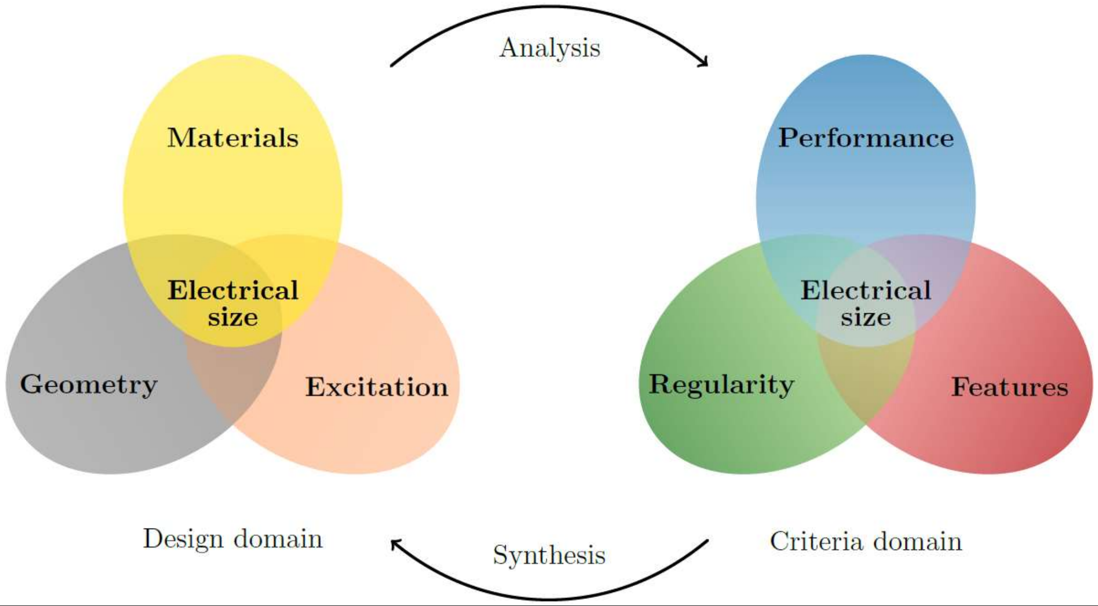
The 18th European Conference on Antennas and Propagation (EuCAP)
17 - 22 March 2024

Optimal Antennas: Operators, Limits, and Design

Abstract:

The success of computational electromagnetics in recent decades stems from the possibility to numerically approach non-canonical scenarios, i.e., those that cannot be solved analytically. This short course summarizes recent advancements in evaluating fundamental bounds, inverse design, and modal decomposition. An efficient framework utilizing matrix formalism is necessary for all these diverse techniques. This formalism, including various techniques, tricks, and identities, will be presented. The course aims to provide a good balance between mathematics, electromagnetic theory, code implementation, and live demonstrations that cover diverse applications.

Graphical abstract:



Recommended prerequisites for attendees:

Basic knowledge of MoM is advantageous but not a prerequisite.

Learning objectives:

After the course, the participant will be able to:

- Identify and evaluate matrices corresponding to various operators stemming from integral equations,
- formulate antenna problems and solve them using convex optimization,
- quantify the cost of extra design constraints (self-resonance, restricted controllable region, etc.),
- use software to compute bounds for practical design cases and - if needed - to implement his/her own codes,
- use topology optimization to improve antenna designs and to automate antenna design,

- apply the presented methodology to optimization problems involving antenna arrays and multiport antennas,
- understand unsolved problems in the field and start his/her own research in that area.

The participants will be provided with codes determining the bounds on the antenna metrics (gain, radiation efficiency, Q-factor) and performing topology optimization. A worksheet with analytical solutions will be distributed as well.

Course outline:

Optimal Antennas: Operators, Limits, and Design

1. Introduction (15 minutes)
2. Integral equations and related operators (30 minutes)
   Physical background
   Numerical evaluation of the operators
   Algebraic properties, modal analysis
   Practical part: live demonstrations (evaluation of impedance, stored energy, far-field and other matrices)
3. Fundamental bounds (45 minutes)
   Theoretical part: convex optimization, formulation of quadratic problems
   Practical part: live demonstrations (min Q,)
   Coffee break
4. Inverse design (45 minutes)
   Theoretical part: properties, available techniques
   Practical part: live demonstrations (gradient-based binary topology optimization)
5. Antenna array port modes (30 minutes)
6. Conclusion (15 minutes)

The participants can bring a laptop with MATLAB installed if they would like to run the provided codes.

Mats Gustafsson received the M.Sc. degree in Engineering Physics 1994, the Ph.D. degree in Electromagnetic Theory 2000, was appointed Docent 2005, and Professor of Electromagnetic Theory 2011, all from Lund University, Sweden.

He co-founded the company Phase holographic imaging AB in 2004. His research interests are in scattering and antenna theory and inverse scattering and imaging. He has written over 100 peer-reviewed journal papers and over 100 conference papers. Prof. Gustafsson received the IEEE Schelkunoff Transactions Prize Paper Award 2010, IEEE Uslenghi Letters Prize Paper Award 2019, and Best Paper Awards at EuCAP 2007 and 2013. He served as an IEEE AP-S Distinguished Lecturer 2013-15.

Miloslav Capek was born in Ceske Budejovice, Czech Republic, in March 1985. He received the M.Sc. degree in Electrical Engineering 2009, the Ph.D. degree in 2014, and was appointed Associate Professor in 2017, all from the Czech Technical University in Prague, Czech Republic.

Miloslav is a senior member of the IEEE. He serves as an associate editor of IET Microwaves, Antennas & Propagation. He was a member of the Delegate Assembly of EurAAP between 2015 and 2020 (Group 8). He leads the development of the AToM (Antenna Toolbox for MATLAB) package and serves as a vice-chair of EurAAP "Software and Modeling" working group. He is the author or co-author of over 150 journal and conference papers. His current research interests include the area of electromagnetic theory, electrically small antennas, numerical techniques, and optimization. He received the 2023 IEEE Antennas and Propagation Edward E. Altshuler Prize Paper Award. For detailed information, see `capek.elmag.org`

- Volakis, J. L., Chen, Ch., and Fujimoto, K.: Small Antennas: Miniaturization Techniques & Applications, McGraw-Hill, 2010.
- Fujimoto, K. and Morishita, H.: Modern Small Antennas, Cambridge University Press, 2013.
- Harrington. R. F.: Field Computation by Moment Methods, Wiley - IEEE Press, 1993.
- Gustafsson, M., Tayli, D., and Cismasu, M.: Physical bounds of antennas, In: Chen, Z. (eds) Handbook of Antenna Technologies. Springer, Singapore, 2015.
- Molesky, S., Lin, Z., Piggott, A.Y. et al.: Inverse Design in Nanophotonics, Nature Photonics, Vol. 12, pp. 659 – 670, 2018.
- Chao, P., Strekha, B., Defo, R. K., Molesky, S., Rodriguez, A. W.: Physical Limits in Electromagnetism, Nature Reviews Physics, July 2022.
- Gustafsson, M and Nordebo S., Optimal antenna currents for Q, superdirectivity, and radiation patterns using convex optimization, IEEE Trans. Antennas Propag., vol. 61, no. 3, pp. 1109–1118, Mar. 2013.
- Gustafsson, M., Tayli, D., Ehrenborg, C., Cismasu, M., and Norbedo, S.: Antenna Current Optimization using MATLAB and CVX, FERMAT, 2016.
- Jelinek, L., Capek, M.: Optimal Currents on Arbitrarily Shaped Surfaces, IEEE Trans. Antennas Propag., Vol. 65, No. 1, p. 329-341, 2017.
- Capek, M., Gustafsson, M., and Schab, K.: Minimization of Antenna Quality Factor, IEEE Transactions on Antennas and Propagation, Vol. 65, No. 8, pp. 4115-4123, Aug. 2017.
- Gustafsson, M., Capek, M., and Schab, K.: Tradeoff Between Antenna Efficiency and Q-Factor, IEEE Transactions on Antennas and Propagation, Vol. 67, No. 4, pp. 2482–2493, April 2019.
- Capek, M., Jelinek, L., and Gustafsson, M.: Shape Synthesis Based on Topology Sensitivity, IEEE Transactions on Antennas and Propagation, Vol. 67, No. 6, pp. 3889–3901, June 2019.
- Boyd S.P. and Vandenberghe L., Convex Optimization. Cambridge Univ. Pr., 2004.
- Vandenbosch G. A. E., Reactive energies, impedance, and Q factor of radiating structures, IEEE Trans. Antennas Propag., vol. 58, no. 4, pp. 1112–1127, Apr. 2010.
- Capek, M., Jelinek, L., Schab, K., Gustafsson, M., Jonsson, B. L. G., Ferrero, F., and Ehrenborg, C.: Optimal Planar Electric Dipole Antennas: Searching for Antennas Reaching the Fundamental Bounds on Selected Metrics, IEEE Antennas Propagation Magazine, Vol. 61, No. 4, pp. 19–29, August 2019.
- Best, S. R.: Electrically Small Resonant Planar Antennas, IEEE Antennas Propagation Magazine, Vol. 57, No. 3, pp. 38–47, June 2015.
- Schab, K., Jelinek, L., Capek, M., Ehrenborg, C., Tayli, D., Vandenbosch, G. A. E., and Gustafsson, M.: Energy Stored by Radiating Systems, IEEE Access, Vol. 6, pp. 10553–10568, 2018.
- Rahmat-Samii, Y. and Michielssen, E.: Electromagnetic Optimization by Genetic Algorithm, Wiley, 1999.
- Erentok, A. and Sigmund, O.: Topology Optimization of Sub-Wavelength Antennas, IEEE Transactions on Antennas and Propagation, Vol. 59, No. 1, pp. 58–69, January 2011.
- Hassan, E., Wadbro, E., and Berggren, M.: Topology Optimization of Metallic Antennas, IEEE Transactions on Antennas and Propagation, Vol. 62, No. 5, pp. 2488–2500, May 2014

- Capek M., Jelinek L., Kadlec P., Gustafsson M., Optimal Inverse Design Based on Memetic Algorithms-Part 1: Theory and Implementation, IEEE Transactions on Antennas and Propagation, Vol. 71, No. 11, pp. 8806 - 8816, 2023.
- Capek M., Jelinek L., Kadlec P., Gustafsson M., Optimal Inverse Design Based on Memetic Algorithms- Part 2: Examples and Properties, IEEE Transactions on Antennas and Propagation, Vol. 71, No. 11, pp. 8817 - 8829, 2023
- Ehrenborg, C., Gustafsson, M., Capek, M.: Capacity Bounds and Degrees of Freedom for MIMO Antennas Constrained by Q-Factor, IEEE Transactions on Antennas and Propagation, vol. 69, no. 9, pp. 5388-5400, 2021
- Christiansen, R. E., Sigmund, O.: Compact 200 Line MATLAB Code for Inverse Design in Photonics by Topology Optimization: Tutorial, Journal of the Optical Society of America B, Vol. 38, No. 2 pp. 510-520, 2021.