inductors placed on the element [9], or shorting pins between the elements and a ground plane [8] are utilized in order to suppress those modes which are responsible for the coupling. In [10], a sophisticated parasitic structure placed between the antenna elements is designed based on CMA.

Multi-port antennas should also be treated on the inter-element level as they can be interpreted as virtual antenna arrays whose elements are all located at the same point in space. Consequently, they can be analyzed in a similar way as described above, i.e., by analyzing the modes which are excited by the different ports and identifying those modes which couple to several ports [11] (e.g., by means of the modal weighting coefficients). Hence, the mutual coupling is not defined with respect to different antenna elements, but with respect to different antenna ports. Ideally, each port excites a unique set of modes which does not couple to any other port (for more details, see section III). If this is not possible, e.g. due to geometric constraints, a so-called mode-decoupling network may be employed as proposed in [12].

C. *Array Level*

Towards the design of an array, the most common approach is the arrangement of identical antenna elements as, e.g., optimized in Section II-A [2]–[4]. The resulting array is then treated by means of the well-known array theory. In addition, a CMA of the whole array can be conducted in order to gain a more thorough understanding about its electromagnetic behavior, e.g., with respect to edge effects or surface wave propagation. As antenna arrays belong to the class of electrically large problems, efficient computation techniques are purposeful for such analyses [13], [21]. A comprehensive summary is also presented in [48] in this special issue. For example, a modal analysis on the array level is performed in [22] where both bandwidth and gain of a predefined end-fire array are improved. By exciting suitable modes with different resonance frequencies, but similar end-fire characteristics simultaneously, the desired performance is achieved. In contrast to the element level, the array is treated as a whole.

An alternative analysis technique for antenna arrays is the characteristic port mode method [23]–[24]. Instead of performing a characteristic mode analysis of the whole array, the array is represented by its port impedance matrix. This impedance matrix can then be decomposed in terms of the so-called characteristic port modes analogously to the traditional characteristic modes. The advantage is a considerable reduction of the computation space, as illustrated in [25] by means of a dipole array. As the information about the modal currents on the individual antenna elements is lost this way, the port mode method is particularly useful for arrays which consist of known elements (e.g., dipole arrays [25]) or whose elements have been optimized individually (cf. Section II-A). As mutual coupling is taken into account by the port impedance matrix, the port mode method enables the optimization of the array as a whole. One of the first applications of this technique was the synthesis of desired radiation patterns by a weighted superposition of characteristic port modes [26]. More recently, port excitation tapers have been derived for tightly coupled dipole arrays by means of the characteristic port modes [27], [28]. The excitation coefficients of the individual dipoles are chosen in such a way that they resemble a characteristic port mode which is significant over a wide bandwidth. Consequently, such a so-called characteristic excitation taper enables broadband impedance matching for all array elements, especially the edge elements, in the presence of strong mutual coupling.

Array techniques such as pattern synthesis, beam shaping, or beam steering are also enabled by multiport antennas [16], [19]. Again, the proper excitation and the resulting superposition of characteristic modes are key to synthesizing a desired pattern. First, a CMA is conducted, then the desired pattern is decomposed into the modal patterns, and finally appropriate exciters are designed. For example, null steering is conducted in [14]–[15] by exciting suitable characteristic modes on a rectangular plate by means of capacitive coupling elements. As another example, a rectangular box is enabled to provide beam steering capabilities by introducing inductive coupling elements in order to excite the desired superpositions of characteristic modes [29]. More examples of such platform-based antennas are also discussed in [49], a related paper of this special issue.

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Apart from using CMA for the design of conventional arrays on all three levels, new concepts of multiantenna systems inspired by CM have been presented recently. The following two sections review advanced multi-mode antenna designs inspired by CMA, targeting challenging tasks for multiple antenna systems from the perspectives of antenna element, inter-element coupling, and array level.

III. MULTI-MODE MULTI-PORT ANTENNAS – M³PA

Massive MIMO requires antenna arrays with a huge number of uncorrelated elements. Under the paradigm of characteristic modes, new concepts for space-efficient multiantenna systems can be found intuitively. Consider a characteristic mode decomposition of the current density on an antenna patch. Depending on some symmetry properties of the patch, a certain number of uncorrelated sets of modes can be identified within the overall current distribution. If we assume that ports can be generated on the antenna patch that excite different current distributions such that each of them contains only mutually uncorrelated modes, then the ports are inherently mutually decoupled as well. This way, we are able to generate a multi-mode multi-port antenna (M³PA) element, which then can be used in order to set up a massive multi-port array based on a comparatively small number of physical antenna elements.

Pioneering designs achieved the excitation of uncorrelated current distributions intuitively by examining the respective characteristic surface current densities and placing exciters accordingly, e.g., [11, 19, 30, 31]. It was later shown by fundamental proof that uncorrelated current densities can be generated systematically only on symmetric antenna structures and the level of symmetry dictates their upper bound [17]. Thanks to this generalized approach, the operation principle of the designs mentioned above can be readily explained based on formal symmetry considerations. For example, it can be shown in a fundamental way that the quadratic antenna patch used for an intuitive four-port design in [19] in fact offers six uncorrelated sets of characteristic modes. Thus, six uncorrelated ports can eventually be generated to excite those sets selectively. This knowledge is gained *a priori* by analyzing the symmetry. Figure 1 shows a 6-port multi-mode antenna that has been realized based on this idea [18].

A. Six-port multi-mode multi-port antenna (6M³PA) element

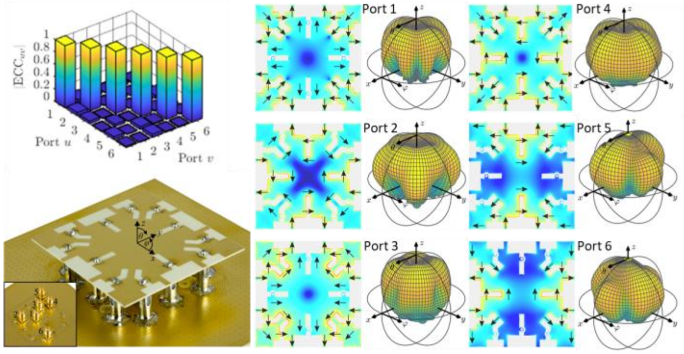

Fig. 1. 6-port multi-mode antenna (6M³PA) element (bottom left) [28]; current densities on antenna patch and respective antenna patterns of ports 1-6 (right); envelope correlation coefficient of mutual antenna ports (top left).

On the element level, the principal task is to choose a suitable antenna geometry (here: square plate) which offers a desired number of uncorrelated antenna ports due to its symmetry [17]. Then, a CMA is carried out in order to identify the uncorrelated sets of modes and the corresponding significant modes. The antenna size may have to be adjusted so that a sufficient number of modes are significant.

A number of slots are introduced to the square patch to enable sets of feed points for excitation [18, 19]. Of course, the slot structure must be chosen such that the initial symmetry is maintained [18]. Six feed networks take care for the desired amplitude and phase at the feed points on the patch and terminate in the six antenna ports on the backplane as shown in Fig. 1 (bottom left). On the right hand side of Fig. 1, the six current distributions excited by feeding the respective ports are shown together with their respective radiation patterns.

B. Uncorrelated Ports by Leveraging the Symmetry

Viewed from the inter-element level, we are interested in the coupling and the correlation of the six antenna ports. The envelope correlation coefficients calculated from the measured radiation patterns as depicted in the upper left part of Fig. 1 show that all six radiation patterns are practically uncorrelated.

As illustrated, leveraging symmetry in conjunction with CMA helps to find uncorrelated modes as well as designing the feed points. By combining the theory of characteristic modes (TCM) with the general Theory of Symmetry, a thorough procedure can be found based on the so-called Projection Operator Method to generate the optimal port configuration for any structure automatically. This is shown in [18], together with a more detailed description of the antenna of Fig. 1, yielding a systematic design method for individual M³PAs on the inter-element level. The pioneering designs discussed above can be readily explained within this framework.

C. Massive arrays based M³PAs enabling additional degrees of freedom

Going on to the array level, the M³PAs can be conveniently arranged in an array. Setting up antenna arrays based on M³PAs comes along with different advantages and disadvantages compared to conventional arrays with single-mode elements. On the one hand, and as explained earlier, the M³PA approach enables space-efficient arrays with a huge number of uncorrelated ports as each of the physical array elements comes with a number of uncorrelated ports by itself. For example, in [19] a 484-port array based on 11 × 11 4-port multi-mode multi-port elements (4M³PA) is presented. It is by 54% smaller than a crossed-dipole array (i.e., two ports per element) also having 484 ports in total and also offering a similar level of mutual coupling of all ports. On the other hand, M³PA elements are typically larger than conventional λ/2-dipoles as they require multiple modes to be significant. As a consequence, a potential beamforming pattern may suffer more from grating lobes than an array using conventional elements as the inter-element spacing is larger due to the larger M³PA elements themselves. Also, due to the fundamental fact that only certain modes belong to a specific uncorrelated set [17], [18], there is only limited flexibility to shape

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the port patterns. For instance, in Fig. 1 there are just two broadside port patterns, but four off-broadside port patterns that even have a null in broadside direction. In summary, it is worth discussing the pros and cons.

It is expected that there is some kind of trade-off between the excess degrees of freedom offered by multiple uncorrelated ports per element and the limitations related to the element size and the port patterns with respect to a specific application. Fig. 2 shows an illustration of a 10 × 10 array composed out of the 6M³PA elements of Fig. 1 [18]. In total, the array possesses 600 antenna ports. Conventional beam scanning and beam forming is still enabled by controlling amplitude and phase of the input signals at the elements, as in conventional arrays. In addition, the selection and weighting of the different port patterns per element comes into play as an excess degree of freedom. With respect to beam scanning, we can now preselect an appropriate element pattern, i.e., broadside or off-broadside among the available port patterns depending on the scan direction and the desired polarization. Grating lobes, that may appear earlier because of the larger element distance, can partially be compensated by superposition of appropriate modal patterns of other elements if desired. Some beam scanning and beam forming examples are illustrated in Fig. 2.

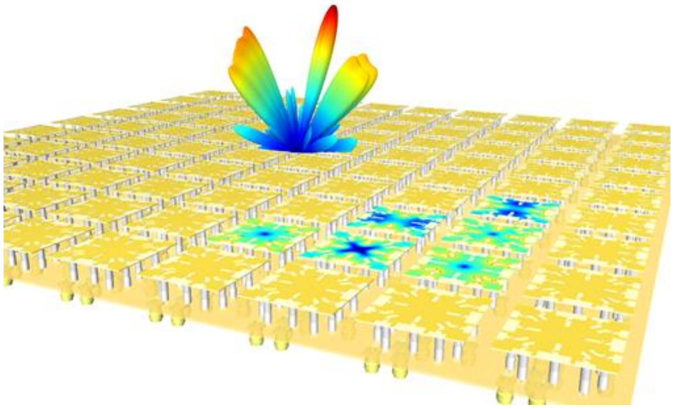
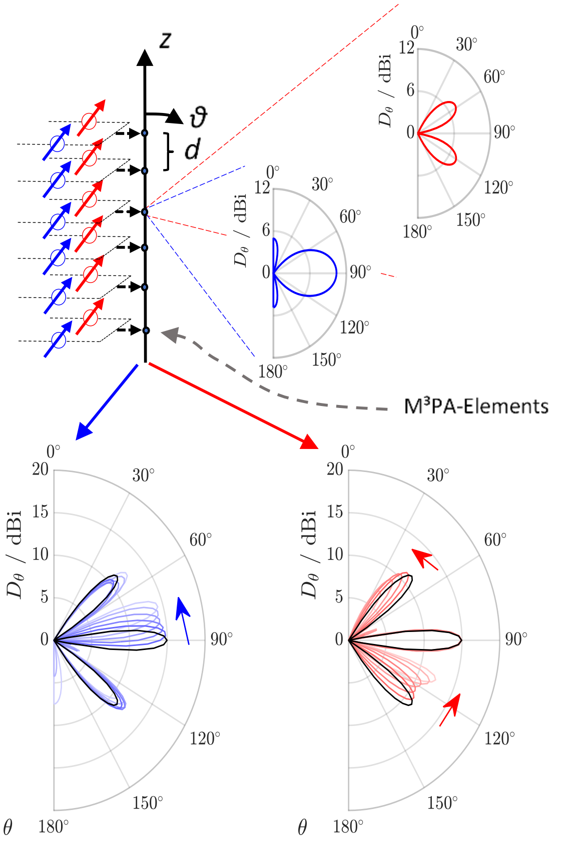


Fig. 2. A 600-port antenna array consisting of 10×10 6M³PAs. The six different current distributions which can be excited by the corresponding ports on the individual M^{3}PA elements are shown on selected elements (cf. Fig. 1). The pattern shown in the figure is synthesized by a weighted superposition of these current distributions on all elements.

In order to evaluate this further, let us discuss a more specific beam scanning scenario as a simple example. Consider a one-dimensional phased antenna array along the *z*-axis as shown in the top part of Fig. 3. The antenna consists of 2M³PA elements having a broadside pattern on port 1 (blue) and an off-broadside pattern on port 2 (red). When scanning, we can now use the broadside element pattern for near broadside scanning and the off-broadside pattern for off-broadside scanning, respectively. In particular, the two patterns can be scanned independently.

This is just a simple example illustrating the excess degree of freedom offered by pre-selectable port patterns. It is expected that many other applications will benefit from the availability of multiple diverse patterns and the capability of flexibly combining them. The concept has recently found applications in communications engineering in terms of beamforming for MIMO systems [32] and navigation by means of direction-of-arrival estimation [33].



(a) (b)

Fig. 3. Beam scanning using phased array of multi-mode multi-port antennas. (a) Scanning the broadside pattern provided by port 1 independently (blue curves). (b) Scanning the off-broadside pattern provided by port 2 independently (red curves). For reference, the black curves in both figures denote the same case where all elements and ports are driven in-phase.

IV. METANTENNAS

The previous two sections reviewed the advancement of antenna pattern control on the element level, high-density multiport antenna system on the inter-element level, and innovative beam shaping and scanning on the array level, by exploring the relationship between the mode distribution, geometrical symmetry and multi-mode combination with the aid of CMA. On the other hand, the emerging concept of metamaterials (MTM), particularly its two-dimensional equivalent of metasurfaces (MTS), offers a new perspective to shape the mode distribution and combination to improve antenna performance from another point of view of volume material properties or surface impedance. This has led to the concept of Metantennas, which also focus on the aforementioned three levels but from a different perspective, hence reviewed in a parallel section herein [34]–[46].

An MTS is a two-dimensional surface composed of an array of sub-wavelength unit cells, with which the electromagnetic waves can be controlled at a microscopic level, so are the CMs that expand the waves. So, in this part, the primary challenge is

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to design the unit cells for modifying the modes of interest, so that the element performance, the inter-element characteristics and finally array performance can be optimized. In early studies, an MTS is often assumed infinitely large and under plane-wave illumination. The two assumptions vanish in most antenna problems due to complicated near-field interaction between an MTS and its feeding structure. As conventional analysis methods lose (at least partially) the power of handling non-TEM waves in the near field, new methods are needed to handle (1) the rapid near-field variation, (2) the edge diffraction, and (3) the mutual coupling between resonators. These demands have driven a timely marriage of TCM and MTS, giving birth to mode-based MTS antennas for antenna elements, multi-antenna and array systems. In a similar manner, on all the aforementioned three levels, the following subsections review the recent development of Metantennas with the aid of CMA and illustrate how CMA helps handling complex near-field problems for challenging antenna design.

A. Metasurface for Antenna Elements

For an element design, CMA provides a new perspective for analyzing the modal behavior of a truncated MTS resonator, which advances antenna element designs by addressing issues such as bandwidth, multi-port access, miniaturization, reconfigurability, radiation pattern, electromagnetic compatibility, and modeling. For example, a truncated MTS resonator resonates at the fundamental quasi-TM_{30} mode instead of TM_{10} mode, enabling higher gain-bandwidth product for a single element [34]. Therein, CMA allows the MTS to be analyzed as an entity including the near-field coupling between the MTS and others. The new framework is soon adapted for the design of a single-port dual-band MTS antenna, where multiple desired modes are identified and engineered to resonate at separate frequency bands by CMA-supervised unit-cell design [35]. Furthermore, by modifying the symmetry of the unit cells, the degenerated modes can be separated in frequency for a miniaturized circular-polarized (CP) antenna using phased modes [36]. A design follows to integrate the LP and CP radiation into a single MTS antenna by switching for higher aperture efficiency [37], where CMA helps determine the loading positions of the switches for minimized adverse effects on the functional modes, which is often challenging in conventional designs.

Also in the element level but considering the operating modes, the higher-order modes may well be utilized in addition to lower-order modes [38]. This has been possible because the coupling between the unit cells shapes the dispersion of wave propagation along the MTS hence richer mode spectrum, which is now unboxed by the CMA. For example, loading a dielectric-resonator an MTS shapes the current distribution of its higher-order modes for improved gain bandwidth. On the other hand, CMA also helps finding the optimum loading positions of lossy components for electromagnetic compatibility of a system, in addition to reactive components [39].

Furthermore, the CMA also contributes to developing new modeling of truncated MTS and illustrating new physical phenomena. With unit cells shrinking to sub-wavelength from resonant size in [34]–[39], the concept of local-resonant MTS evolves to global-resonant MTS [40]. When an impedance boundary condition is used to model a truncated and homogenized MTS, the method of moment (MoM) appears as the most natural solver. This is because it directly follows the physical instinct that the impedance matrix, built from the impedance boundary that models an MTS, contains all the characteristic solutions. As a result, the CMA-enabled new modeling of global-resonant metasurface opens new possibilities for more advanced antenna designs.

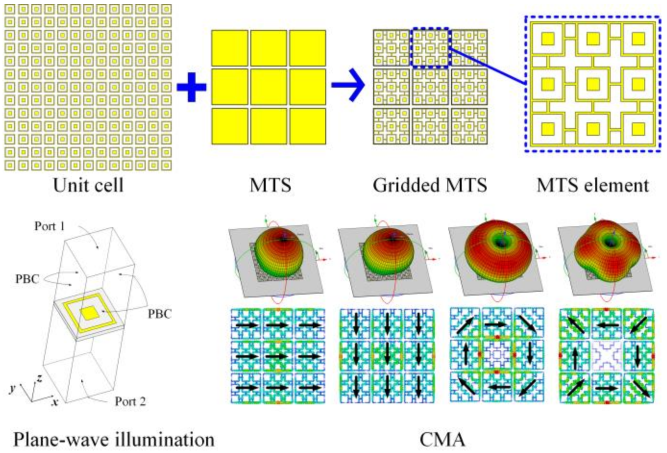

Fig. 4. Hybrid characterization method for co-aperture MTS. The CMA and plane-wave illumination are used to characterize the modal behaviors of MTS at S-band and the passband feature of unit cell at K-band, respectively. The MTS is finally gridded by the unit cell for co-aperture implementation.

B. Metasurface for Antenna Arrays and Multi-Port Antennas

CMA has also inspired novel MTS solutions to multi-antenna problems, including arrays and multi-port antennas. For antenna arrays, CMA is used to suppress the higher-order modes that distort the radiation pattern of tightly coupled antenna arrays for gain improvement [41]. Also, CMA inspires the concept of multi-mode cancellation for novel unit-cell design in high-gain MTS-lens antenna design [42].

For multi-port antennas, the use of CMA is different from what has been summarized in Section II.B, where CMA is used to identify the contributing modes to mutual coupling without suggesting how to suppress them. Leveraging the unit-cell of MTS, the field distribution of the desired modes gives direct hint to countermeasures for suppressing the undesired modes of a multi-port antenna, leading to significant improvement of radiation pattern for massive MIMO applications without occupying extra space due to external loadings [43]. On the other hand, the engineering of the unit cells for resonating the desired modes at desired frequencies also enables a compact co-aperture solution to multi-port multi-band antennas [44]–[46]. Two examples are detailed below.

Example 1: Hybrid Characterization Method with CMA for Co-Aperture MTS Antenna

When moving to a co-aperture antenna design with primary S- and K-band antennas under a MTS [45], the major challenges are to characterize the MTS with a large frequency ratio and then to modify the modes at the desired frequencies. There are very few methods to determine the unit cell and MTS for the multi-band operation simultaneously. A hybrid characterization

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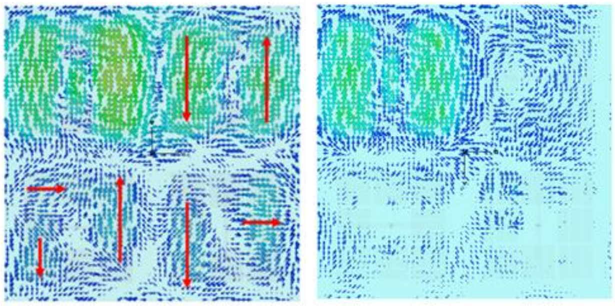
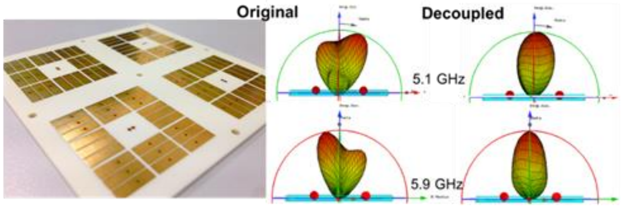


Current distribution over the ground plane before and after suppressing the contributing modes to pattern distortion.



A four-port metasurface antenna (the dipole exciter on top of each metausrface is not shown for a clearer view) and its radiation patterns before and after suppressing the contributing modes to pattern distortion.

Fig. 5. CMA-enabled metasurface for simultaneous radiation and isolation.

technique, including plane-wave illumination and CMA, is a timely solution. Fig. 4 shows the evolution of the MTS. Based on the hybrid characterization method, especially with the help of CMA, the co-aperture multi-band MTS antenna is efficiently realized. Furthermore, the CMA results provide an all-round perspective for S-band operation, i.e., the effect of gridding for the modes of interest. Inspired by this, an alternative unit cell with partially reflective characteristics has been proposed for Fabry-Perot resonance [46]. An intuitive rationale is confirmed by CMA that the inner-patch of the unit cell has no effect on the modes of the MTS, which enables flexibility for the antennas. As a result, the hybrid characterization method with CMA enriched the design of the co-aperture MTS antennas.

Example 2: CMA-Enabled Pattern-Correction Techniques

The second example addresses another challenging issue, i.e., pattern distortion due to mutual coupling. Fig. 5 shows a wideband four-port antenna system. Each antenna occupies a corner and works with two modes. However, the radiation patterns are severely distorted with four antennas closely spaced with a center-to-center spacing of 0.6 wavelength at the lowest operating frequency. By CMA, the spread current distribution, which accounts for the distorted patterns, can be optimized. The solution is developed by strictly following the CMA results clearly indicating the nulls of desired modes and the peaks of undesired modes for the accurate placement of the shorting-pins and slots to suppress the undesired modes without interference to the desired modes. As a result, the radiation patterns and current distribution are both optimized as if the surrounding antennas do not exist.

C. Future Directions

The concept of metantennas should not be limited to a special type of microstrip antennas that replaces a metallic patch with geometrically perforated surfaces or electrically reactive surfaces, although they are mostly investigated by far. With the tool of CMA and the concept of meta-structure in hands, the concept of metantennas can be generalized to other types of resonant antennas, where a meta-structure can be a radiator, an auxiliary loading, an impedance transformer and more. A nature question also arises that whether MTS antennas can be used to further compose an antenna array. This shall be looked at from two sides. Firstly, the use of a capacitive metasurface as a radiator expands the aperture size so for a high gain purpose, it appears more desirable to design a bigger MTS, though an MTS may work equally well at the expense of additional cost from the feeding network. On the other hand, if the purpose is for wideband wide-angle scanning, the primary challenge is to reduce the size of an MTS antenna without sacrificing its bandwidth to avoid grating lobes from occurring.

V. CONCLUSION

As has been shown throughout this article, CMA has assisted, improved, and even inspired the design of novel multiple antennas and arrays at the levels of unit cells, antenna elements, and arrays. It should be noted that the applications of CMA in the design of complicated antennas and arrays are still at an exploratory stage with many remaining challenges. In this regard, not all of the advanced numerical concepts as discussed in Section II have even been utilized to full extent so far.

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