Harnessing multiple-scattering electromagnetic environments for wave-control via in-situ adjoint optimization

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Abstract: We develop an in-situ time- and energy-efficient adjoint optimization (AO) methodology for the manipulation of wave scattering in multiple scattering systems and demonstrate wave-driven functionalities like targeted channel emission, coherent perfect absorption and camouflage. Our paradigm leverages the highly multi-path nature of these complex environments which dramatically amplifies small local system variations since the wave is repeatedly scattered by these AO-informed perturbations. Our approach can find immediate application to in-door wireless technologies while it can also be incorporated into a variety of wave-based frameworks including imaging, power electronic and optical neural networks.

We experimentally demonstrate an in-situ optimization protocol that leverages adjoint sensitivity analysis to control and harness complex wave dynamics. The protocol is built around three components: in-situ measurements, targeted perturbations, and an external control mechanism, which collectively enable the real-time optimization of wave networks through two sequential field propagations -- forward and adjoint. First, local probes are employed to measure both the forward and adjoint wave fields at specific elements within the system. Forward propagation is utilized to compute a desired merit (or cost) function and to determine the excitation profile required for the subsequent adjoint propagation. The adjoint field, in turn, provides a comprehensive and simultaneous measurement of all targeted sensitivities. An external control mechanism evaluates these sensitivities to identify the potential perturbations which could enhance (or diminish) the merit (cost) function. These adjustments are then delivered by local actuators to the targeted components (i.e., the tunable degrees of freedom of the system). The cycle is repeated as many times as necessary to maximize (minimize) the merit (cost) function. To demonstrate the versatility of our protocol we showcase three different modalities, namely, targeted channel emission, coherent perfect absorption, and camouflaging, using a microwave experimental platform. The latter consists of a network of coupled coaxial microwave cables whose wave transport demonstrates features characterizing wave chaotic systems. These networks are frequently used as models for mesoscopic quantum transport, sound propagation, and electromagnetic wave behavior in complex interconnected structures such as buildings, ships, and aircrafts and therefore constitute a simple and versatile platform for experimentally implementing our in-situ optimization protocol.

We acknowledge partial funding from NSF-RINGS ECCS (2148318), Simons Foundation (SFI-MPS-EWP-00008530-08) and MURI ONR-N000142412548.

References

1. Guillamon, J., CZ. Wang, Z. Lin, and T. Kottos, "Harnessing multiple-scattering electromagnetic environments for wave-control via in-situ adjoint optimization," submitted 2025.