Coherent Control of Wave Scattering via Engineering of Complex Spectra

A. Douglas Stone[1]***,*** *Ali Alhulaymi*[1], *Philipp del Hougne*[2], *Owen D. Miller*[1]
Yale University, Dept of Applied Physics
University of Rennes, CNRS

Controlling multiple scattering of waves in higher dimensional geometries has been an area where analytic methods and mathematical insight has been lacking and black-box optimization is considered the only viable approach. However, the theory of Coherent Perfect Absorption[1] (CPA) and Reflectionless Scattering Modes[2] (RSM) has shown that there exist discrete solutions to scattering of linear waves, even in high dimensional multiple-scattering geometries, that achieve important control functions: perfect transduction (CPA) and perfect (reflectionless) impedance matching (RSM). Generically, the solutions are at complex frequency and are only accessible transiently; but with tuning of two system parameters, they can be realized in steady-state at a given real frequency. Here we show[3] the existence of a wider class of such functionalized scattering solutions in the complex plane, including transmission zeros, which can be tuned to become steady-state solutions in the same manner. We refer to such solutions as critically constrained scattering modes (CCONs), as they have boundary conditions which lead to discrete complex spectra. We show theoretically[3] that with more tuning parameters, more highly constrained control functions can be achieved, such as routing or demultiplexing, using CCONs as building blocks. Mathematically these functions are equivalent to creating a d-fold coincidence of complex eigenvalues at the same real frequency; we find that 2d tuning parameters are needed to achieve routing between ports; for example, routing a signal without any reflection between three ports requires four tuning parameters.

For heuristic reasons we expect an open low-loss wave-chaotic cavity with tunable scattering elements to be optimal for achieving such routing functions, since such a cavity has overlapping, pseudo-random resonances, making it frequency agnostic, and easily reprogrammable. We will present the results of recent experiments[4] and simulations[3,4] of such a cavity that have confirmed this conjecture in the microwave frequency range. Thus, these discrete spectra provide a new framework for understanding the extent to which reverberation and interference can be harnessed for control functions based on a *definite* number of control knobs. Since these systems are easily reprogrammable and flexible, they are robust to perturbations and to fabrication defects, and they have the potential to be uniquely effective for applications where frequency-agile performance is required.

1. "Coherent Perfect Absorbers: Time-reversed Lasers", Y.D. Chong, L. Ge, H. Cao, and A. D. Stone, Physical Review Letters, **105**, 053901 (2010).
2. "Theory of Reflectionless Scattering Modes", William R. Sweeney, Chia Wei Hsu, and A. Douglas Stone, Phys. Rev. A, 2020, https://link.aps.org/doi/10.1103/PhysRevA.102.063511
3. "Coherent Control of Scattering of Waves via Engineering of Complex Spectra", in preparation, A. Alhulaymi, N. Pyvovar, P. Del Hougne, O. D. Miller, A. D. Stone.
4. "Agile Free-Form Signal Filtering and Routing with a Chaotic-Cavity-Backed Non-Local Programmable Metasurface", F. T. Faul, L. Cronier, A. Alhulaymi, A. D. Stone, P. del Hougne, Advanced Science, DOI: 10.1002/advs.202500796.