Wave basis of Ohm's law: observation and impact of transmission and velocity zeros

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The quantum conductance and its classical wave analogue, the transmittance, are given by the sum of the eigenvalues of the transmission matrix. Here, we measure spectra of microwave transmission matrices of random waveguides and find the spectra of all transmission eigenvalues, even at dips in the lowest transmission eigenchannel that are ten orders of magnitude below the noise in the transmission matrix. Transmission vanishes both at topological transmission zeros, at which the energy density at the sample output vanishes, and at crossovers to new channels, where the longitudinal velocity vanishes. The longitudinal velocities of different transmission eigenchannels are distinct and independent of length for samples longer than the mean free path. The statistics of the eigenchannel velocities on the incident and output surfaces of the sample are identical. Zeros of transmission pull down all the transmission eigenvalues and thereby produce dips in the transmittance. These dips and the ability to probe the characteristics of even the lowest transmission eigenchannel are due to correlation among the eigenvalues. The precise tracking of dips in the conductance by peaks in the density of states points to a further correlation between zeros and poles of the transmission matrix. The conductance approaches Ohm's law as the sample width increases in accord with the correspondence principle.

1. E. N. Economu and C. M. Soukouis, "Static conductance and scaling theory of localization in one dimension," Phys. Rev. Lett. 46, 618 (1981)
2. Kang and Azriel Z. Genack, "Transmission zeros with topological symmetry in complex systems," Yuhao Phys. Rev. B **103**, L100201 (2021).
3. A. Z. Genack, Y. Huang, A. Maor and Z. Shi, "Velocities of transmission eigenchannels and diffusion," Nature Commun. **16**, 2606 (2024).
4. J. Krishna I. Kurtz, Z. Shi and A. Z. Genack "Ohm's law lost and regained: observation and impact of zeros and poles," Nature Commun. **15**, 10616 (2024).anack@qc.cuny.edu