Blind Beamforming for IRS: Theory and Practice

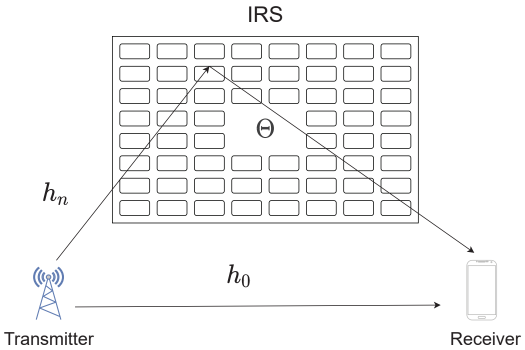
Kaiming Shen

joint work with Shuyi Ren, Jiawei Yao, Wenhai Lai, Wenyu Wang, Fan Xu, Xin Li, Xin Chen, Shaobo Niu, and Prof. Zhi-Quan Luo

October 21, 2023

香港中文大學(深圳)
The Chinese University of Hong Kong, Shenzhen

What is IRS?



- Intelligent reflecting surface (IRS) is a passive reflective device.
- Each reflective element induces phase shift in its reflected channel.
- Coordinate phase shifts to concentrate signal on the receiver.

Notation

- N: number of reflective elements at IRS.
- h_0: direct channel from Tx to Rx.
- h_n: reflected channel of the nth reflective element.
- θ_n: phase shift of the nth reflective element.

Problem Formulation

- $\text{SNR} = \left|h_0 + \sum_{n=1}^{N} h_n e^{j\theta_n}\right|^2 P/\sigma^2.$
- We seek optimal $\boldsymbol{\theta}$ to maximize SNR:

$$\begin{aligned} \underset{\boldsymbol{\theta}}{\text{maximize}} \quad & \left|h_0 + \sum_{n=1}^{N} h_n e^{j\theta_n}\right|^2 \\ \text{subject to} \quad & \theta_n \in \{\phi_1, \phi_2, \ldots, \phi_K\}. \end{aligned}$$

- There are totally K^N possible combinations of θ_n's!

Optimal Solving with CSI

- A natural idea is to choose θ_n so as to rotate $h_n e^{j\theta_n}$ to the closest possible position to h_0, namely closest point projection (CPP):

$$\cos^2(\pi/K) \cdot f^\star \leq f(\boldsymbol{\theta}^{\mathsf{CPP}}) \leq f^\star.$$

- Surprisingly, global optimum can be obtained in linear time!

S. Ren, K. Shen, X. Li, X. Chen, and Z.-Q. Luo, "A Linear Time Algorithm for the Optimal Discrete IRS Beamforming", *IEEE Wireless Commun. Lett.*, Mar. 2023.

Blind Beamforming without CSI

- Why not channel estimation?

  (i) Protocol (ii) Cost (iii) Error

- Generate $\boldsymbol{\theta}_t = (\theta_{1t}, \ldots, \theta_{Nt})$ at random, $t = 1, \ldots, T$.

- For each random sample t, the corresponding received signal is

$$Y_t = h_0 X_t + \sum_{n=1}^{N} h_n e^{j\theta_{nt}} X_t + Z_t.$$

- Random-Max Sampling (RMS) picks the best $\boldsymbol{\theta}_t$ out of samples:

$$\boldsymbol{\theta}^{\text{RMS}} = \boldsymbol{\theta}_{t_0} \ \text{ where } \ t_0 = \arg \max_{1 \le t \le T} |Y_t|^2.$$

Scaling Law of RMS

Proposition 0.1

The expected SNR boost achieved by the RMS method has the following order bounds:

$$\mathbb{E}[f(\boldsymbol{\theta}^{\mathsf{RMS}})] = \Omega(N \log T) \;\; \textit{if } T = o(\sqrt{N})$$
$$\mathbb{E}[f(\boldsymbol{\theta}^{\mathsf{RMS}})] = O(N \log T) \;\; \textit{in general}$$

where the expectation is taken over random samples.

Remark: This is also the fundamental limit of beam sweeping when codebook size is T.

S. Ren, K. Shen, X. Li, X. Chen, and Z.-Q. Luo, "Configuring Intelligent Reflecting Surface with Performance Guarantees: Blind Beamforming", *IEEE Trans. Wireless Commun.*, May. 2023.

Conditional Sample Mean (CSM)

- Still generate T random samples.
- Compute conditional sample mean $\mathbb{E}\big[|Y_t|^2|\theta_n = \phi_k\big]$.
- Choose each θ_n to maximize the conditional sample mean:

$$\theta_n^{\mathsf{CSM}} = \arg\max_{\phi_k \in \Phi_K} \mathbb{E}\big[|Y_t|^2|\theta_n = \phi_k\big].$$

V. Arun and H. Balakrishnan, "RFocus: Beamforming using thousands of passive antennas," in *USENIX Symp. Netw. Sys. Design Implementation (NSDI)*, Feb. 2020, pp. 1047–1061.

S. Ren, K. Shen, X. Li, X. Chen, and Z.-Q. Luo, "Configuring Intelligent Reflecting Surface with Performance Guarantees: Blind Beamforming", *IEEE Trans. Wireless Commun.*, May. 2023.

A Toy Example

Index	1	2	3	4	5	6
$\boldsymbol{\theta}$	$(0,\pi,0,0)$	$(0,0,0,0)$	$(\pi,\pi,\pi,0)$	$(\pi,0,\pi,\pi)$	$(\pi,\pi,0,\pi)$	$(0,0,\pi,\pi)$
SNR	2.8	1.0	1.5	3.3	0.3	0.4
θ_1	0	0	π	π	π	0

- Find the mean SNR conditioned on $\theta_1 = 0$:

$$\mathbb{E}[\text{SNR}|\theta_1 = 0] = \frac{2.8 + 1.0 + 0.4}{3} = 1.4,$$

- Find the mean SNR conditioned on $\theta_1 = \pi$:

$$\mathbb{E}[\text{SNR}|\theta_1 = \pi] = \frac{1.5 + 3.3 + 0.3}{3} = 1.7.$$

- Solution $(\pi, 0, \pi, 0)$ does NOT appear in the six random samples.

Scaling Law of CSM

Proposition 0.2

The expected SNR boost achieved by the CSM method has the following order bounds:

$$\mathbb{E}[f(\boldsymbol{\theta}^{\mathsf{CSM}})] = \Theta(N^2) \ \ \textit{if} \ T = \Omega(N^2(\log N)^3),$$

where the expectation is taken over random samples.

S. Ren, K. Shen, X. Li, X. Chen, and Z.-Q. Luo, "Configuring Intelligent Reflecting Surface with Performance Guarantees: Blind Beamforming", *IEEE Trans. Wireless Commun.*, May. 2023.

Intuition of CSM

- As $T \to \infty$, $\widehat{\mathbb{E}}\big[|Y|^2 : \theta_n = \varphi\big]$ converges to $\mathbb{E}\big[|Y|^2 : \theta_n = \varphi\big]$.

- It can be shown that

$$\mathbb{E}[|Y|^2 : \theta_n = \varphi] = \mathbb{E}\left[\left|h_0 X + \sum_{n=1}^{N} h_n e^{j\theta_n} X + Z\right|^2 : \theta_n = \varphi\right]$$
$$\propto |h_0| \cdot \cos\left(\angle h_n + \varphi - \angle h_0\right) + \text{const.}$$

- Thus, CSM is equivalent to minimizing $|\angle h_n + \varphi - \angle h_0|$, namely CPP.

Generalized CSM Method

- How about multiple users & multiple antennas?
- We now extend CSM to account for a general utility function $U(\boldsymbol{\theta})$.
- Compute the conditional sample mean of U:

$$\hat{\mathbb{E}}[U|\theta_n = \varphi] = \frac{1}{|\mathcal{Q}_{nk}|} \sum_{t \in \mathcal{Q}_{nk}} U_t.$$

- Generalized CSM method:

$$\theta_n = \arg \max_{\varphi \in \Phi_K} \hat{\mathbb{E}}[U|\theta_n = \varphi].$$

A subtle issue

- Recall that CSM chooses φ to maximize

$$|h_0| \cdot \cos\left(\angle h_n + \varphi - \angle h_0\right) + \text{const.}$$

- If $|h_0| \to 0$, then φ does NOT impact the above function, so CSM cannot decide θ_n anymore.

- To resolve this issue, we may combine some h_n's with h_0 to form a new "direct channel" that is bounded away from zero.

W. Wang, W. Lai, S. Ren, L. Xiang, X. Li, S. Niu, and K. Shen, "Adaptive Beamforming for Non-Line-of-Sight IRS-Assisted Communications without CSI", *IEEE PIMRC*, Sept. 2023.

Multi-IRS System

Proposition 0.3

When there are L IRSs, running CSM sequentially across these IRSs yields:

$$\mathbb{E}[f(\boldsymbol{\theta}^{\mathsf{CSM}})] = \Theta(N^{2L})$$

provided that

- $T = \Omega(N^2(\log N)^3)$
- $K \geq 2L - 1$
- $|h_0|$ *is sufficiently small.*

In contrast, [Mei-Zhang, 21] shows this scaling law only when

- CSI is known
- $K \to \infty$
- only longest channel is nonzero

Multi-IRS System

- Consider 2 IRSs with their in-between channels completely blocked.
- Then the 2 IRSs can be recognized as a single merged IRS, so the improvement is at most $(2N)^2 \ll N^4$.
- When optimizing θ_n, the gain from the previous IRSs can disappear!

Fan Xu, Jiawei Yao, Wenhai Lai, Kaiming Shen, Xin Li, Xin Chen, and Zhi-Quan Luo, "Coordinating Multiple Intelligent Reflecting Surfaces without Channel Information", preprint, Feb 2023.

Parameters

- Downlink transmission at 2.6 GHz.
- Non-line-of-sight propagation from base station to user terminal.
- $N = 256$, $\Phi_K = \{0, \pi/2, \pi, 3\pi/2\}$, $T = 2560$.

- OFF: Fixed Phase Shifts.
- RMS: Random-Max Sampling.
- CSM: Conditional Sample Mean.
- ECSM: Enhanced Conditional Sample Mean

Case 1

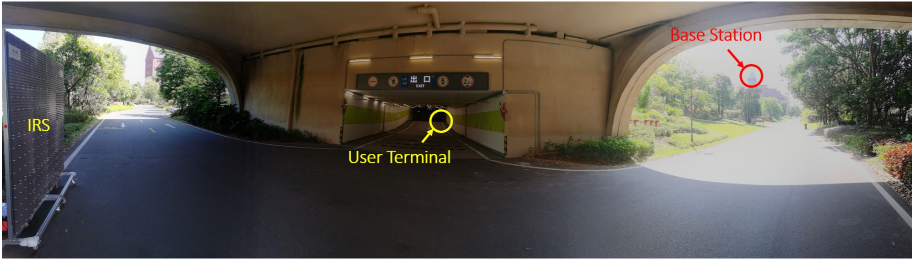
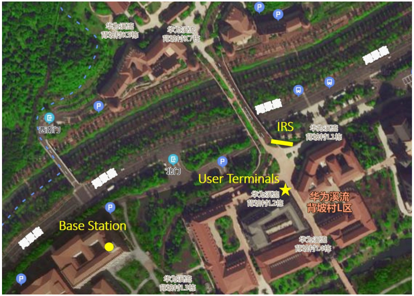


Figure: A panoramic view of the field test site. The base station is located on a 20-meter-high terrace while the user terminal is located inside an underground parking lot. The IRS is placed at the entrance of the parking lot. The IRS is approximately 250 meters away from the base station, and the user terminals are approximately 40 meters away from the IRS.

Case 1



Case 1

Table: Average Performance of the Various Algorithms

	SISO		MIMO
Algorithm	RSRP Boost (dB)	SINR Boost (dB)	SE Increment (bps/Hz)
CSM	4.02	3.57	2.02
ECSM	4.62	3.81	2.08
RMS	-3.93	-3.84	1.97
OFF	-1.69	-1.69	0.77

Case 2

Goal: Use IRS to enable high-quality live stream.

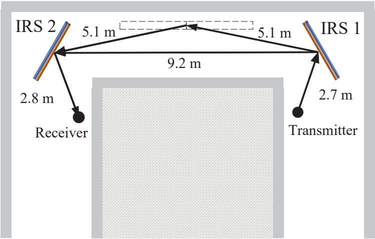
Demonstration Video

Parameters of Multi-IRS System

- Transmit power: -5 dBm;
- Carrier frequency: 2.6 GHz;
- The following three IRSs are used:
  - IRS 1: $N = 294$ and $\Phi_K = \{0, \pi\}$;
  - IRS 2: $N = 294$ and $\Phi_K = \{0, \pi\}$;
  - IRS 3: $N = 64$ and $\Phi_K = \{0, \pi/2, \pi, 3\pi/2\}$;
- The following methods are compared:

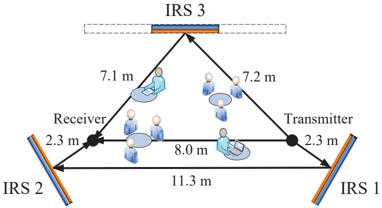
Method	The number of random samples
Without IRS	0
Zero Phase Shifts	0
Random Beamforming	$L \times 1000$
Virtual Single-IRS	$L \times 1000$
Physical Single-IRS	$L \times 1000$
SCSM	1000 per IRS

Indoor Environment



- Deploy IRS 1 and IRS 2 in a U-shaped hallway; The transmission is blocked by the walls.

Outdoor Environment



- Deploy three IRSs alongside an open café; The transmission is occasionally blocked by the crowd.

Results

	SNR Boost (dB)	
Method	Indoor	Outdoor
Zero Phase Shifts	2.74	2.91
Random Beamforming	5.33	8.48
Virtual Single-IRS	12.07	10.80
Physical Single-IRS	3.31	7.06
Blind Beamforming	17.08	14.09

- Proposed blind beamforming method outperforms others significantly.

Recap & Open Problem

- Blind beamforming by CSM does NOT require CSI.
- CSM yields provable performance.
- CSM versus Channel Estimation Based Approach.?
- At least CSM can act as a sophisticated benchmark.

References

- S. Ren, K. Shen, X. Li, X. Chen, and Z.-Q. Luo, "Configuring Intelligent Reflecting Surface with Performance Guarantees: Blind Beamforming", *IEEE Trans. Wireless Commun.*, 2023.
- S. Ren, K. Shen, X. Li, X. Chen, and Z.-Q. Luo, "A Linear Time Algorithm for the Optimal Discrete IRS Beamforming", *IEEE Wireless Commun. Lett.*, Mar. 2023.
- F. Xu, J. Yao, W. Lai, K. Shen, X. Li, X. Chen, and Z.-Q. Luo, "Coordinating Multiple Intelligent Reflecting Surfaces without Channel Information", preprint, 2023.
- W. Wang, W. Lai, S. Ren, L. Xiang, X. Li, S. Niu, and K. Shen, "Adaptive Beamforming for Non-Line-of-Sight IRS-Assisted Communications without CSI", *IEEE PIMRC*, Sep. 2023.

Find more at https://kaimingshen.github.io/publications.html

or e-mail me at

shenkaiming@cuhk.edu.cn