Transmission Design for Intelligent Reflecting Surface-Aided Communications

Dr. Cunhua Pan

Queen Mary University of London

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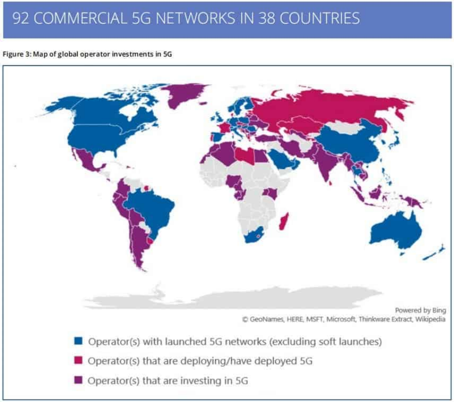
Outline

Research Background

Why need IRS?

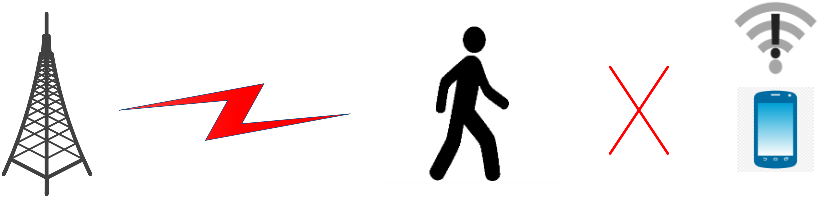
5G Worldwide Commercial Deployment



Key Physical Layer Technique: Sub-6 GHz Massive MIMO, no mmWave

Why need IRS?

Issues in mmWave Communications

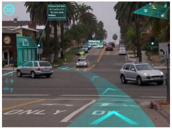


Drawbacks:

- High penetration loss
- High frequency → Small wavelength → Weak diffraction → Sensitivity to blockage → Limited coverage and unreliable communications.

Why need IRS?

Current and Future New Applications



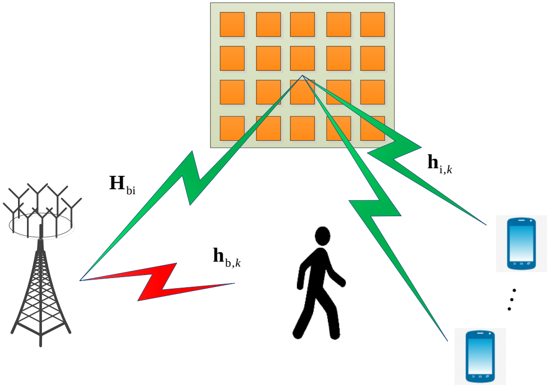
KPI: Extremely high date rate, ultra-low latency, ultra-high reliability.

Inevitable trend for mmWave or THz communication!

How to address the blockage issue?

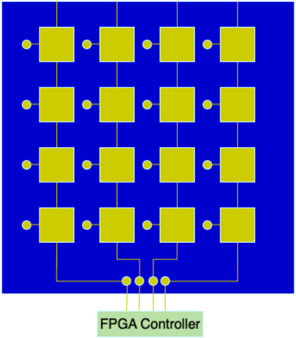
Why need IRS?

A Promising Technique: Intelligent Reflecting Surface (IRS)

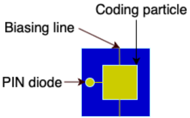


Remarks: An alternative transmission link can be constructed via the IRS.

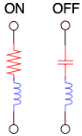
What is IRS?



(a) Schematic of a configurable meta-surface prototype



(b) Geometry of a reflecting element



(c) Equivalent circuit model of the PIN diode

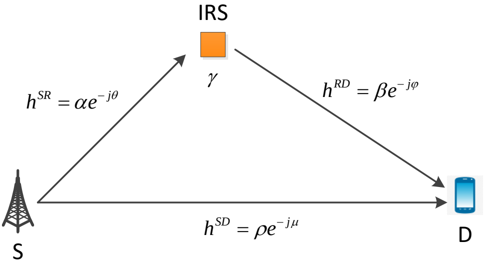
1. Each reflection element includes one or more PIN diodes
2. The reflection coefficients by varying the load impedance (changing values of resistors/capacitors)
3. Discrete reflection coefficient is controlled by the FPGA controller

Comparison with Relay

Table 1: **IRS vs. Relay**

	IRS	**AF Relay**	**DF Relay**	**Full-duplex Relay**
With RF Chains?	No	Yes	Yes	Yes
SP Capability?	No	No	Yes	Yes
Noise?	No	Yes	Yes	Yes
Duplex	Full	Half	Half	Full
Hardware cost	Low	Median	High	Very high
Power Consumption	Low	Median	High	Very high

Application of IRS in Sub-6GHz Systems



- Received signal at D is

$$y = \sqrt{p_t}\left(\rho e^{-j\mu} + \alpha\beta\gamma e^{-j(\theta+\varphi)}\right)x + w \tag{1}$$

- Signal-to-noise ratio (SNR) is

$$\eta = \frac{\left|\rho e^{-j\mu} + \alpha\beta\gamma e^{-j(\theta+\varphi)}\right|^2 p_t}{N_0} \tag{2}$$

Application of IRS in Sub-6GHz Systems

Without IRS

$$\eta_{\text{NoIRS}} = \frac{\rho^2 p_t}{N_0} \tag{3}$$

Function I: Signal Enhancement

$$\eta_{\text{SE}} = \max_{|\gamma|\leq 1} \eta = \frac{(\rho + \alpha\beta)^2 p_t}{N_0} > \eta_{\text{NoIRS}}, \text{ where } \gamma^\star = e^{j(\theta+\varphi-\mu)} \tag{4}$$

Function II: Signal Neutralization

$$\eta_{\text{NoIRS}} > \eta_{\text{SN}} = \min_{|\gamma|\leq 1} \eta = \begin{cases} 0, & \text{if } \rho \leq \alpha\beta, \\ \frac{(\rho-\alpha\beta)^2 p_t}{N_0}, & \text{if } \rho > \alpha\beta. \end{cases} \tag{5}$$

For the first one, the optimal γ is $\gamma^\star = \frac{\rho}{\alpha\beta} e^{j(\theta+\varphi-\mu+\pi)}$. For the second case, the optimal γ is $\gamma^\star = e^{j(\theta+\varphi-\mu+\pi)}$.

Transmission Design in IRS Systems

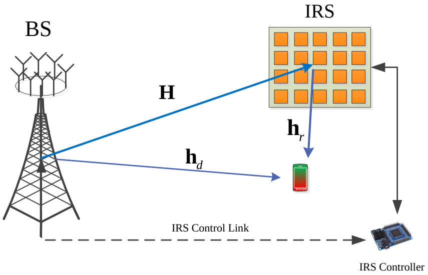


Figure 1: A multiple-antenna IRS-aided single-user communication system.

Received signal at the user is:

$$y = \left(\mathbf{h}_d^{\mathrm{H}} + \mathbf{h}_r^{\mathrm{H}} \boldsymbol{\Phi} \mathbf{H}\right) \mathbf{w} s + n \qquad (6)$$

where $\mathbf{w}$ is the beamforming vector at the BS, $\boldsymbol{\Phi}$ is the phase shift matrix at the IRS, given by

$$\boldsymbol{\Phi} = \mathrm{diag}(e_1, \cdots, e_M) \in \mathbb{C}^{M \times M},$$

where $|e_m|^2 = 1, m = 1, \cdots, M$.

Transmission data rate is

$$R\left(\mathbf{w}, \boldsymbol{\Phi}\right) = \log_2 \left(1 + \frac{\left|\left(\mathbf{h}_d^{\mathrm{H}} + \mathbf{h}_r^{\mathrm{H}} \boldsymbol{\Phi} \mathbf{H}\right) \mathbf{w}\right|^2}{\sigma^2}\right). \qquad (7)$$

Transmission Design in IRS Systems

How to jointly optimize the phase shift matrix $\mathbf{\Phi}$ and beamforming vector $\mathbf{w}$ to achieve the desired target remains a challenging problem.

Rate Maximization

$$\max_{\mathbf{w},\mathbf{\Phi}} \quad R(\mathbf{w},\mathbf{\Phi}) \tag{8a}$$

$$\text{s.t.} \ \|\mathbf{w}\|^2 \le P_{\max}, \tag{8b}$$

$$|e_m|^2 = 1, \forall m, \tag{8c}$$

where (8b) is power constraint, and (8c) is the unit-modulus constraint.

Power Minimization

$$\min_{\mathbf{w},\mathbf{\Phi}} \quad \|\mathbf{w}\|^2 \tag{9a}$$

$$\text{s.t.} \ R(\mathbf{w},\mathbf{\Phi}) \ge R_{\min}, \tag{9b}$$

$$|e_m|^2 = 1, \forall m, \tag{9c}$$

where (9b) is rate requirement, (9c) is the unit-modulus constraint.

Recent Work

Transmission Design from Three Aspects

1. Perfect Instantaneous CSI
2. Imperfect Instantaneous CSI
3. Long-term CSI

Perfect Instantaneous CSI

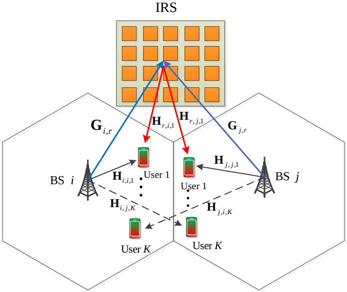
IRS-aided Multicell MIMO Networks

Challenges in Multicell Networks

- Weak signal power at the cell edge
- Cell-edge users suffer from severe inter-cell interference

IRS-aided Multicell Networks

- Inter-cell interference can be alleviated
- Useful signal strength can be enhanced



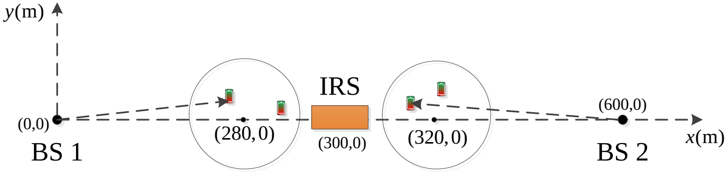
Design Objective: Maximize the weighted sum-rate (WSR) of the system under two constraints:

- Each BS's individual power constraint
- Unit-modulus constraint of the IRS phase shifts

C. Pan, H. Ren, K. Wang, W. Xu, M. Elkashlan, A. Nallanathan, and L. Hanzo, "Multicell MIMO communications relying on intelligent reflecting surface", IEEE Transactions on Wireless Communications, vol. 19, no. 8, pp. 5218-5233, Aug. 2020.

IRS-aided Multicell MIMO Networks

Two-cell Setup



Boundary Point

Main Simulation Parameters

Heights of BSs, IRSs, and users are 30 m, 10 m, and 1.5 m. Path-loss exponents of the BS-IRS link, of the IRS-user link and BS-user link are $\alpha_{\rm BI} = \alpha_{\rm IU} \triangleq \alpha_{\rm IRS} = 2.2$, and $\alpha_{\rm BU} = 3.75$. Number of phase shifts is 50.

C. Pan, H. Ren, K. Wang, W. Xu, M. Elkashlan, A. Nallanathan, and L. Hanzo, "Multicell MIMO communications relying on intelligent reflecting surface", IEEE Transactions on Wireless Communications, vol. 19, no. 8, pp. 5218-5233, Aug. 2020.

IRS-aided Multicell MIMO Networks

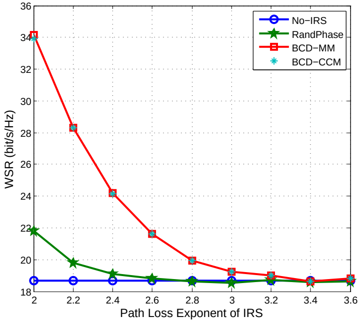


Figure 2: Achievable WSR versus IRS-related path loss exponent.

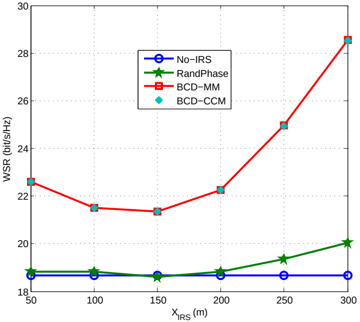
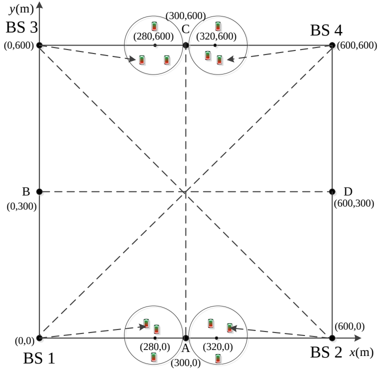


Figure 3: Achievable WSR versus the location of the IRS x_{IRS}.

C. Pan, H. Ren, K. Wang, W. Xu, M. Elkashlan, A. Nallanathan, and L. Hanzo, "Multicell MIMO communications relying on intelligent reflecting surface", IEEE Transactions on Wireless Communications, vol. 19, no. 8, pp. 5218-5233, Aug. 2020.

IRS-aided Multicell MIMO Networks

Four-cell Setup



Notes

1. Each cell has three users.
2. Each BS has two antennas.
3. Four points (i.e., A,B,C,D) are located at the middle of the corresponding two BSs.
4. The total number of phase shifts is 50

C. Pan, H. Ren, K. Wang, W. Xu, M. Elkashlan, A. Nallanathan, and L. Hanzo, "Multicell MIMO communications relying on intelligent reflecting surface", IEEE Transactions on Wireless Communications, vol. 19, no. 8, pp. 5218-5233, Aug. 2020.

IRS-aided Multicell MIMO Networks

Single-IRS scenario

1. Scheme-1: IRS moves from BS 1 to BS 2
2. Scheme-2: IRS moves from point B to point D
3. Scheme-3: IRS moves from BS 3 to BS 2

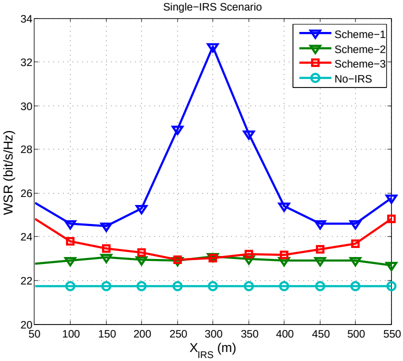


Figure 4: WSR versus various IRS deployment schemes for single-IRS case.

C. Pan, H. Ren, K. Wang, W. Xu, M. Elkashlan, A. Nallanathan, and L. Hanzo, "Multicell MIMO communications relying on intelligent reflecting surface", IEEE Transactions on Wireless Communications, vol. 19, no. 8, pp. 5218-5233, Aug. 2020.

IRS-aided Multicell MIMO Networks

Two-IRS scenario

1. Scheme-1: IRS 1 moves from BS 1 to BS 2, and IRS moves from BS 3 to BS 4
2. Scheme-2: IRS 1 moves from BS 1 to BS 4, and IRS 2 moves from BS 3 to BS 2
3. Scheme-3: IRS 1 moves from point B to point D, and IRS 2 moves from point C to point A

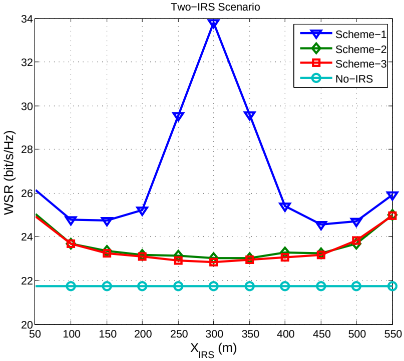


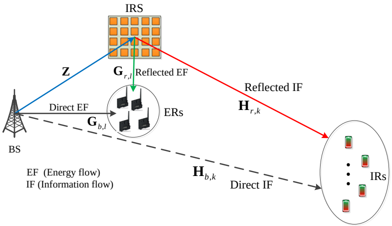
Figure 5: WSR versus various IRS deployment schemes for two-IRS case.

C. Pan, H. Ren, K. Wang, W. Xu, M. Elkashlan, A. Nallanathan, and L. Hanzo, "Multicell MIMO communications relying on intelligent reflecting surface", IEEE Transactions on Wireless Communications, vol. 19, no. 8, pp. 5218-5233, Aug. 2020.

IRS-aided MIMO Broadcasting for SWIPT

Hurdles in SWIPT: Limited energy can be harvested due to severe signal attenuation

IRS- aided SWIPT: Enhance the harvested power at the energy receivers (ERs)



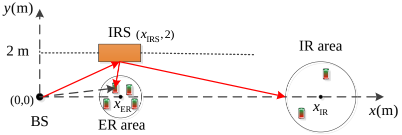
Design Objective: Maximize the WSR of the information receivers (IRs) under three constraints:

- BS's total power constraint
- Unit-modulus constraint of the IRS phase shifts
- Satisfy the energy harvesting requirement of the ERs

C. Pan, H. Ren, K. Wang, M. Elkashlan, J. Wang, and A. Nallanathan, L. Hanzo, "Intelligent Reflecting Surface Aided MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer", IEEE Journal on Selected Areas in Communications, vol. 38, no. 8, pp. 1719-1734, Aug. 2020.

IRS-aided MIMO Broadcasting for SWIPT

Simulation Setup



1. More energy can be harvested with the aid of IRS
2. The amount of harvested energy increases rapidly with M
3. Operational range of the ERs is extended with the aid of IRS

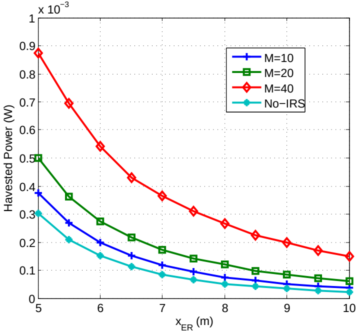
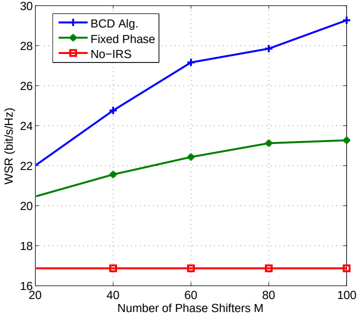
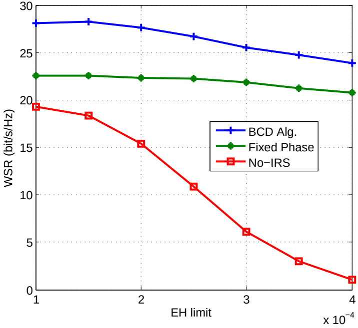


Figure 6: Maximum harvested power achieved by various schemes.

C. Pan, H. Ren, K. Wang, M. Elkashlan, J. Wang, and A. Nallanathan, L. Hanzo, "Intelligent Reflecting Surface Aided MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer", IEEE Journal on Selected Areas in Communications, vol. 38, no. 8, pp. 1719-1734, Aug. 2020.

IRS-aided MIMO Broadcasting for SWIPT





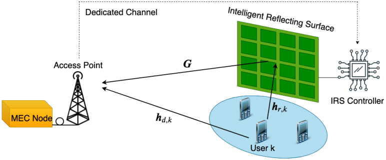
1. Significant WSR gain can be achieved by using IRS over No-IRS
2. Performance gain increases with the number of phase shifts
3. Performance gain increases with harvested power requirement

C. Pan, H. Ren, K. Wang, M. Elkashlan, J. Wang, and A. Nallanathan, L. Hanzo, "Intelligent Reflecting Surface Aided MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer", IEEE Journal on Selected Areas in Communications, vol. 38, no. 8, pp. 1719-1734, Aug. 2020.

IRS-aided MEC Communications

Challenges in MEC Communications

1. Communication link for offloading may experience severe path loss
2. High offloading delay can be incurred due to weak channel gains



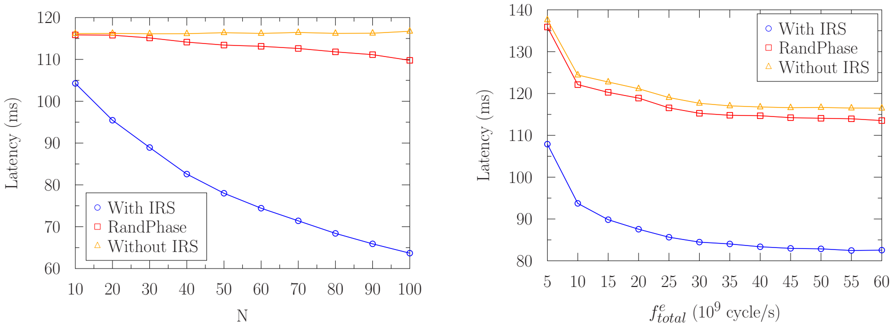
IRS- aided MEC communication: Direct channel links can be combined constructively with those from the reflected signals from the IRS to enhance the propagation link strength

Design Objective: Minimize the total latency through jointly optimizing the computation offloading volume, edge computing resources, decoding vectors and phase shift matrix subject to:

- Total computing resource at the MEC node
- Unit-modulus constraint of the IRS phase shifts

T. Bai, **C. Pan (Corres. Author)**, Y. Deng, M. Elkashlan, A. Nallanathan and L. Hanzo, "Latency Minimization for Intelligent Reflecting Surface Aided Mobile Edge Computing," early access in IEEE Journal on Selected Areas in Communications.

IRS-aided MEC Communications



IRS is beneficial in reducing the latency, and performance gain increases with the number of phase shifts and total amount of computing resource

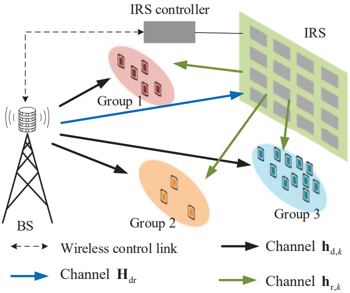
T. Bai, **C. Pan (Corres. Author)**, Y. Deng, M. Elkashlan, A. Nallanathan and L. Hanzo, "Latency Minimization for Intelligent Reflecting Surface Aided Mobile Edge Computing," early access in IEEE Journal on Selected Areas in Communications.

IRS-aided Multigroup Multicast Communications

Challenges in Multicast Comm.

1. Date rate in each group is limited by the user with the worst channel condition
2. Some users may be blocked or experience severe path loss

IRS-aided Multicast Comm.: Channel conditions for the worst-case user can be improved with the aid of IRS

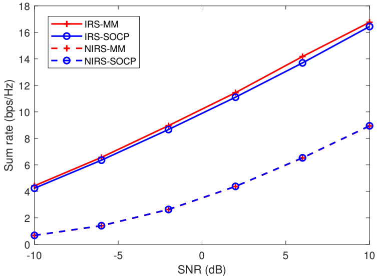


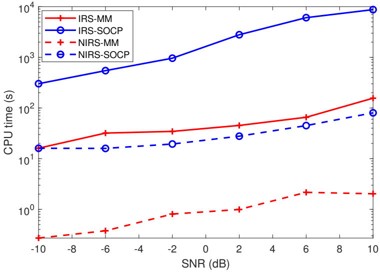
Design Objective: Maximize the system capacity through jointly optimizing the active beamforming vectors and phase shift matrix subject to:

- Total power constraint at the BS
- Unit-modulus constraint of the IRS phase shifts

G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang and A. Nallanathan, "Intelligent Reflecting Surface Aided Multigroup Multicast MISO Communication Systems," IEEE Transactions on Signal Processing, vol. 68, pp. 3236-3251, 2020.

IRS-aided Multigroup Multicast Communications





1. IRS can be beneficial in boosting the system sum rate
2. IRS-MM has slightly higher rate than IRS-SOCP method

1. More computation time is required when deploying an IRS
2. IRS-MM requires much less computation time than IRS-SOCP

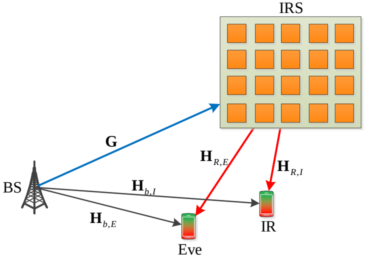
G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang and A. Nallanathan, "Intelligent Reflecting Surface Aided Multigroup Multicast MISO Communication Systems," IEEE Transactions on Signal Processing, vol. 68, pp. 3236-3251, 2020.

IRS-aided MIMO Secure Communications

Challenges in Secure Comm.

1. Eavesdroppers are more close to the BS than the desired users or align with the desired users
2. Secrecy rate can approach zero in conventional secure system

IRS-aided Secure Comm.: Directed signal at the eavesdropper can be added destructively with the reflected signals



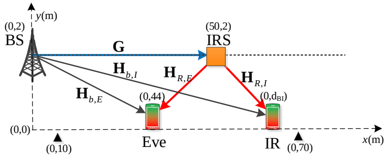
Design Objective: Maximize the secrecy rate through jointly optimizing the precoding matrix, artificial noise matrix, and phase shift matrix subject to:

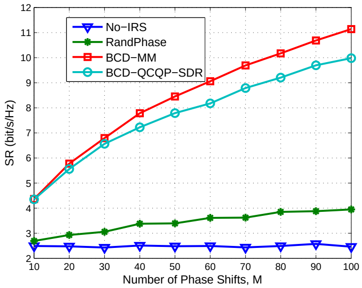
- Total power constraint at the BS
- Unit-modulus constraint of the IRS phase shifts

S. Hong, **C. Pan (Corres. Author)**, H. Ren, K. Wang, and A. Nallanathan, "Artificial-Noise-Aided Secure MIMO Wireless Communications via Intelligent Reflecting Surface", early access in IEEE Transactions on Communications.

IRS-aided MIMO Secure Communications

Simulation Setup





Key Parameters

The path loss exponents: $\alpha_{\mathrm{BE}} = 3.5$, $\alpha_{\mathrm{BI}} = 3.5$, $\alpha_{\mathrm{RE}} = 2.5$ and $\alpha_{\mathrm{RI}} = 2.5$.

Our proposed algorithm outperforms the well-known SDR method, and performance gain increases with the number of phase shifts.

S. Hong, **C. Pan (Corres. Author)**, H. Ren, K. Wang, and A. Nallanathan, "Artificial-Noise-Aided Secure MIMO Wireless Communications via Intelligent Reflecting Surface", early access in IEEE Transactions on Communications.

Other Works

1. **IRS-aided Full-Duplex Two-way Communication Systems:**
   Z. Peng, Z. Zhang, **C. Pan (Corres. Author)**, "Multiuser Full-Duplex Two-Way Communications via Intelligent Reflecting Surface", major revision in IEEE Transactions on Signal Processing, https://arxiv.org/abs/2006.05147
2. **IRS-aided Wireless Powered MEC Networks:**
   T. Bai, **C. Pan (Corres. Author)**, H. Ren, Y. Deng, M. Elkashlan, and A. Nallanathan, "Resource Allocation for Intelligent Reflecting Surface Aided Wireless Powered Mobile Edge Computing in OFDM Systems", major revision in IEEE Transactions on Wireless Communications, https://arxiv.org/abs/2003.05511
3. **IRS-aided Cognitive Radio Networks:**
   L. Zhang, Y. Wang, W. Tao, Z. Jia, T. Song and **C. Pan**, "Intelligent Reflecting Surface Aided MIMO Cognitive Radio Systems," early access in IEEE Transactions on Vehicular Technology.

Imperfect Instantaneous CSI

Two Channel Estimation Methods - Method I

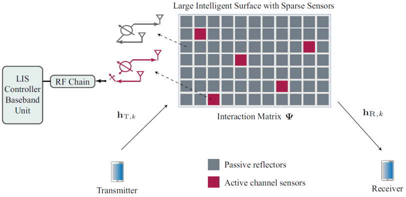


Figure 7: Active Sensor-aided CE

Drawbacks:

1. Require additional baseband units, incurs more hardware cost
2. Consume more energy consumption
3. Additional feedback overhead for the IRS
4. High pilot training overhead
5. Increased size and weight

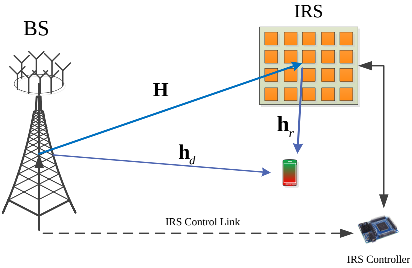
Main idea:

1. Insert active channel sensors
2. Estimate BS-IRS channel and IRS-UE channel individually
3. Feedback the estimated channels to the BS

Taha, Abdelrahman, Muhammad Alrabeiah, and Ahmed Alkhateeb. "Enabling large intelligent surfaces with compressive sensing and deep learning." arXiv preprint arXiv:1904.10136 (2019).

Any Better Method?

Observation - Recall Previous Example



Received signal at the user is:

$$y = \left(\mathbf{h}_d^{\mathrm{H}} + \mathbf{h}_r^{\mathrm{H}} \mathbf{\Phi} \mathbf{H}\right) \mathbf{w} s + n, \quad (10)$$

where $\mathbf{w}$ is the beamforming vector at the BS, $\mathbf{\Phi}$ is the phase shift matrix at the IRS, given by

$$\mathbf{\Phi} = \mathrm{diag}(e_1, \cdots, e_M) \in \mathbb{C}^{M \times M}.$$

Denote by $\mathbf{G} = \mathrm{diag}(\mathbf{h}_r^{\mathrm{H}})\mathbf{H}$ and $\mathbf{e} = [e_1, \cdots, e_M]^{\mathrm{T}} \in \mathbb{C}^{M \times 1}$, (10) can be rewritten as

$$y = \left(\mathbf{h}_d^{\mathrm{H}} + \mathbf{e}^{\mathrm{H}} \mathbf{G}\right) \mathbf{w} s + n. \quad (11)$$

Hence, $\mathbf{G}$, named as the cascaded channels, is sufficient for transmission design.

Two Channel Estimation Methods - Method II

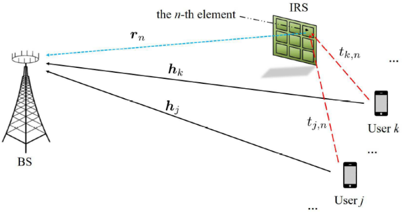


Figure 8: Passive Cascaded CE

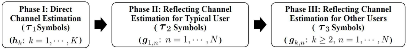


Figure 9: Three-phase CE Graph

Main idea:

1. Exploit the fact that all the users share the common BS-IRS channels
2. Others' cascaded CSI can be obtained by using typical user's CSI

Advantages:

1. Fully passive, reduced hardware cost and power consumption
2. Reduced channel training overhead and feedback overhead

Z. Wang, L. Liu and S. Cui, "Channel Estimation for Intelligent Reflecting Surface Assisted Multiuser Communications: Framework, Algorithms, and Analysis," early access in IEEE Transactions on Wireless Communications.

Robust Design based on CE Method I

Robust Design based on CE Method I

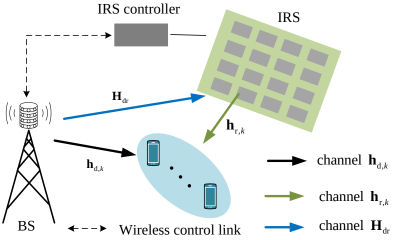


Figure 10: IRS-aided multiuser system

Denote

- Data symbol vector: $\mathbf{s} = [s_1, \cdots, s_K]^{\mathrm{T}} \in \mathbb{C}^{K\times 1}$
- Beamforming vectors: $\mathbf{F} = [\mathbf{f}_1, \cdots, \mathbf{f}_K] \in \mathbb{C}^{N\times K}$
- Phase shift matrix: $\mathbf{\Phi}$

Received signal at user k is:

$$y_k = (\mathbf{h}_{\mathrm{d},k}^{\mathrm{H}} + \mathbf{h}_{\mathrm{r},k}^{\mathrm{H}}\mathbf{\Phi}\mathbf{H}_{\mathrm{dr}})\mathbf{F}\mathbf{s} + n_k. \quad (12)$$

Data rate for user k is

$$R_k(\mathbf{F}, \mathbf{\Phi}) = \log_2\left(1 + \left|\left(\mathbf{h}_{\mathrm{d},k}^{\mathrm{H}} + \mathbf{h}_{\mathrm{r},k}^{\mathrm{H}}\mathbf{\Phi}\mathbf{H}_{\mathrm{dr}}\right)\mathbf{f}_k\right|^2 / \beta_k\right) \quad (13)$$

where $\beta_k = ||(\mathbf{h}_{\mathrm{d},k}^{\mathrm{H}} + \mathbf{h}_{\mathrm{r},k}^{\mathrm{H}}\mathbf{\Phi}\mathbf{H}_{\mathrm{dr}})\mathbf{F}_{-k}||_2^2 + \sigma_k^2$ is the interference plus noise.

G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang, M. Di Renzo and A. Nallanathan, "Robust Beamforming Design for Intelligent Reflecting Surface Aided MISO Communication Systems," early access in IEEE Wireless Communications Letters.

Robust Design based on CE Method I

Channel Error Model

The IRS-user channel $\{\mathbf{h}_{\mathrm{r},k}\}_{\forall k\in\mathcal{K}}$ can be modeled as

$$\{\mathbf{h}_{\mathrm{r},k} = \widehat{\mathbf{h}}_{\mathrm{r},k} + \triangle_k\}_{\forall k\in\mathcal{K}}. \tag{14}$$

Bounded channel error model is adopted: $\{||\triangle_k||_2 \le \varepsilon_k\}_{\forall k\in\mathcal{K}}$, where ε_k is the radius of the uncertainty region.

Problem Formulation

$$\min_{\mathbf{F},\mathbf{\Phi}} \ ||\mathbf{F}||_F^2 \tag{15a}$$

$$\text{s.t.} \ R_k(\mathbf{F},\mathbf{\Phi}) \ge r_k, \forall \|\triangle_k\|_2 \le \varepsilon_k, \forall k \in \mathcal{K}, \tag{15b}$$

$$\left|\mathbf{\Phi}_{[m,m]}\right| = 1, 1 \le m \le M. \tag{15c}$$

G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang, M. Di Renzo and A. Nallanathan, "Robust Beamforming Design for Intelligent Reflecting Surface Aided MISO Communication Systems," early access in IEEE Wireless Communications Letters.

Robust Design based on CE Method I

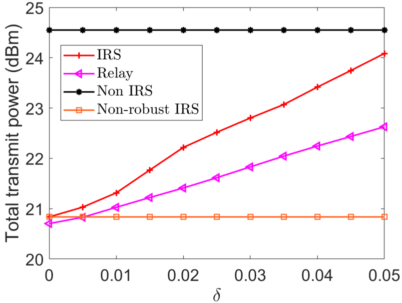


Figure 11: Power vs channel error

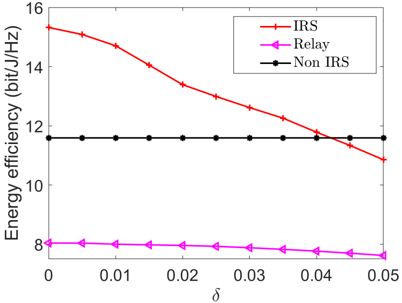


Figure 12: EE vs channel error

- Relay outperforms IRS in terms of minimum transmit power
- IRS outperforms Relay in terms of EE

G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang, M. Di Renzo and A. Nallanathan, "Robust Beamforming Design for Intelligent Reflecting Surface Aided MISO Communication Systems," early access in IEEE Wireless Communications Letters.

Robust Design based on CE Method I

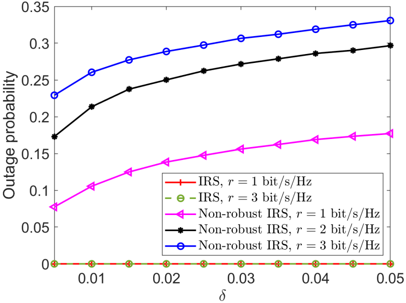


Figure 13: Outage probability of rate versus the channel uncertainty level δ

Observations:

- Our robust design can always guarantee the QoS requirements
- The naive non-robust cannot guarantee the QoS targets, and violation probability increases with δ
- The effectiveness of our proposed robust algorithm

G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang, M. Di Renzo and A. Nallanathan, "Robust Beamforming Design for Intelligent Reflecting Surface Aided MISO Communication Systems," early access in IEEE Wireless Communications Letters.

Robust Design based on CE Method II

Robust Design based on CE Method II

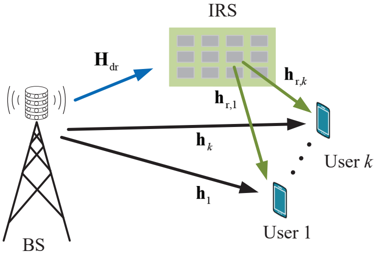


Figure 14: IRS-aided multiuser system

Received signal at user k is:

$$y_k = (\mathbf{h}_k^{\mathrm{H}} + \mathbf{h}_{\mathrm{r},k}^{\mathrm{H}} \mathbf{\Phi} \mathbf{H}_{\mathrm{dr}}) \mathbf{F}\mathbf{s} + n_k, \quad (16)$$

where $\mathbf{\Phi} = \mathrm{diag}(e_1, \cdots, e_M) \in \mathbb{C}^{M \times M}$ with $|e_m|^2 = 1, \forall m$.

Denote cascaded channel $\mathbf{G}_k = \mathrm{diag}(\mathbf{h}_{\mathrm{r},k}^{\mathrm{H}}) \mathbf{H}_{\mathrm{dr}} \in \mathbb{C}^{M \times N}$ and $\mathbf{e} = [e_1, \cdots, e_M]^{\mathrm{T}} \in \mathbb{C}^{M \times 1}$. (16) can be rewritten as

$$y_k = (\mathbf{h}_k^{\mathrm{H}} + \mathbf{e}^{\mathrm{H}} \mathbf{G}_k) \mathbf{F}\mathbf{s} + n_k. \quad (17)$$

Data rate for user k is

$$R_k(\mathbf{F}, \mathbf{e}) = \log_2 \left(1 + \left| \left(\mathbf{h}_k^{\mathrm{H}} + \mathbf{e}^{\mathrm{H}} \mathbf{G}_k\right) \mathbf{f}_k \right|^2 / \beta_k \right) \quad (18)$$

where $\beta_k = ||(\mathbf{h}_k^{\mathrm{H}} + \mathbf{e}^{\mathrm{H}} \mathbf{G}_k) \mathbf{F}_{-k}||_2^2 + \sigma_k^2$ is the interference plus noise power.

G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang and A. Nallanathan, "A Framework of Robust Transmission Design for IRS-Aided MISO Communications With Imperfect Cascaded Channels," IEEE Transactions on Signal Processing, vol. 68, pp. 5092-5106, 2020.

Robust Design based on CE Method II

The cascaded channel model can be written as

$$\mathbf{G}_k = \widehat{\mathbf{G}}_k + \triangle\mathbf{G}_k, \forall k \in \mathcal{K}. \tag{19}$$

where $\widehat{\mathbf{G}}_k$ is the estimated cascaded channel and $\triangle\mathbf{G}_k$ is the corresponding channel error matrix.

Bounded CSI error model (BCEM):

$$\mathcal{E}_k \triangleq \{\triangle\mathbf{G}_k | \, \|\triangle\mathbf{G}_k\|_F \leq \xi_{\mathrm{g},k}\}$$

Problem Formulation:

$$\min_{\mathbf{F},\mathbf{e}} \ ||\mathbf{F}||_F^2 \tag{20a}$$
$$\text{s.t. } \mathcal{R}_k(\mathbf{F},\mathbf{e}) \geq R_k, \forall \triangle\mathbf{G}_k \in \mathcal{E}_k,$$
$$|e_m|^2 = 1, 1 \leq m \leq M.$$

Statistical CSI error model (SCEM):

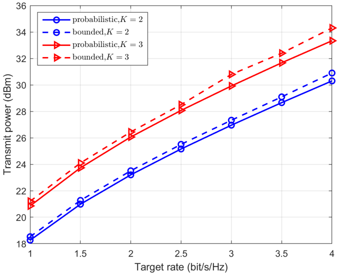
$$\mathrm{vec}(\triangle\mathbf{G}_k) \sim \mathcal{CN}(\mathbf{0}, \mathbf{\Sigma}_{\mathrm{g},k}), \mathbf{\Sigma}_{\mathrm{g},k} \succeq \mathbf{0}, \forall k$$

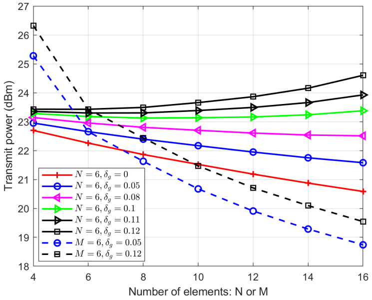
Problem Formulation:

$$\min_{\mathbf{F},\mathbf{e}} \ ||\mathbf{F}||_F^2 \tag{21a}$$
$$\text{s.t. } \Pr\{\mathcal{R}_k(\mathbf{F},\mathbf{e}) \leq R_k\} \leq \rho_k,$$
$$|e_m|^2 = 1, 1 \leq m \leq M.$$

G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang and A. Nallanathan, "A Framework of Robust Transmission Design for IRS-Aided MISO Communications With Imperfect Cascaded Channels," IEEE Transactions on Signal Processing, vol. 68, pp. 5092-5106, 2020.

Robust Design based on CE Method II





- Worst-case robust design performs worse than the statistical one
- When channel uncertainty is small, the required power decreases with M
- When channel uncertainty is large, the required power increases with M

G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang and A. Nallanathan, "A Framework of Robust Transmission Design for IRS-Aided MISO Communications With Imperfect Cascaded Channels," IEEE Transactions on Signal Processing, vol. 68, pp. 5092-5106, 2020.

Recent Works on Robust Design based on Imperfect Cascaded CSI

1. **Robust Design in Secure Communications:**
   S. Hong, **C. Pan (Corres. Author)**, H. Ren, K. Wang, K. Chai, A. Nallanathan, "Robust Transmission Design for Intelligent Reflecting Surface Aided Secure Communication Systems with Imperfect Cascaded CSI", major revision in IEEE Transactions on Wireless Communications, https://arxiv.org/abs/2004.11580
2. **Robust Design in Cognitive Radio Communications:**
   L. Zhang, **C. Pan (Corres. Author)**, Y. Wang, H. Ren, K. Wang, A. Nallanathan, "Robust Beamforming Design for Intelligent Reflecting Surface Aided Cognitive Radio Systems with Imperfect Cascaded CSI", submit to IEEE Transactions on Communications, https://arxiv.org/abs/2004.04595
3. **Robust Design in SWIPT-aided Secure Communications:**
   G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang, A. Nallanathan, K. Wong, "User Cooperation for IRS-aided Secure SWIPT MIMO: Active Attacks and Passive Eavesdropping," to be submitted, https://arxiv.org/abs/2006.05347

Long-term CSI

Motivations

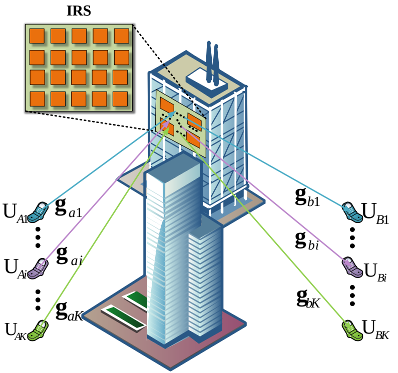
Drawbacks of using Instantaneous CSI:

1. High training overhead
2. High computational complexity
3. High feedback overhead

Benefits of using Long-term CSI:

1. Low training overhead
2. Low feedback overhead
3. Low computational complexity

Transmission Design for Multi-pair Communications



Channel between U_{Ai} and the RIS is

$$\mathbf{g}_{ai} = \sqrt{\alpha_{ai}} \left(\sqrt{\frac{\varepsilon_i}{\varepsilon_i + 1}} \overline{\mathbf{h}}_{ai} + \sqrt{\frac{1}{\varepsilon_i + 1}} \tilde{\mathbf{h}}_{ai} \right)$$

- α_{ai}: large-scale fading coefficient
- ε_i: Rician factor
- $\tilde{\mathbf{h}}_{bi}$: fast fading NLoS channel vector
- $\overline{\mathbf{h}}_{ai}$: LoS channel vector given by
  $\overline{\mathbf{h}}_{ai} = [1, e^{j2\pi \frac{d}{\lambda} \sin\varsigma_i}, \ldots, e^{j2\pi \frac{d}{\lambda}(L-1)\sin\varsigma_i}]^T$

The signal received at U_{Bi} is given by

$$y_i = \sqrt{p_i} \mathbf{g}_{bi}^T \mathbf{\Theta} \mathbf{g}_{ai} x_i + \sum_{j=1, j\neq i}^{K} \sqrt{p_j} \mathbf{g}_{bi}^T \mathbf{\Theta} \mathbf{g}_{aj} x_j + n_i,$$

where $\mathbf{\Theta} = diag(e^{j\theta_1}, \ldots, e^{j\theta_\ell}, \ldots, e^{j\theta_L})$ is the phase shift matrix.

Z. Peng, T. Li, **C. Pan (Corres. Author)**, H. Ren, W. Xu and M. Renzo, "Analysis and Optimization for IRS-Aided Multi-pair Communications Relying on Statistical CSI," submitted to IEEE Transactions on Vehicular Technology, https://arxiv.org/abs/2007.11704

Transmission Design for Multi-pair Communications

SINR at user U_{Bi} is given by

$$\gamma_i = \frac{p_i \alpha_{bi} \alpha_{ai} \left| \mathbf{h}_{bi}^T \boldsymbol{\Theta} \mathbf{h}_{ai} \right|^2}{\sum_{j=1, j\neq i}^{K} \left(p_j \alpha_{bi} \alpha_{aj} \left| \mathbf{h}_{bi}^T \boldsymbol{\Theta} \mathbf{h}_{aj} \right|^2 \right) + \sigma_i^2}. \tag{22}$$

Ergodic achievable rate for U_{Bi} can be expressed as $R_i = \mathbb{E}\{\log_2(1+\gamma_i)\}$.
Problem formulation:

$$\begin{aligned} \max_{\boldsymbol{\Theta}} \quad & \sum_{i=1}^{K} R_i \\ \text{s.t.} \quad & \theta_\ell \in [0, 2\pi) \ \forall \ell, \\ & \text{or } \hat{\theta}_\ell \in \{0, 2\pi/2^B, \ldots, 2\pi(2^B-1)/2^B\}, \forall \ell. \end{aligned} \tag{23a}$$

Z. Peng, T. Li, **C. Pan (Corres. Author)**, H. Ren, W. Xu and M. Renzo, "Analysis and Optimization for IRS-Aided Multi-pair Communications Relying on Statistical CSI," submitted to IEEE Transactions on Vehicular Technology, https://arxiv.org/abs/2007.11704

Transmission Design for Multi-pair Communications

In an RIS-aided multi-pair communication system, the average achievable rate of U_{Bi} can be approximated as

$$R_i \approx \tilde{R}_i \triangleq \log_2\left(1+\frac{p_i\alpha_{bi}\alpha_{ai}\frac{\varepsilon_i\beta_i\Omega_{i,i}+L(\varepsilon_i+\beta_i)+L}{(\varepsilon_i+1)(\beta_i+1)}}{\sum\limits_{j=1,j\neq i}^{K}\left(p_j\alpha_{bi}\alpha_{aj}\frac{\varepsilon_i\beta_j\Omega_{i,j}+L(\varepsilon_i+\beta_j)+L}{(\varepsilon_i+1)(\beta_j+1)}\right)+\sigma_i^2}\right)$$

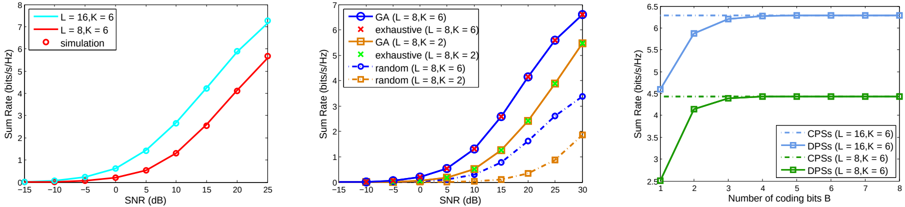
where $\Omega_{i,i}$ and $\Omega_{i,j}$ are, respectively, defined as

$$\Omega_{i,i} = L + 2\sum_{1\leq m<n\leq L}\cos[\theta_n-\theta_m+(n-m)\pi(\sin\varphi_i+\sin\varsigma_i)],$$

$$\Omega_{i,j} = L + 2\sum_{1\leq m<n\leq L}\cos[\theta_n-\theta_m+(n-m)\pi(\sin\varphi_i+\sin\varsigma_j)].$$

Z. Peng, T. Li, **C. Pan (Corres. Author)**, H. Ren, W. Xu and M. Renzo, "Analysis and Optimization for IRS-Aided Multi-pair Communications Relying on Statistical CSI," submitted to IEEE Transactions on Vehicular Technology, https://arxiv.org/abs/2007.11704

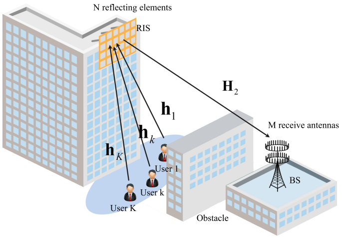
Transmission Design for Multi-pair Communications



- Derived results match well with simulation results
- Proposed GA algorithm has almost the same performance as the exhaustive search method
- Three bits for quantizing the phase shifts are enough

Z. Peng, T. Li, **C. Pan (Corres. Author)**, H. Ren, W. Xu and M. Renzo, "Analysis and Optimization for IRS-Aided Multi-pair Communications Relying on Statistical CSI," submitted to IEEE Transactions on Vehicular Technology, https://arxiv.org/abs/2007.11704

Transmission Design for RIS-aided Massive MIMO Systems



Channel between user k and the RIS is

$$\mathbf{h}_k = \sqrt{\alpha_k}\left(\sqrt{\frac{\varepsilon_k}{\varepsilon_k+1}}\bar{\mathbf{h}}_k + \sqrt{\frac{1}{\varepsilon_k+1}}\tilde{\mathbf{h}}_k\right)$$

Channel between the RIS and the BS is

$$\mathbf{H}_2 = \sqrt{\beta}\left(\sqrt{\frac{\delta}{\delta+1}}\bar{\mathbf{H}}_2 + \sqrt{\frac{1}{\delta+1}}\tilde{\mathbf{H}}_2\right)$$

- α_k and β: large-scale fading coefficients
- ε_k and δ: Rician factors
- $\tilde{\mathbf{h}}_k$ and $\tilde{\mathbf{H}}_2$: fast fading NLoS channel vectors/matrix
- $\bar{\mathbf{h}}_k$ and $\bar{\mathbf{H}}_2$: LoS channel vectors given by

$$\bar{\mathbf{h}}_k = \mathbf{a}_N\left(\varphi_{kr}^a, \varphi_{kr}^e\right),$$
$$\bar{\mathbf{H}}_2 = \mathbf{a}_M\left(\phi_r^a, \phi_r^e\right)\mathbf{a}_N^H\left(\varphi_t^a, \varphi_t^e\right),$$

K. Zhi, **C. Pan (Corres. Author)**, H. Ren, K. Wang, "Power Scaling Law Analysis and Phase Shift Optimization of RIS-aided Massive MIMO Systems with Statistical CSI," https://arxiv.org/abs/2010.13525

Transmission Design for RIS-aided Massive MIMO Systems

Using MRC technique, the uplink achievable rate of user k can be expressed as

$$R_k = \mathbb{E}\left\{\log_2\left(1+\frac{p_k\left\|\mathbf{g}_k\right\|^4}{\sum_{i=1,i\neq k}^{K} p_i\left|\mathbf{g}_k^H\mathbf{g}_i\right|^2+\sigma^2\left\|\mathbf{g}_k\right\|^2}\right)\right\}, \tag{24}$$

where $\mathbf{g}_k = \mathbf{H}_2\mathbf{\Phi}\mathbf{h}_k$.

Rate Maximization

$$\max_{\mathbf{\Phi}} \quad \sum_{k=1}^{K} R_k$$

$$\text{s.t. } \theta_n \in [0, 2\pi), \forall n, \text{or}$$

$$\theta_n \in \left\{0, \frac{2\pi}{2^b}, \ldots, \left(2^b-1\right)\frac{2\pi}{2^b}\right\}, \forall n,$$

Max-min Problem

$$\max_{\mathbf{\Phi}} \quad \min_{k} \quad R_k \tag{26a}$$

$$\text{s.t. } \theta_n \in [0, 2\pi), \forall n, \text{or}$$

$$\theta_n \in \left\{0, \frac{2\pi}{2^b}, \ldots, \left(2^b-1\right)\frac{2\pi}{2^b}\right\}, \forall n, .$$

K. Zhi, **C. Pan (Corres. Author)**, H. Ren, K. Wang, "Power Scaling Law Analysis and Phase Shift Optimization of RIS-aided Massive MIMO Systems with Statistical CSI," https://arxiv.org/abs/2010.13525

Transmission Design for RIS-aided Massive MIMO Systems

Theorem 1 In the RIS-aided massive MIMO systems, the uplink achievable rate of user k can be approximated as

$$R_k \approx \log_2\left(1 + \frac{p_k E_k^{(signal)}(\mathbf{\Phi})}{\sum_{i=1, i\neq k}^{K} p_i I_{ki}(\mathbf{\Phi}) + \sigma^2 E_k^{(noise)}(\mathbf{\Phi})}\right), \tag{27}$$

where $E_k^{(signal)}(\mathbf{\Phi}) \triangleq \mathbb{E}\left\{\|\mathbf{g}_k\|^4\right\}$, $I_{ki}(\mathbf{\Phi}) \triangleq \mathbb{E}\left\{\left|\mathbf{g}_k^H \mathbf{g}_i\right|^2\right\}$, and $E_k^{(noise)}(\mathbf{\Phi}) \triangleq \mathbb{E}\left\{\|\mathbf{g}_k\|^2\right\}$.

K. Zhi, **C. Pan (Corres. Author)**, H. Ren, K. Wang, "Power Scaling Law Analysis and Phase Shift Optimization of RIS-aided Massive MIMO Systems with Statistical CSI," https://arxiv.org/abs/2010.13525

Transmission Design for RIS-aided Massive MIMO Systems

Theorem 2 Assume that the transmit power of each user is scaled with the number of antennas at the BS according to $p_k = \frac{E_u}{M}$, $\forall k$, where E_u is fixed. When $M \to \infty$, we have

$$R_k \xrightarrow{a.s.} \log_2\left(1+\frac{E_u \frac{\beta\alpha_k}{(\delta+1)(\varepsilon_k+1)}\left(\left(\delta\varepsilon_k\left|f_k(\mathbf{\Phi})\right|^2+\tilde{N}\right)\right)^2}{E_u\sum\limits_{i=1,i\neq k}^{K}\frac{\beta\alpha_i\varepsilon_k\varepsilon_i}{(\delta+1)(\varepsilon_i+1)}\left|\delta f_k^H(\mathbf{\Phi})f_i(\mathbf{\Phi})+\overline{\mathbf{h}}_k^H\overline{\mathbf{h}}_i\right|^2+\sigma^2\left(\delta\varepsilon_k\left|f_k(\mathbf{\Phi})\right|^2+\tilde{N}\right)}\right).$$

where $\tilde{N} = (\delta + \varepsilon_k + 1)\, N$.

K. Zhi, **C. Pan (Corres. Author)**, H. Ren, K. Wang, "Power Scaling Law Analysis and Phase Shift Optimization of RIS-aided Massive MIMO Systems with Statistical CSI," https://arxiv.org/abs/2010.13525

Transmission Design for RIS-aided Massive MIMO Systems

Corollary 1: If the phase shifts of RIS are aligned to user k, the transmit power of user k is scaled down by $p_k = \frac{E_u}{MN^2}$ and the transmit power of other users are scaled down by $p_i = \frac{E_u}{MN}, \forall i \neq k$. When both M and N are large, we have

$$R_k \to \log_2 \left(1 + \frac{E_u \frac{\varepsilon_k}{(\varepsilon_k+1)}}{E_u \sum_{i=1, i\neq k}^{K} \frac{\alpha_i}{(\varepsilon_i+1)\alpha_k} + \left(1 + \frac{1}{\delta}\right) \frac{\sigma^2}{\beta\alpha_k}} \right), \quad (28)$$

$$R_i \to 0, \forall i \neq k, \quad (29)$$

Corollary 2: If the phase shift matrix $\mathbf{\Phi}$ is randomly adjusted in each time block, when $N \to \infty$ and $M \to \infty$, we have

$$R_k \to \log_2 \left(1 + \frac{p_k \alpha_k \left(2\delta^2 + 2\delta + 1\right)}{\sum_{i=1, i\neq k}^{K} p_i \alpha_i \delta^2} \right). \quad (30)$$

K. Zhi, **C. Pan (Corres. Author)**, H. Ren, K. Wang, "Power Scaling Law Analysis and Phase Shift Optimization of RIS-aided Massive MIMO Systems with Statistical CSI," https://arxiv.org/abs/2010.13525

Transmission Design for RIS-aided Massive MIMO Systems

Corollary 3: When $\delta = \varepsilon_k \to \infty, \forall k$, i.e., only LoS paths exist, we have

$$R_k \to \log_2 \left(1 + \frac{p_k \beta \alpha_k M \left| f_k(\mathbf{\Phi}) \right|^2}{\sum_{i=1, i \neq k}^{K} p_i \beta \alpha_i M \left| f_i(\mathbf{\Phi}) \right|^2 + \sigma^2} \right). \tag{31}$$

Corollary 4: If $\delta = \varepsilon_k = 0, \forall k$, i.e., only NLoS paths exist in the environment, we have

$$R_k \to \log_2 \left(1 + \frac{p_k \beta \alpha_k (MN + N + 2)}{\sum_{i=1, i \neq k}^{K} p_i \beta \alpha_i (M + N) + \sigma^2} \right). \tag{32}$$

Corollary 5: In the RIS-aided massive MIMO systems, if the RIS has discrete phase shifts with b bits resolution, the sum achievable rate can still achieve a gain of $\mathcal{O}\left(\log_2(N)\right)$.

K. Zhi, **C. Pan (Corres. Author)**, H. Ren, K. Wang, "Power Scaling Law Analysis and Phase Shift Optimization of RIS-aided Massive MIMO Systems with Statistical CSI," https://arxiv.org/abs/2010.13525

Transmission Design for RIS-aided Massive MIMO Systems

GA method to solve the phase shift optimization problem

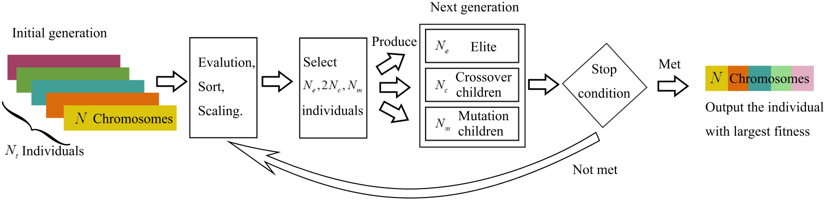
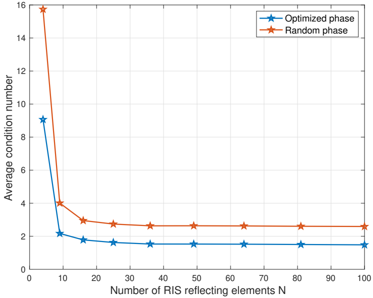
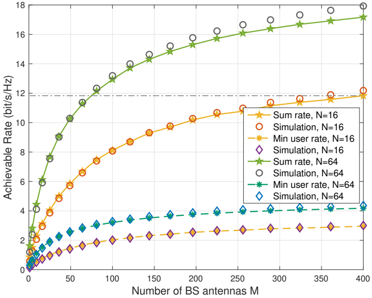


Figure 15: The diagram of GA-based method.

K. Zhi, **C. Pan (Corres. Author)**, H. Ren, K. Wang, "Power Scaling Law Analysis and Phase Shift Optimization of RIS-aided Massive MIMO Systems with Statistical CSI," https://arxiv.org/abs/2010.13525

Transmission Design for RIS-aided Massive MIMO Systems

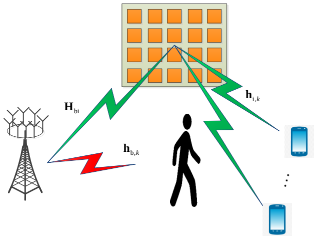




1. Condition number decreases rapidly with the number of reflecting elements
2. Only a moderate number of antennas are enough to bring promising throughput when increasing the number of reflecting elements

K. Zhi, **C. Pan (Corres. Author)**, H. Ren, K. Wang, "Power Scaling Law Analysis and Phase Shift Optimization of RIS-aided Massive MIMO Systems with Statistical CSI," https://arxiv.org/abs/2010.13525

MmWave Communications with Random Blockage



- $\mathbf{D} = [\mathbf{d}_1, \cdots, \mathbf{d}_K]$: Digital precoding matrix
- $\mathbf{A}$: Analog precoding matrix
- $\mathbf{E} = \text{diag}([e_1, \ldots, e_M])$: Phase shift matrix

The channel of the BS-RIS link is

$$\mathbf{H}_{\text{bi}} = \sqrt{\frac{1}{L_{BI}}} \sum_{l=1}^{L_{BI}} g_l^{\text{bi}} \mathbf{a}_P \left(\theta_l^{\text{i},r}, \phi_l^{\text{i},r}\right) \mathbf{a}_L \left(\theta_l^{\text{b},t}\right)^{\text{H}}.$$

The channel of the BS-user link is

$$\mathbf{h}_{\text{b},k} = \sqrt{\frac{1}{L_{BU}}} \sum_{l=1}^{L_{BU}} \omega_{k,l} g_{k,l}^{\text{b}} \mathbf{a}_L \left(\theta_{k,l}^{\text{b},t}\right).$$

The channel of the RIS-user link is

$$\mathbf{h}_{\text{i},k} = \sqrt{\frac{1}{L_{IU}}} \sum_{l=1}^{L_{IU}} g_{k,l}^{\text{i}} \mathbf{a}_P \left(\theta_{k,l}^{\text{i},t}, \phi_{k,l}^{\text{i},t}\right),$$

$\omega_{k,l} \in \{0, 1\}$ is a Bernoulli random parameter with probability p_{block}.

G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang, M. Elkashlan and M. Renzo, "Stochastic Learning-Based Robust Beamforming Design for RIS-Aided Millimeter-Wave Systems in the Presence of Random Blockages," submitted to IEEE Transactions on Vehicular Technology, https://arxiv.org/abs/2009.09716

MmWave Communications with Random Blockage

Received signal at user k is

$$y_k = (\mathbf{h}_{\mathrm{b},k}^{\mathrm{H}} + \mathbf{h}_{\mathrm{i},k}^{\mathrm{H}} \mathbf{E} \mathbf{H}_{\mathrm{bi}}) \mathbf{A} \mathbf{D} \mathbf{s} + n_k.$$

The SINR of user k is

$$\Gamma_k (\mathbf{D}, \mathbf{A}, \mathbf{E}) = \frac{|(\mathbf{h}_{\mathrm{b},k}^{\mathrm{H}} + \mathbf{h}_{\mathrm{i},k}^{\mathrm{H}} \mathbf{E} \mathbf{H}_{\mathrm{bi}}) \mathbf{A} \mathbf{d}_k|^2}{\sum_{i \neq k}^{K} |(\mathbf{h}_{\mathrm{b},k}^{\mathrm{H}} + \mathbf{h}_{\mathrm{i},k}^{\mathrm{H}} \mathbf{E} \mathbf{H}_{\mathrm{bi}}) \mathbf{A} \mathbf{d}_i|^2 + \sigma_k^2}.$$

Problem Formulation

$$\min_{\mathbf{D}, \mathbf{A}, \mathbf{E}} \sum_{k \in \mathcal{K}} \Pr\{\Gamma_k (\mathbf{D}, \mathbf{A}, \mathbf{E}) \leq \gamma_k\} \tag{33a}$$

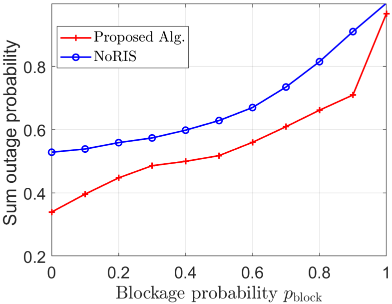
$$\text{s.t.} \quad ||\mathbf{A}\mathbf{D}||_F^2 \leq P_{max} \tag{33b}$$

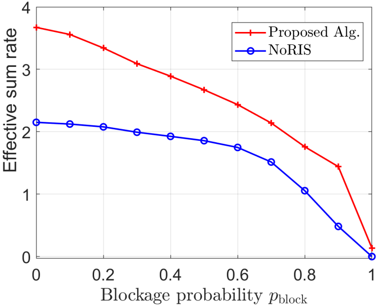
$$|\mathbf{A}_{m,n}|^2 = 1, \forall m, n, \tag{33c}$$

$$|\mathbf{E}_{m,m}|^2 = 1, 1 \leq m \leq M. \tag{33d}$$

G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang, M. Elkashlan and M. Renzo, "Stochastic Learning-Based Robust Beamforming Design for RIS-Aided Millimeter-Wave Systems in the Presence of Random Blockages," submitted to IEEE Transactions on Vehicular Technology, https://arxiv.org/abs/2009.09716

MmWave Communications with Random Blockage





- Our proposed algorithm is more robust to blockage
- Effective rate of user k is defined as $R_{\text{eff},k} \triangleq \mathbb{E}[\log_2(1+\Gamma_k(\mathbf{D},\mathbf{A},\mathbf{e}))]$ if $\Gamma_k(\mathbf{D},\mathbf{A},\mathbf{e}) \geq \gamma_k$ and $R_{\text{eff},k} \triangleq 0$ otherwise

G. Zhou, **C. Pan (Corres. Author)**, H. Ren, K. Wang, M. Elkashlan and M. Renzo, "Stochastic Learning-Based Robust Beamforming Design for RIS-Aided Millimeter-Wave Systems in the Presence of Random Blockages," submitted to IEEE Transactions on Vehicular Technology, https://arxiv.org/abs/2009.09716

Other Works on Transmission Design Relying on Long-term CSI

IRS-aided MmWave communications:

- K. Zhi, **C. Pan (Corres. Author)**, H. Ren, and K. Wang, "Uplink Achievable Rate of Intelligent Reflecting Surface-Aided Millimeter-Wave Communications with Low-Resolution ADC and Phase Noise", https://arxiv.org/abs/2008.00437

IRS-aided Terahertz Communications:

- Y. Pan, K. Wang, **C. Pan (Corres. Author)**, H. Zhu, and J. Wang, "Sum Rate Maximization for Intelligent Reflecting Surface Assisted Terahertz Communications", https://arxiv.org/abs/2008.12246
- Y. Pan, K. Wang, **C. Pan (Corres. Author)**, H. Zhu, and J. Wang, "UAV-Assisted and Intelligent Reflecting Surfaces-Supported Terahertz Communications", https://arxiv.org/abs/2010.14223

IRS-aided UAV communications:

- M. Hua, L. Yang, Q. Wu, **C. Pan**, C. Li, and A. Swindlehurst, "UAV-Assisted Intelligent Reflecting Surface Symbiotic Radio System", https://arxiv.org/abs/2007.14029
- L. Wang, K. Wang, **C. Pan**, W. Xu, N. Aslam, "Joint Trajectory and Passive Beamforming Design for Intelligent Reflecting Surface-Aided UAV Communications: A Deep Reinforcement Learning Approach", https://arxiv.org/abs/2007.08380
- Y. Pan, K. Wang, **C. Pan (Corres. Author)**, H. Zhu, and J. Wang, "UAV-Assisted and Intelligent Reflecting Surfaces-Supported Terahertz Communications", https://arxiv.org/abs/2010.14223

IRS-aided MIMO Mutiuser communications:

- Li. You, J. Xiong, Y. Huang, D. W. K. Ng, **C. Pan**, W. Wang, X. Gao, "Reconfigurable Intelligent Surfaces-Assisted Multiuser MIMO Uplink Transmission with Partial CSI", https://arxiv.org/abs/2009.00473

Future Research Directions

1. Integration of IRS in emerging applications, i.e., MEC, SWIPT, UAV...
2. Robust algorithm based on imperfect cascaded CSI
3. Robust design/performance analysis for hardware impairment, e.g., low-resolution ADC, discrete phase shift control,...
4. Transmission design based on long-term CSI
5. Angle/location estimation
6. Low overhead channel estimation for Sub-6 GHz IRS-aided Communication systems
7. Channel estimation and feedback design for IRS-aided FDD systems
8. Distributed algorithm with low overhead exchange
9. Joint channel estimation and transmission design
10. Hardware design and standardization

Acknowledgement

Acknowledge all my team members and collaborators.

Recruitment Ad

Recruitment Information

- Three CSC funded PhD students
- Two CSC funded visiting PhD students
- Two visiting scholars

Research directions

- Intelligent reflecting surface (IRS) /reconfigurable intelligent surface (RIS)
- Ultra-reliable low latency communication (URLLC)
- Machine learning-aided wireless communications

Pls send your CV to c.pan@qmul.ac.uk if you are interested.

Conclusions

- Perfect Instantaneous CSI
  - IRS-aided Multicell
  - IRS-aided SWIPT
  - IRS-aided MEC
  - IRS-aided Secure Communications
  - IRS-aided Multi-group Multicast Communications
  - .....
- Imperfect Instantaneous CSI
  - Robust Design based on Imperfect Individual CSI
  - Robust Design based on Imperfect Cascaded CSI
  - ....
- Long-term CSI
  - IRS-aided Multi-pair Communications
  - Transmission Design for Uplink RIS-aided Massive MIMO Systems
  - MmWave communications with random blockage
  - .....

Thank you!

If you need slides, pls feel free to contact me: c.pan@qmul.ac.uk