Characteristic Modes Special Interest Group

CM SIG

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Scholar Spotlight:

Leonardo Mörlein received the B.Sc. and M.Sc. degrees in electrical engineering from Leibniz University Hannover, Hannover, Germany, in 2017 and 2020, respectively. He is currently a Research Assistant with the Institute of Microwave and Wireless Systems, Leibniz University Hannover. His current research focuses on the use of multiport multimode antennas in beamforming scenarios. Further research interests include antenna integration and the use of modal decompositions and channel modeling.

Dirk Manteuffel received the Dipl.-Ing. and Dr.-Ing. degrees in electrical engineering from the University of Duisburg–Essen, Duisburg, Germany, in 1998 and 2002, respectively. Since June 2016, he has been a Full Professor and the Executive Director of the Institute of Microwave and Wireless Systems, Leibniz University Hannover, Hannover, Germany. His research interests include electromagnetics, antenna integration, and EM modeling for mobile communications and biomedical applications.

Featured Article

Array Synthesis in Terms of Characteristic Modes and Generalized Scattering Matrices

by Leonardo Mörlein, Dirk Manteuffel

In our recent paper, we proposed a synthesis approach for arrays with characteristic modes [1]. The basic idea is that an array of elements is built up first, whereby abstract modal properties (like eigenvalues and excited modal weighting coefficients) on every element are to be found first under the consideration of coupling and a geometrical realization of the desired modal parameters is found afterwards.

However, initially, we realized that the existing characteristic mode tools are not sufficient to describe scattering of antenna elements properly, even outside of the array scope. A good starting point to understand this is the scattering of a scattering object. As shown in [1], scattering of a lossless scattering object can be described in the basis of characteristic modes using the coefficients **a** and **b** of the incident and scattered characteristic fields

$$\mathbf{E} = \sum_n \mathbf{E}_n b_n + \mathbf{E}_n^* a_n, \tag{1}$$

whereby the unitary and diagonal scattering matrix $\mathbf{S}_0$ connects **a** and **b**:

$$\mathbf{b} = \mathbf{S}_0\mathbf{a} = \begin{bmatrix} -\frac{1-\mathrm{j}\lambda_1}{1+\mathrm{j}\lambda_1} & 0 & 0 & \dots \\ 0 & -\frac{1-\mathrm{j}\lambda_2}{1+\mathrm{j}\lambda_2} & 0 & \dots \\ \dots & \dots & \dots & \dots \end{bmatrix} \mathbf{a}. \tag{2}$$

However, this formulation is strictly only applicable, if a scattering object (without ports!) is considered. As soon as ports are involved, as we have it for an antenna, the scattering matrix of a lossless antenna **S** is neither unitary nor equal to the diagonal matrix $\mathbf{S} \neq \mathbf{S}_0$ proposed in [2].

This fact can be understood by considering the conservation of power in the receiving case. Since for some incident field, the port will absorb power, the scattering matrix **S** can no longer be unitary. Instead, the whole system (with the ports included) describes a lossless system, leading to a new unitary matrix $\mathbf{\Psi}$, which is called generalized scattering matrix and is defined by:

$$\underbrace{\begin{bmatrix} \mathbf{S} & \mathbf{T} \\ \mathbf{R} & \mathbf{\Gamma} \end{bmatrix}}_{\mathbf{\Psi}} \begin{bmatrix} \mathbf{a} \\ \mathbf{v} \end{bmatrix} = \begin{bmatrix} \mathbf{b} \\ \mathbf{w} \end{bmatrix}. \tag{3}$$

The additional coefficient vectors **v** and **w** represent the incident and reflected port wave quantities, the antenna transmit matrix **T** contains the information which mode is excited by which port to which extent, the antenna receive matrix **R** contains the information how large the received wave is at which port for which combination of incident modes and $\mathbf{\Gamma}$ simply contains the port scattering parameters of the antenna.

While the eigenvalues λ_n do not directly appear in $\mathbf{\Psi}$, it still is based on the coefficients **a** and **b** of the characteristic fields. Besides other details, we show how the eigenvalues λ_n still play an important role in this formalism. However, for this feature, it is sufficient to summarize that using characteristic modes with this formalism is a well-suited new tool to describe scenarios in which the scattering of antennas is relevant, such as e.g. in arrays.

Now, shifting to the array case, one generalized scattering matrix is defined for every array element. In order to describe coupling between them in an electric-field integral equation scheme, a modal coupling matrix is defined according to:

$$\mathbf{G}^{(k,l)} = \frac{1}{2}\mathbf{I}_{\mathrm{CM}}^{(k)\mathrm{T}}\mathbf{Z}^{(k,l)}\mathbf{I}_{\mathrm{CM}}^{(l)}, \tag{4}$$

whereby $\mathbf{Z}^{(k,l)}$ is the submatrix block of the impedance matrix $\mathbf{Z}$ describing the coupling from the basis functions of the l-th array element to the test functions on the k-th array element and $\mathbf{I}_{\mathrm{CM}}^{(k)}$ and $\mathbf{I}_{\mathrm{CM}}^{(l)}$ are matrices whose columns contain the characteristic modes on the k-th isolated element and the l-th isolated element.

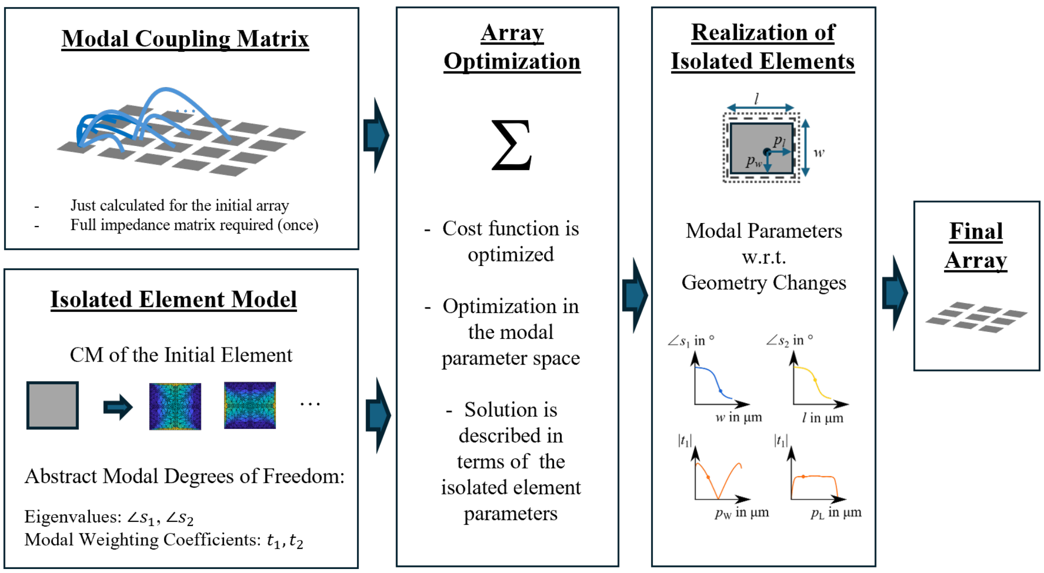
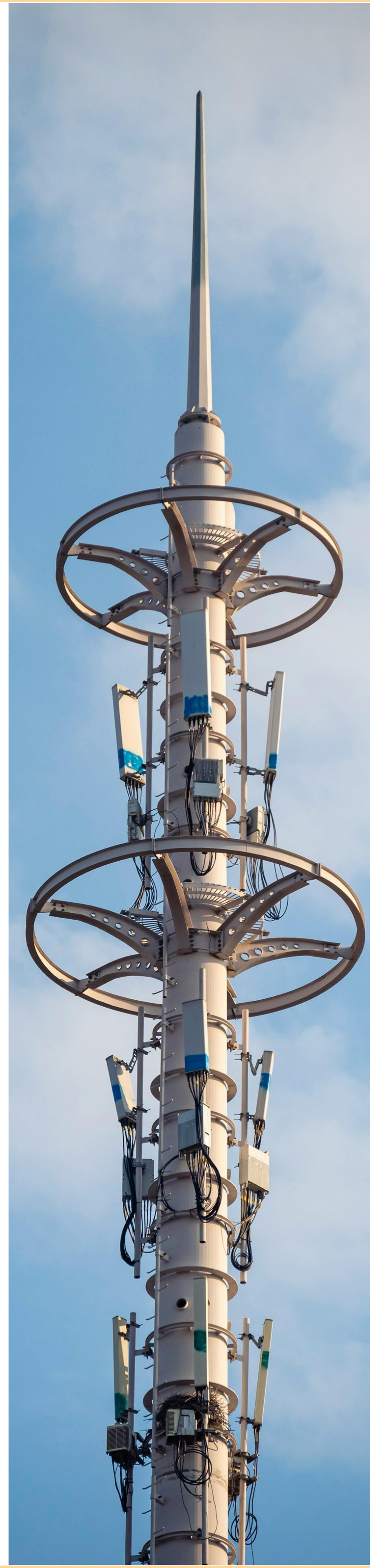


Figure 1: Proposed optimization approach for arrays taking mutual coupling into account.

Based on the generalized scattering matrices of the elements and the modal coupling matrix, an optimization approach is introduced, as seen in Fig. 1. The characteristic modes are thereby used with a twist. Instead of calculating the eigenvalues and modal weighting coefficients of the characteristic modes, as it is often done in conventional characteristic mode analysis, we are proposing to leave them as degrees of freedom. This yields a semi-analytical model, which can be used for optimization on the array level without having a geometrical implementation of the array in mind first. Instead, an optimization algorithm can be used to find the degrees of freedom, that yield the optimal modal parameters to achieve a predefined goal while coupling is already taken into account. In the example of the paper, a high cross-polarization rejection in a circularly polarized array is set as goal. Finally, after the ideal modal parameters are found, a realization of them using actual geometrical modifications is performed for every element on isolated level, using well-known procedures from characteristic mode analysis.

1. L. Mörlein and D. Manteuffel, "Array Synthesis in Terms of Characteristic Modes and Generalized Scattering Matrices," *IEEE Transactions on Antennas and Propagation*, vol. 73, no. 2, pp. 986-997, Feb. 2025, doi: 10.1109/TAP.2024.3515285.
2. R. Harrington and J. Mautz, "Theory of Characteristic Modes for Conducting bodies," *IEEE Transactions on Antennas and Propagation*, vol. 19, no. 5, pp. 622-628, September 1971, doi: 10.1109/TAP.1971.1139999.



News and Events

1. The week-long **European School of Antenna (ESoA) Course on Characteristic Modes** will (soon) be held at **Lund University** (Lund, Sweden) during **9-13 June 2025**: . The instructors are Miloslav Capek (CTU in Prague, Czech Republic), Dirk Manteuffel (Leibniz University Hannover, Germany), Eva Antonino-Daviu (Universitat Politècnica de València, Spain) and Buon Kiong Lau and Johan Lundgren (Lund University, Sweden). We look forward to an exciting week of sharing and learning!

2. The CM-SIG Annual Meeting was successfully held at the **2025 European Conference on Antennas and Propagation (EuCAP'2025)** in Stockholm, Sweden, on 2 April 2025 (see group photo below). The convened session on CMA (**CS16 Characteristic Modes Advanced Antenna Modeling and Design**) was well attended and interesting results and discussions were shared (see photo below). Big thanks to Johan Lundgren and Dirk Manteuffel for convening and chairing the session on behalf of CM-SIG!

Recent Articles on CM Theory

- M. Gustafsson, L. Jelinek, M. Capek, J. Lundgren and K. Schab, "Theory and Computation of Substructure Characteristic Modes," *IEEE Transactions on Antennas and Propagation*, vol. 73, no. 3, pp. 1321-1333, March 2025, doi: 10.1109/TAP.2025.3528478.
- Y. Qi, F. Yang, K. Chen, Y. Chen, J. Hu and S. Yang, "Low-Scattering Broadband Phased Array With Polarization-Selective Metasurface Using Characteristic Mode Analysis," *IEEE Transactions on Antennas and Propagation*, vol. 73, no. 5, pp. 2979-2989, May 2025, doi: 10.1109/TAP.2025.3529178.
- A. C. Escobar, J. D. Baena and L. Jelinek, "Polarizability Tensors From Characteristic Modes," *IEEE Transactions on Antennas and Propagation*, vol. 73, no. 5, pp. 3060-3067, May 2025, doi: 10.1109/TAP.2025.3533910.
- H. Schreiber, P. Herwigk and M. Leone, "An Accelerated Reduced-Order Characteristic Mode Analysis," *IEEE Transactions on Antennas and Propagation*, doi: 10.1109/TAP.2025.3542620.
- H. Ren, B. Wang, J. Chen and S. Yan, "An Alternative N-Port Characteristic-Mode Formulation for Lossy Structures," *IEEE Antennas and Wireless Propagation Letters*, vol. 24, no. 3, pp. 592-596, March 2025, doi: 10.1109/LAWP.2024.3509460.
- L. Grundmann, M. Gerlach, W. Schäfer and D. Manteuffel, "A Cupola-Shaped Multimode Multiport Antenna for Aerial Direction Finding," *IEEE Antennas and Wireless Propagation Letters*, vol. 24, no. 4, pp. 873-877, April 2025, doi: 10.1109/LAWP.2024.3519709.
- Z. -W. Tong, P. Du and G. Zheng, "Characteristic Modes Analysis of Finite Periodic Array With Object Using Entire Domain Basis Function Method and ACA," *IEEE Antennas and Wireless Propagation Letters*, vol. 24, no. 5, pp. 1149-1152, May 2025, doi: 10.1109/LAWP.2025.3527927.

New Member Introduction

Bio: Prof.**Can Ding** received a Bachelor degree in integrated circuit and integrated systems from Xidian University, Xi'an, China, in 2009, and a joint Ph.D. Degree from Xidian University and Macquarie University, Australia, in electromagnetic fields and microwave technology in 2016. He is currently an Associate Professor with the Faculty of Engineering and IT (FEIT) at the University of Technology Sydney (UTS).

His contributions to the antenna and propagation society have been to advance the understanding and the evolution of cutting-edge base station antenna technologies that are leading to the cost-efficient deployment of 5G networks. His accomplishments encompass several research and industry projects, patented innovations, and a portfolio of over 120 publications in top-tier journals and conferences. He was listed in the "Top 2% Scientist by Stanford" for 2022 and 2023 based on his citation matrix in his research area. His publications garnered fourteen best paper awards, a featured article by IEEE Xplore across all fields, a front cover article in a flagship journal, and five featured articles in 'What's hot in Antenna and Propagation'. He also actively contributes to AP-S society, serving on committees like the IEEE AP-S Education Committee, IEEE AP-S Young Professional Committee, IEEE AP-S Technical Committee on Metamaterials, and EurAAP Working Groups. He has co-chaired prestigious conferences like AMS 2020 and ISAP 2022 and serve on the committees for several other conferences. He is acknowledged as a top reviewer for IEEE Transactions on Antennas and Propagation from 2021 to 2023 and an outstanding reviewer in IEEE Antennas and Wireless Propagation Letters in 2022. He currently serves as an associated editor for IEEE AWPL. He is the Early-to-Mid career Educator of the Year in 2023 at FEIT, UTS. He is an Australian ARC DECRA Fellow in 2020, an IEEE AP-S Young Professional Ambassador and an IEEE senior member in 2024.

View on CMA: Characteristic Mode Analysis (CMA) is a powerful and insightful tool in antenna engineering. It decomposes the surface currents on a conducting structure into a set of orthogonal characteristic modes, each associated with a specific eigenvalue. These modes provide a clear understanding of the resonant behavior and radiation properties of the structure, independent of external excitation. CMA allows engineers to tailor the geometry and feeding mechanisms to excite desired modes while suppressing unwanted ones.

Summary of CMA Research: Modern mobile communication systems demand the integration of multiple antennas operating across different frequency bands. However, low-band (LB) antennas often scatter high-band (HB) waves, leading to radiation pattern distortion, impedance mismatches, and increased mutual coupling. Employing CMA, we identify and suppress higher-order modes in LB antennas that are excited by HB signals. This approach enables the design of LB antennas that are electromagnetically transparent to HB frequencies without compromising their own performance. We developed a spiral-based dipole antenna that achieves scattering suppression over a 125% relative bandwidth while maintaining effective radiation in its designated LB. This design enhances cross-band isolation and preserves radiation patterns in HB operations, offering a streamlined solution for multiband antenna systems.

Resources

Open Source Tools for CMA:

- FEKO-student edition
- CM MATLAB Software
- AToM Antenna Toolbox

Webinars:

- Our webinars on YouTube
- Our webinars on Bilibili
- Webinars from FEKO

Available Courses:

- Courses offered by ESoA

Past Special Issues on CMA:

- July 2016 issue of IEEE Trans. Antennas Propag.
- April 2022 issue of IEEE Antennas Propag. Mag.

Past Issues of CM-SIG Newsletter:

- CM-SIG Newsletter

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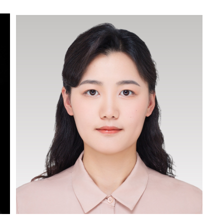

About CM-SIG: Characteristic Modes-Special Interest Group was initiated at the Special Session on CMs during the 2014, IEEE International Symposium on Antennas and Propagation in Memphis, TN, on 10 July 2014. CM-SIG was formed as a platform to promote technical activities in the field of CMs. For more information, please visit our website: http://www.characteristicmodes.org/.