Wesleyan University

Department of Physics
Wave Transport in Complex Systems Lab

In-situ Physical Adjoint Computing in Multiple-Scattering Electromagnetic Environments for Wave Control

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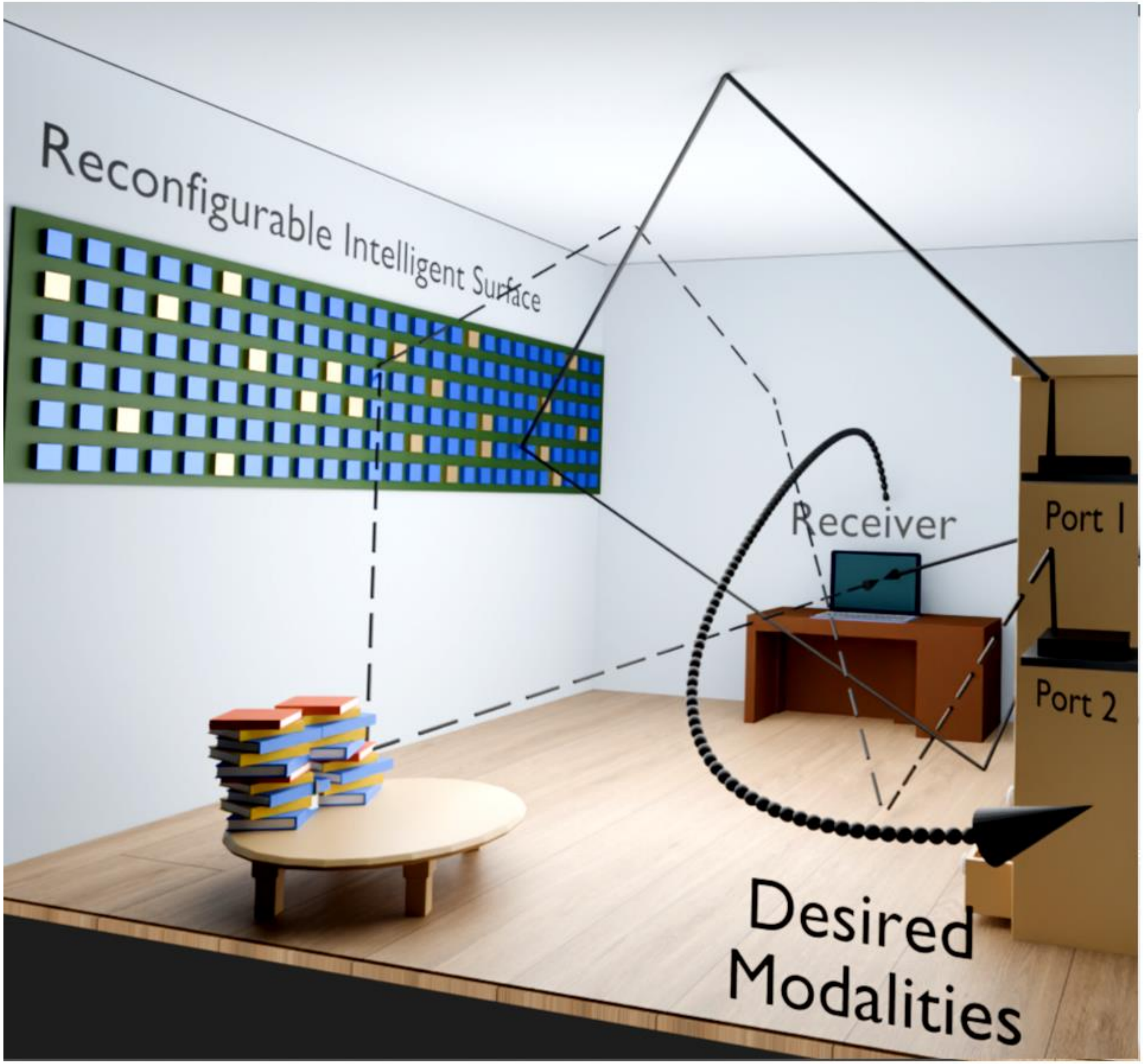
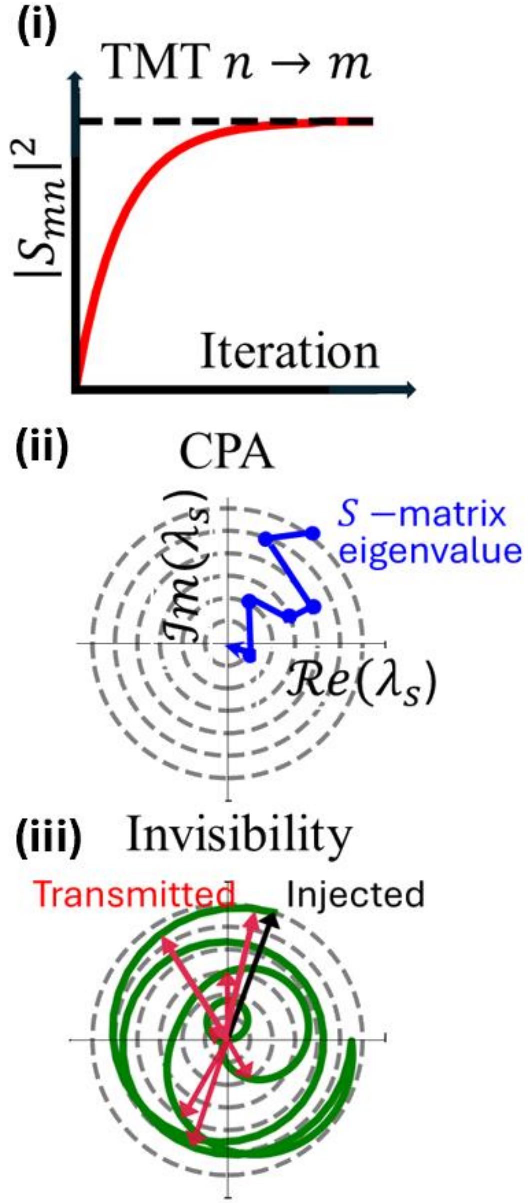
Acknowledgement: Prof. Steven Johnson(MIT)

https://cqdmp.research.wesleyan.edu

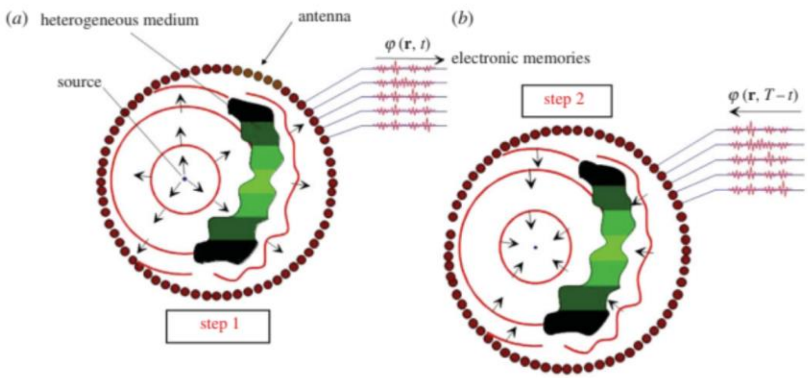
Challenges in Wireless Communications





Fink, M. (2016). From Loschmidt daemons to time-reversed waves. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *374*

Time Reversal

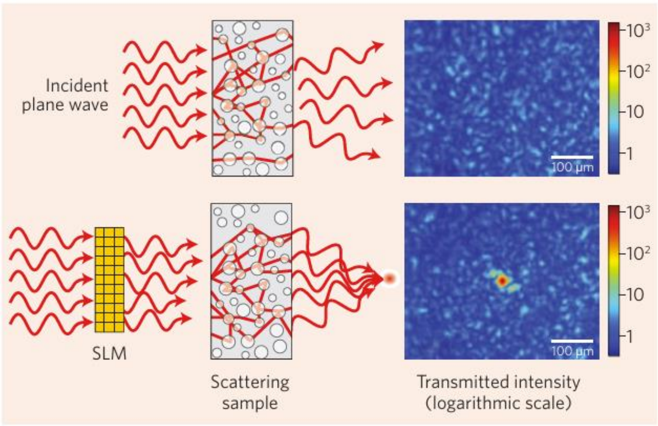


Kaina, N., Dupré, M., Lerosey, G., & Fink, M. (2014). Shaping complex microwave fields in reverberating media with binary tunable metasurfaces. *Scientific reports*, *4*(1), 6693.

Vellekoop, I. M., & Mosk, A. P. (2007). Focusing coherent light through opaque strongly scattering media. *Optics letters*

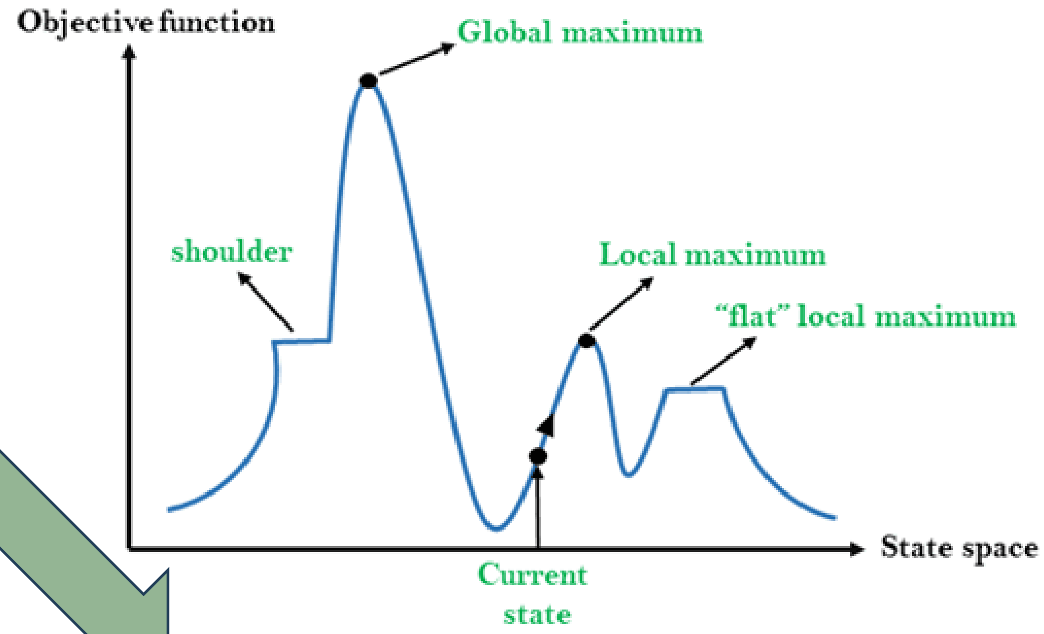
Cavity Shaping

Wavefront Shaping



Adjoint-Based Gradient Optimization

Optimization

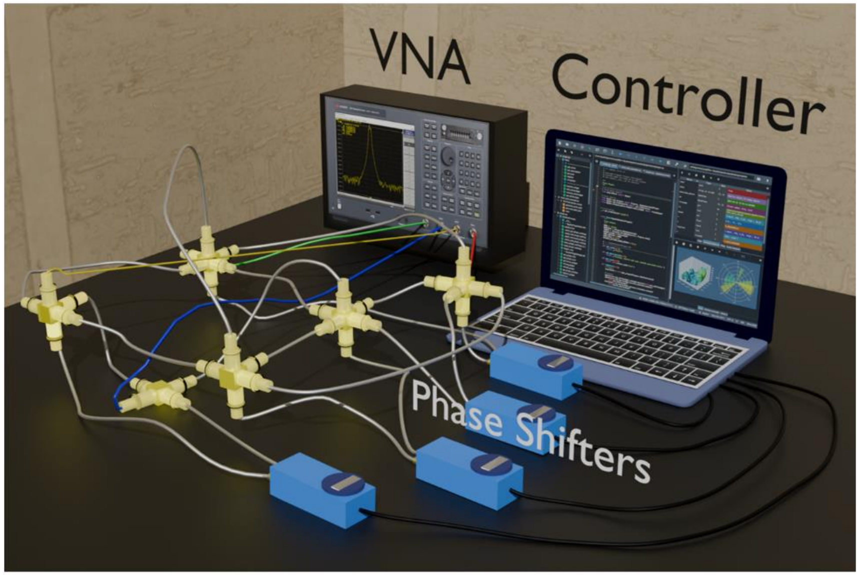


Gradient-Free:
Bayesian
Surrogate

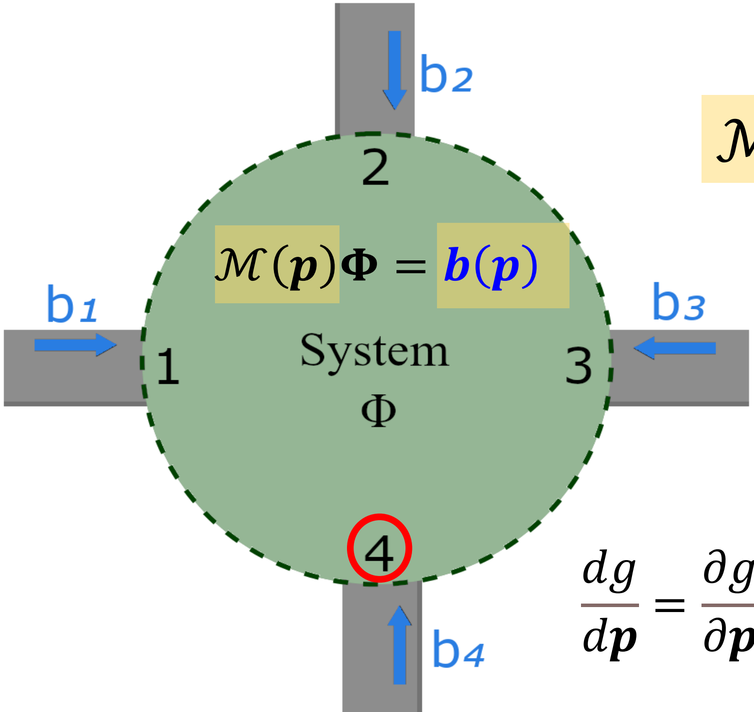
Gradient-Based:
Finite Difference
Adjoint Method

We propose and demonstrate the use of
an *in-situ* (Experimentally Driven)
Adjoint Method

Principles of In-Situ Adjoint Optimization

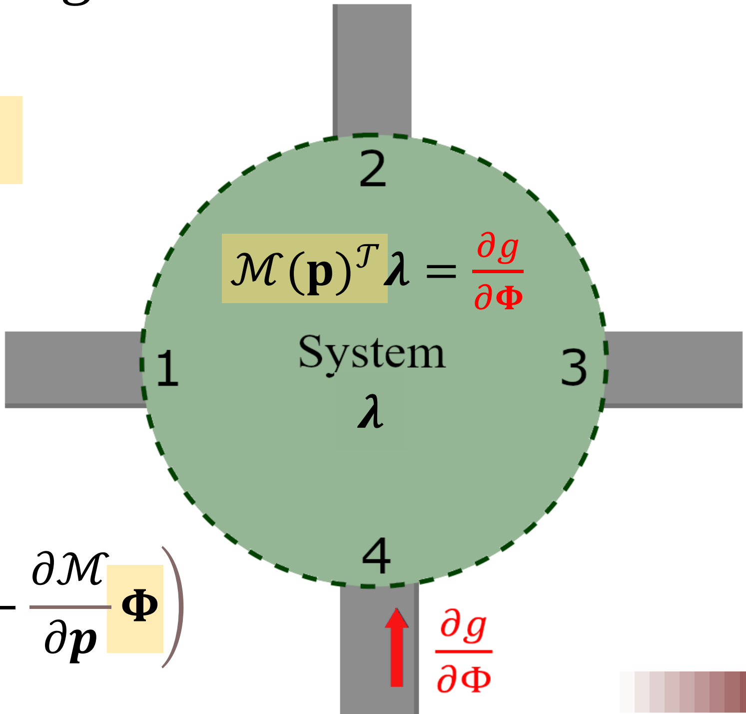


- Exploit reciprocity: Only one additional "adjoint" measurement needed
- In-situ measurements self-calibrate against real-world losses/detuning
- Real-time, gradient-based optimization without big data sets or training neural networks



$$\mathcal{M} = \mathcal{M}^{\mathrm{T}}$$

$$\frac{dg}{d\boldsymbol{p}} = \frac{\partial g}{\partial \boldsymbol{p}} + \boldsymbol{\lambda}^{T}\left(\frac{\partial \boldsymbol{b}}{\partial \boldsymbol{p}} - \frac{\partial \mathcal{M}}{\partial \boldsymbol{p}}\boldsymbol{\Phi}\right)$$

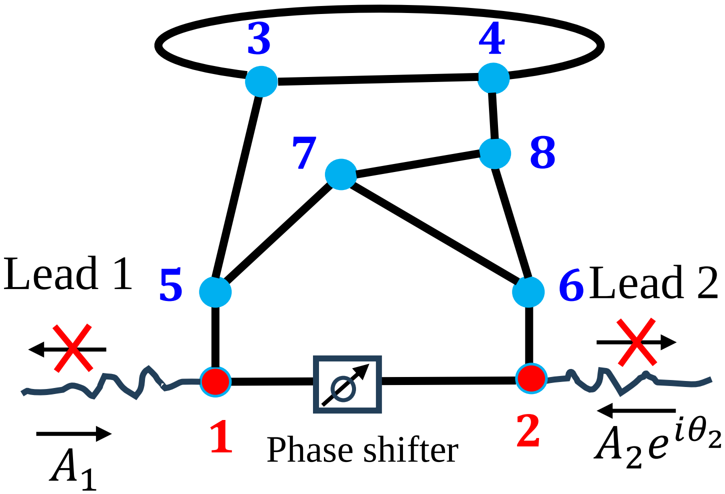


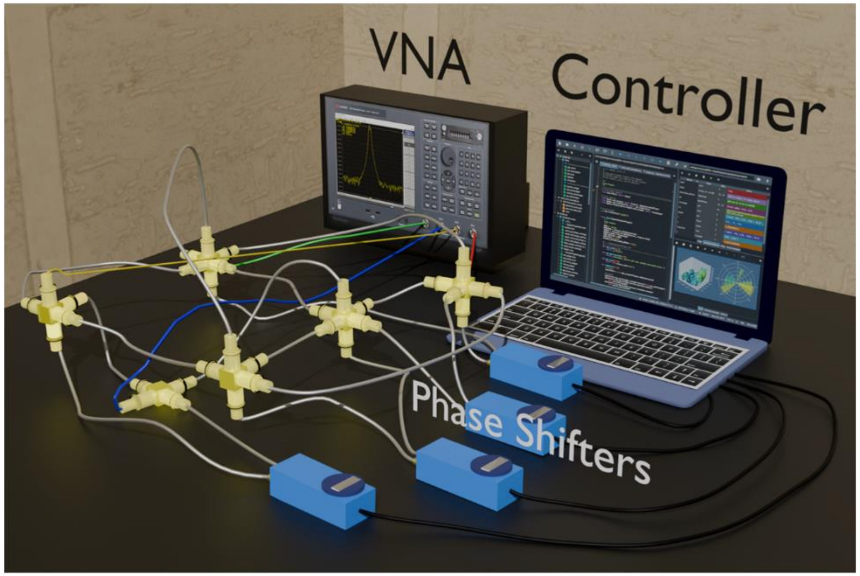
Principles of In-Situ Adjoint Optimization

$$\frac{dg}{d\boldsymbol{p}} = \frac{\partial g}{\partial \boldsymbol{p}} + \underbrace{\lambda^T}_{} \left(\frac{\partial \boldsymbol{b}}{\partial \boldsymbol{p}} - \frac{\partial \mathcal{M}}{\partial \boldsymbol{p}} \underbrace{\boldsymbol{\Phi}}_{} \right)$$

Backward measurement

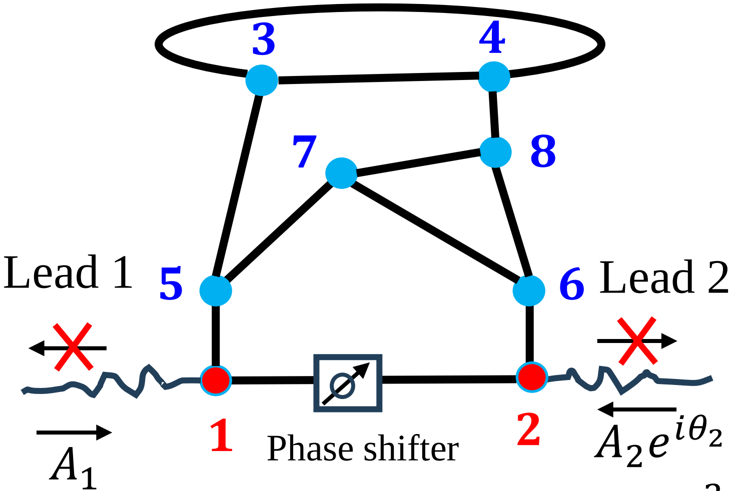
Forward measurement





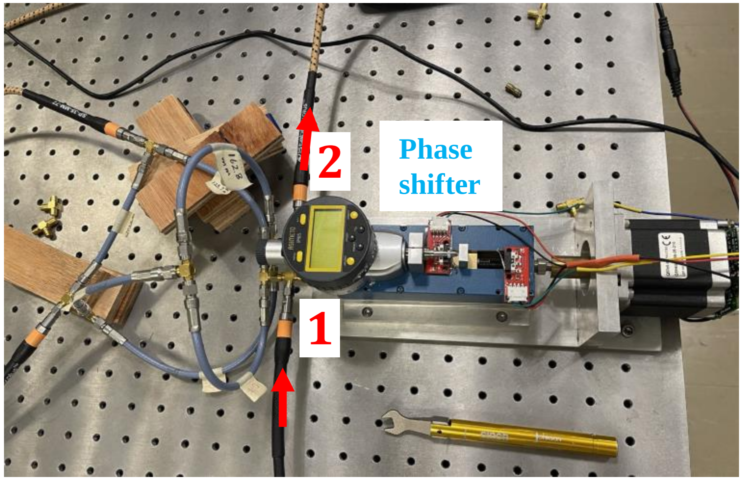
- Measure twice: forward and backward (adjoint) waves, avoid matrix inversion
- We only need to measure the vertices local to our parameters
- Tuning the system locally can change the system dramatically due to wave complexity

Example Modality: Coherent Perfect Absorption

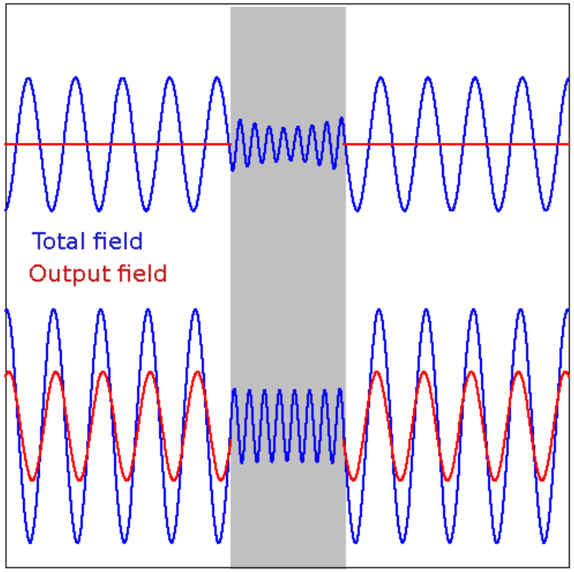


$$g = 1 - \frac{|\phi_1 - A_1|^2 + |\phi_2 - A_2 e^{i\theta_2}|^2}{A_1^2 + A_2^2}$$

1. Forward Measurement
2. Adjoint Measurement
3. Gradient Calculation
4. Parameter Update
5. Iteration & Convergence

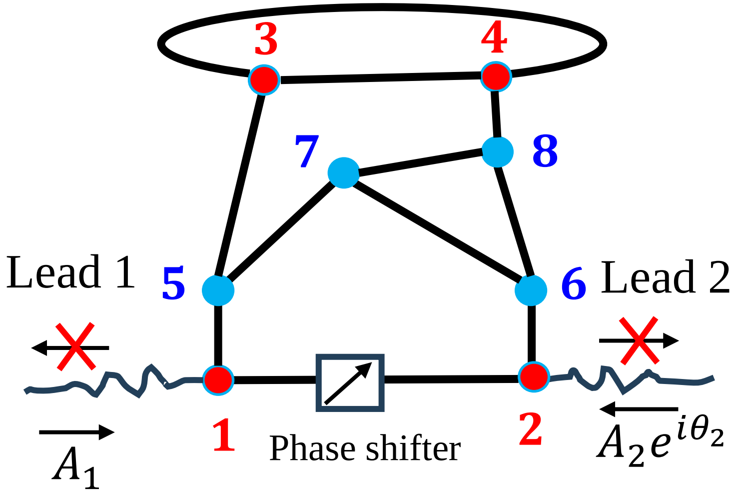


$\boldsymbol{p} = [\mathrm{L}_{12}, \mathrm{A}_3, \theta_3]$:



Chong, Y. D. Stone A.D. , et al. 2010, "Coherent perfect absorbers: time-reversed lasers."

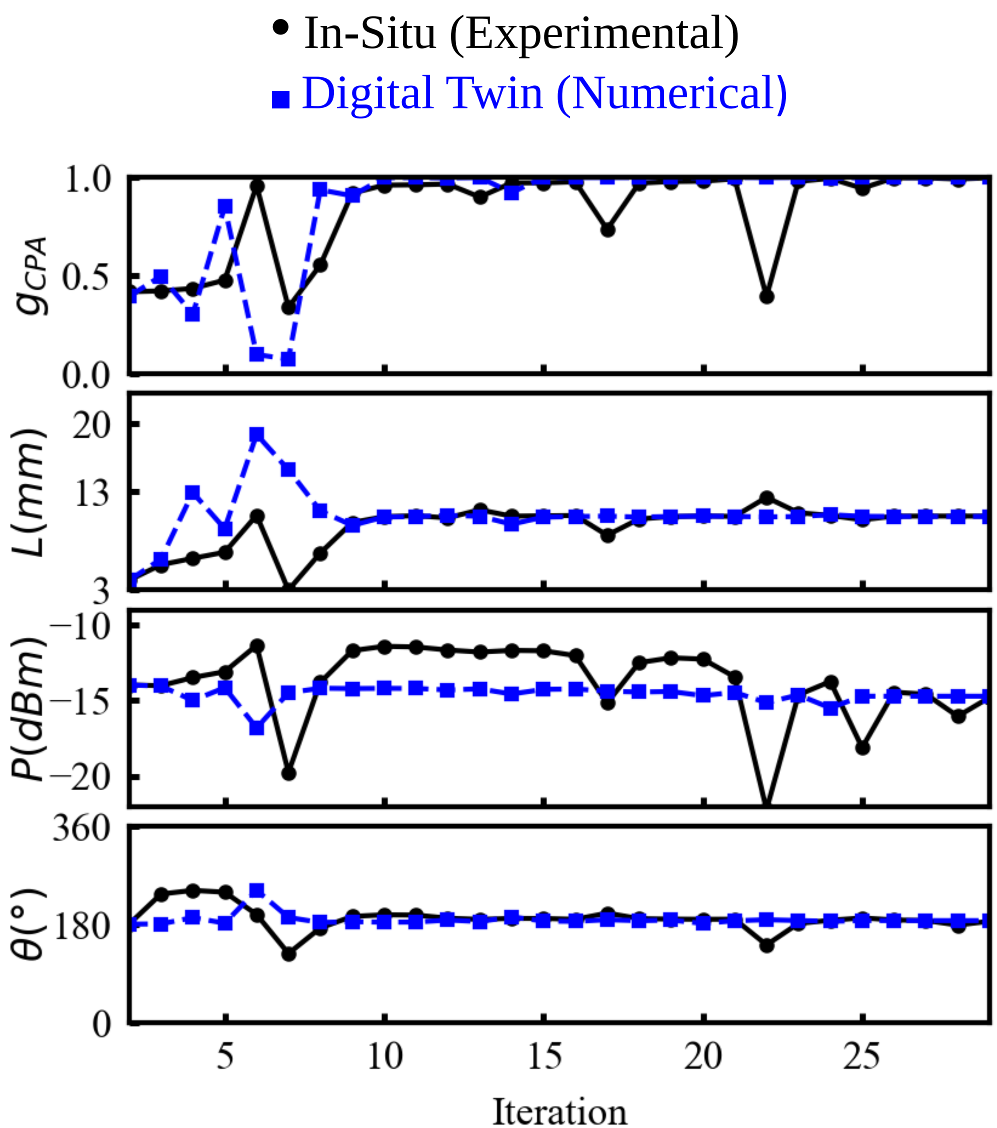
Example Modality: Coherent Perfect Absorption



Maximize the objective function (absorption):

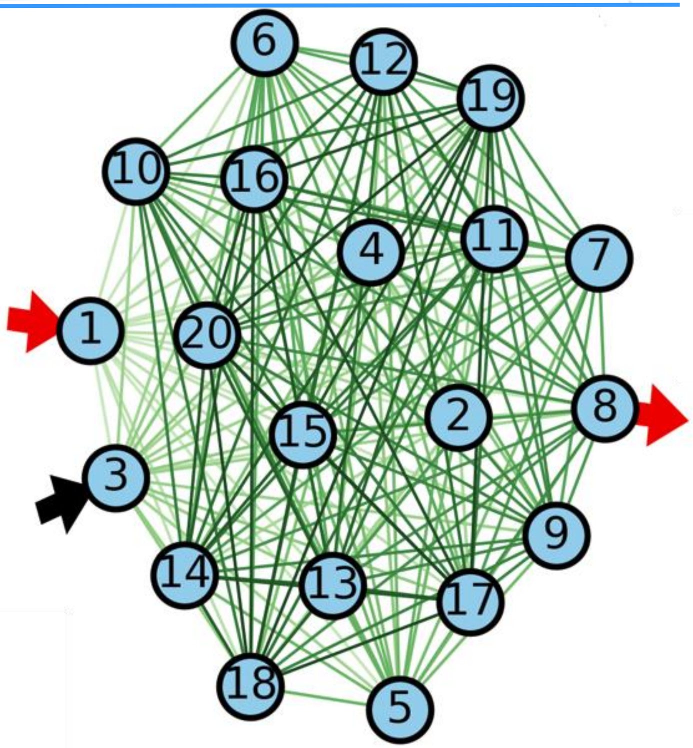
$$g = 1 - \frac{|\phi_1 - A_1|^2 + \left|\phi_2 - A_2 e^{i\theta_2}\right|^2}{A_1^2 + A_2^2}$$

	In situ adjoint	Digital twin
Objective: g	0.999	0.999
L(mm)	10.52	10.48
Power(dBm)	-14.82	-14.72
Phase(°)	185.2	186.4



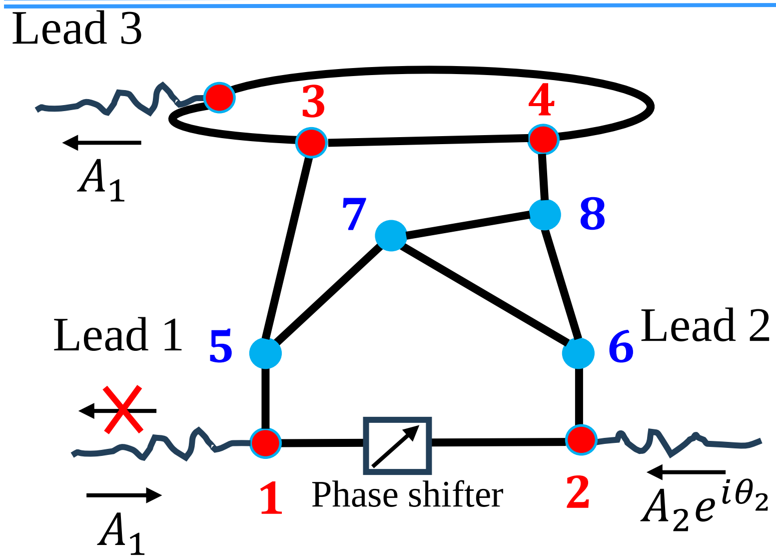
Summary

- We can measure the gradient of a wave control objective function in two measurements
- We only need to measure the vertices local to our parameters
- Tuning the system locally can change the system dramatically due to wave complexity
- Therefore, we extended our protocol to larger networks and other modalities, where computational savings and noise reduction is critical.



Thank you!

Example Modality 3: Invisibility



a1(dBm)	a1(DEG)
-15.0079	-90.5411

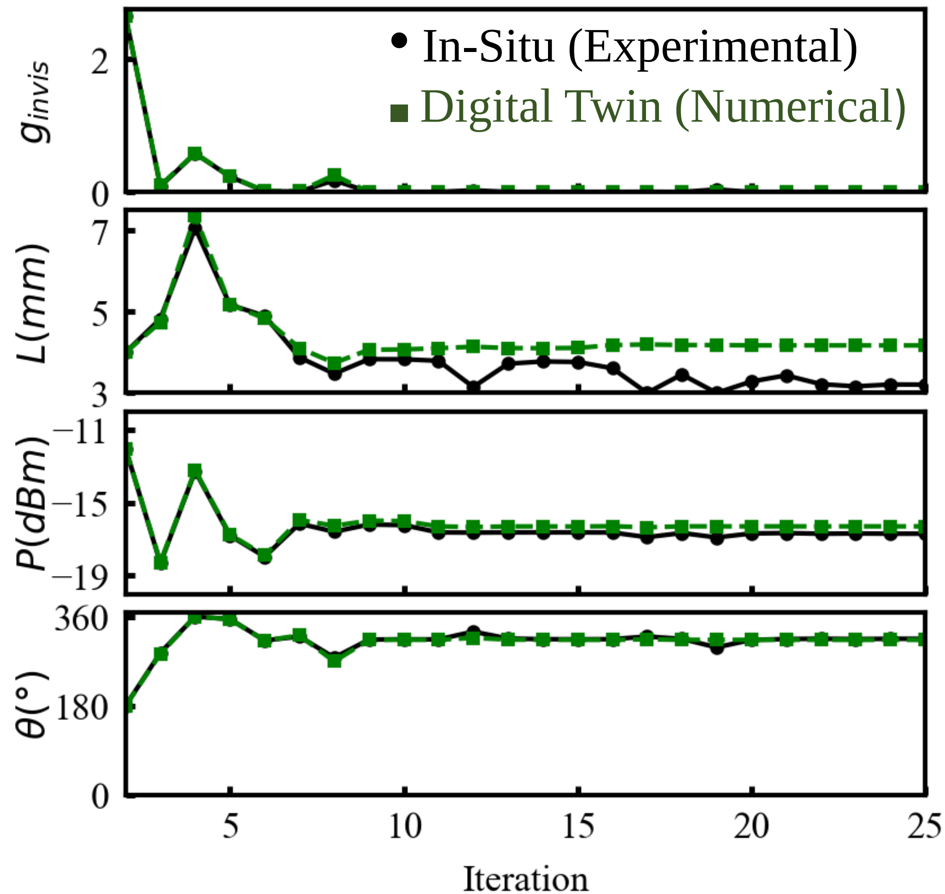
b3(dBm)	b3(DEG)
-14.9878	-90.6914

b1(dBm)
-66.7887

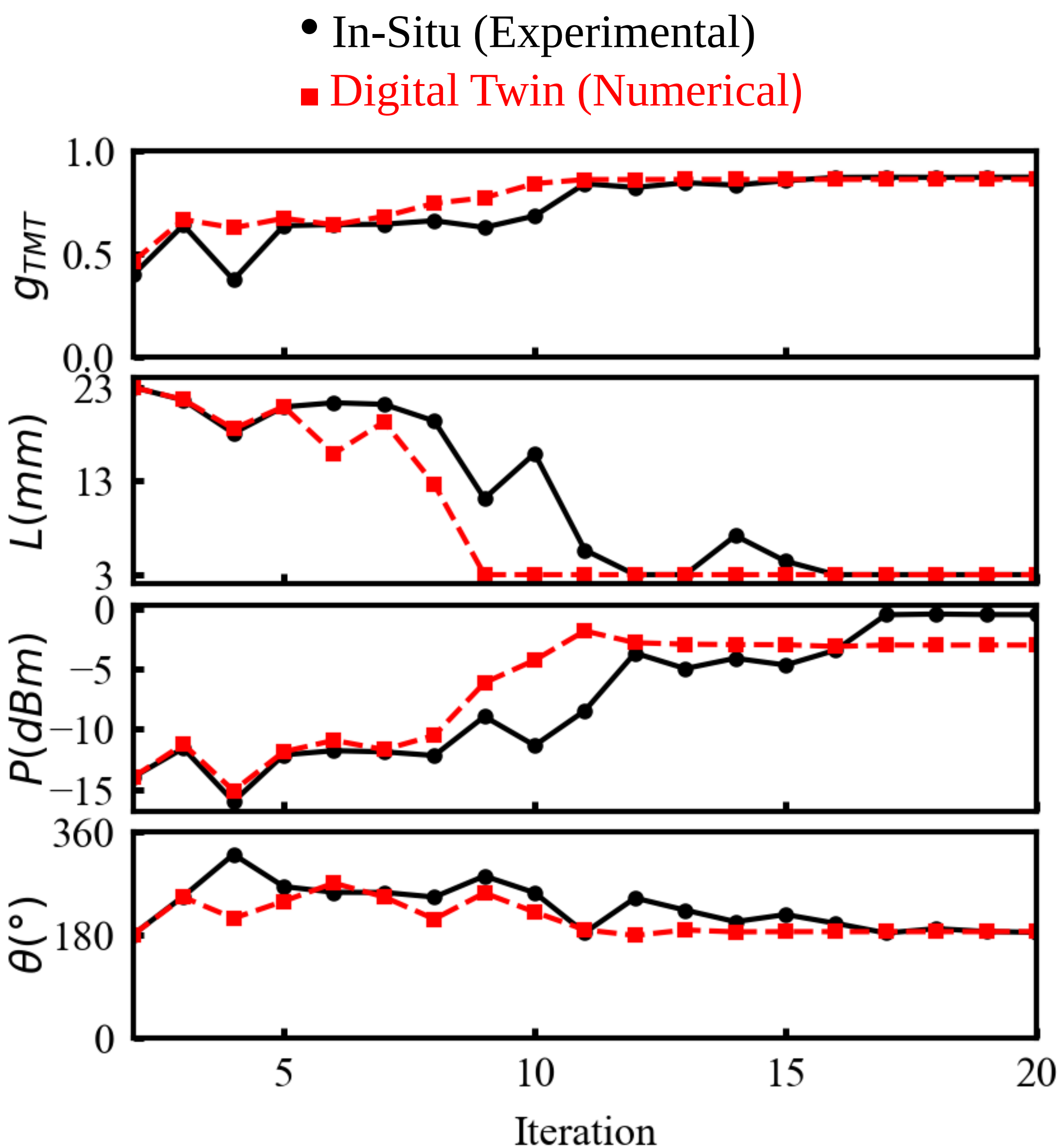
Minimize the objective function (difference):

$$g_{invis} = \frac{|\phi_3 - A_1|^2}{A_1^2} + \frac{|\phi_1 - A_1|^2}{A_1^2 + A_2^2}$$

	In situ adjoint	Digital twin
Objective: g	1.65e-5	4.73e-7
L(mm)	3.19	4.17
Power(dBm)	-16.71	-16.30
Phase(°)	315.1	313.0



Example Modality: Targeted Mode Transmission

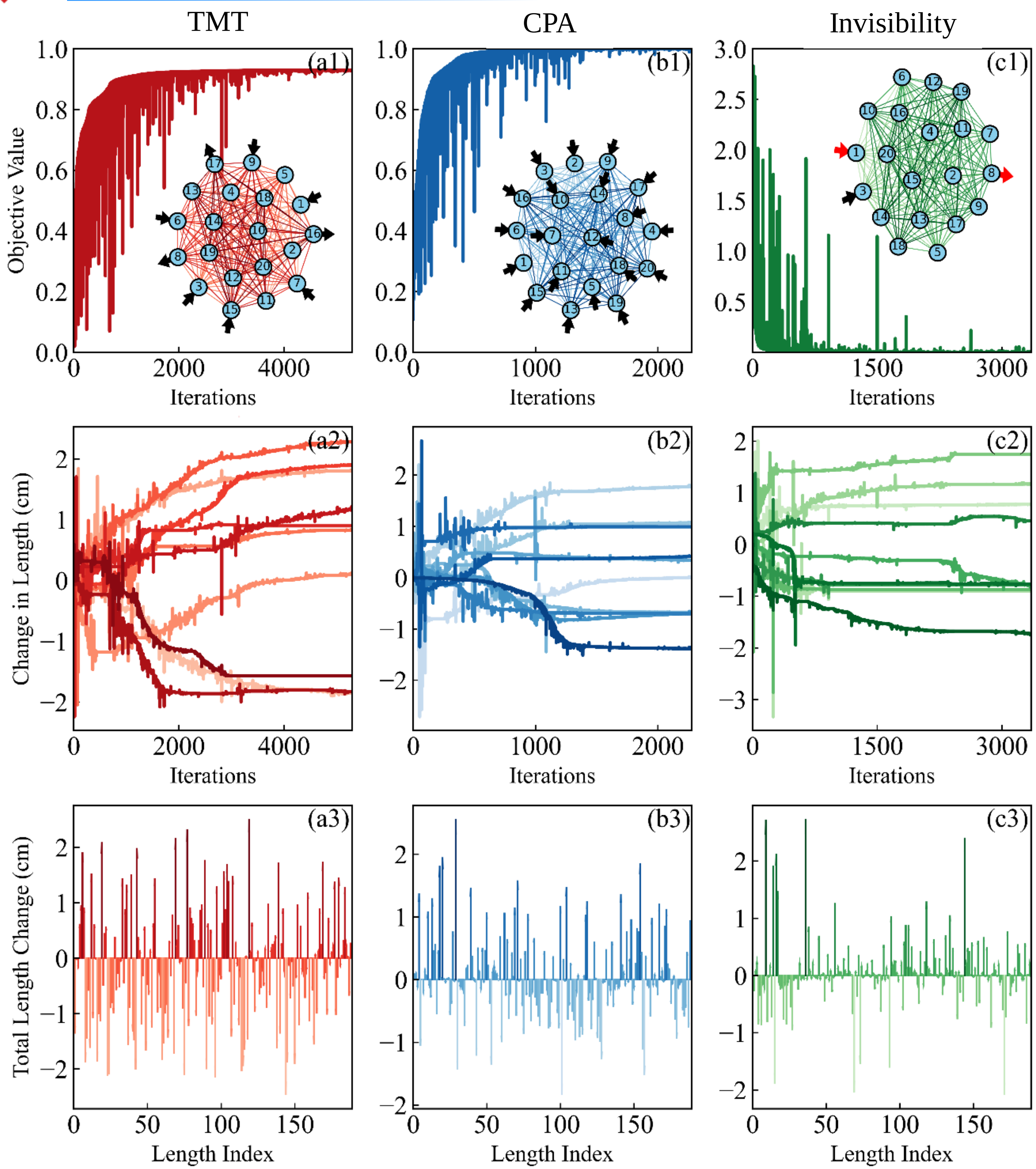


Maximize the objective function:

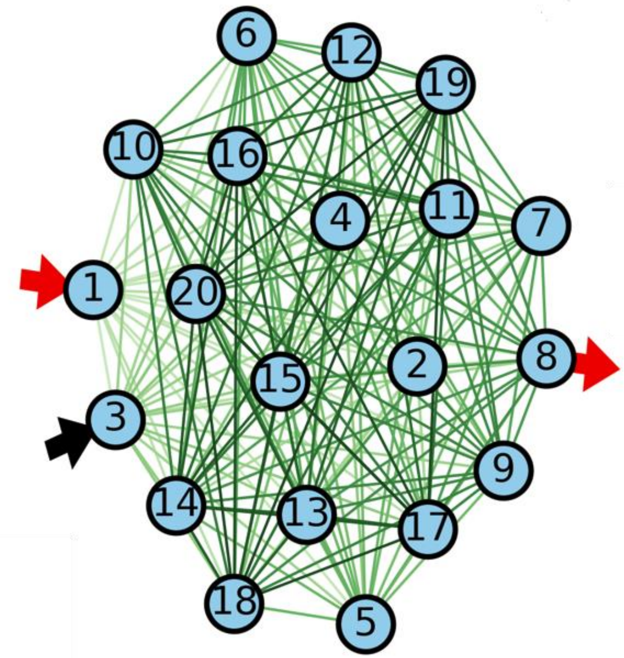
$$g = \frac{|\phi_4|^2}{A_1^2 + A_3^2} = \frac{\phi_4 \phi_4^*}{A_1^2 + A_3^2}$$

	In situ adjoint	Digital twin
Objective: g	0.873	0.862
L(mm)	3.00	3.00
Power(dBm)	-0.47	-2.99
Phase(°)	184.6	185.1

In-Silico (simulations) Using Large Complex Networks



Invisibility



For a fully connected graph:

# of Bonds = $\frac{n(n-1)}{2} \approx n^2$,

In-Situ Adjoint only requires n local measurements!

190 bonds → 20 measurements!