Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Network

Rui Zhang
National University of Singapore
IEEE Fellow, Distinguished Lecturer
Clarivate Analytics Highly Cited Researcher
e-mail: elezhang@nus.edu.sg

Qingqing Wu
University of Macau
e-mail: qingqingwu@um.edu.mo

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Outline

- Part 1: Introduction of Intelligent Reflecting Surface (IRS)
- Part 2: Overview of IRS Communication Design Challenges
- Part 3: Selected Results for IRS-aided Wireless Network
- Part 4: Conclusions and Future Directions

- Part 1 and 2 will be given by Prof Rui Zhang (90 mins)
- After break, Part 3 and 4 will be given by Prof Qingqing Wu (90 mins)
Outline

Part 1: Introduction of Intelligent Reflecting Surface (IRS)
- Motivation
- Hardware architecture
- Reflection and channel models
- Main functions and applications
- Comparison with existing wireless technologies

Part 2: Overview of IRS Communication Design Challenges

Part 3: Selected Results for IRS-aided Wireless Network

Part 4: Conclusions and Future Directions
Have We Reached Shannon’s Capacity Limit?

\[ C = \log \left(1 + \frac{HP}{\sigma^2}\right) \]

- Yes, also No (as wireless channel \( H \) is still random and uncontrolled)
  - Can we make \( H \) arbitrarily large, say from \( H << 1 \) to \( H \rightarrow 1 \)?
  - Can we make \( H \) less random, e.g., from Rayleigh fading to Rician fading?
  - Existing wireless technologies (beamforming, power control, adaptive modulation, etc.) only adapt to \( H \), but have no control over it
  - How to break this ultimate barrier to achieving ultra-high capacity and ultra-high reliability in future wireless communications (e.g., 6G)?

- Promising new paradigm: Smart and Reconfigurable Wireless Environment

- Key enabling technology: Intelligent Reflecting Surface (IRS)
  - Other nomenclature: reconfigurable intelligent surface (RIS), software controlled metasurface, passive intelligent mirror, smart reflect array, ....
What is IRS?

- A digitally-controlled metasurface with massive low-cost passive reflecting elements (each able to induce an amplitude/phase change in the incident signal).
- Low energy consumption (without the use of any transmit RF chains), high spectral efficiency (full-duplex, noiseless reflection).

IRS: Reflection Model

- Baseband equivalent signal model at each IRS element

\[ y_n = \beta_n e^{j\theta_n} x_n, \quad n = 1, \ldots, N \]

where
\[ \beta_n \in [0, 1] : \text{reflection amplitude} \]
\[ \theta_n \in [0, 2\pi) : \text{phase shift} \]
\[ N : \text{No. of elements} \]

\[ \beta_n = 0 : \text{Absorption} \]
\[ \beta_n = 1 : \text{Full reflection} \]

- In practice, both amplitude and phase shift need to be discretized
IRS: Channel Model

- **Baseband equivalent channel model (narrow-band)**
  - Assume isotropic reflection, and no mutual coupling among reflecting elements

  \[ y = \left( \sum_{n=1}^{N} h_n g_n \beta_n e^{i\theta_n} \right) x + z \]

  - \(x\): transmitted signal
  - \(y\): received signal
  - \(h_n\): first link channel
  - \(g_n\): second link channel

- **Product-distance path loss model**
  \[
  |h_n|^2 \propto c_1 d_{1n}^{-\alpha_1} \\
  |g_n|^2 \propto c_2 d_{2n}^{-\alpha_2}
  \]

- **Extendible to wide-band channel, with IRS frequency-flat reflection only**
IRS Path Loss Model: Product Distance or Sum Distance?

- **Product-distance path loss model**
  \[
  |h_n|^2 \propto c_1 d_{1n}^{-\alpha_1} \\
  |g_n|^2 \propto c_2 d_{2n}^{-\alpha_2}
  \]

- **Sum-distance path loss model**
  \[
  P_r \propto \frac{1}{(d_1 + d_2)^2}
  \]

- Applies to free-space propagation and infinitely large perfect electric conductor (PEC) only

- Not applicable to IRS with finite-size elements
Main Functions of IRS in Wireless Communication

- Channel reconfiguration
- Passive relaying/beamforming
- Interference nulling/cancellation
- Others (spatial modulation, sensing/localization, etc.)

IRS for Channel Reconfiguration

- Create virtual LoS link by smart reflection to bypass obstacle
  - Coverage extension for mmWave
- Add extra signal path toward desired direction
  - Improve channel rank and thus spatial multiplexing gain
- Refine channel statistics/distribution
  - Transform Rayleigh/fast fading to Rician/slow fading for ultra-high reliability
IRS functions

IRS-enabled Passive Relaying/Beamforming

- 3D passive beamforming for relaying and broadcasting/multicasting
- Enhance signal power/SNR at “cell edge” and “hot spot”
- Boost network capacity without additional signal transmission
IRS functions

**IRS-assisted Interference Nulling/Cancelation**

- Enhance desired signal power while randomly scattering the interference
- Alternatively, tune the reflected interference to cancel the direct interference (more challenging to implement)
- Both improve cell-edge user’s SINR
- Create a “signal hotspot” as well as “interference-free zone” in the vicinity of IRS

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IRS Applications for 5G/6G

Related Industry Initiatives

- **Metawave**
  - Passive reflector/relay (ECHO)

- **Greenerwave**
  - Reconfigurable binary metasurface

- **Pivotal Commware**
  - Holographic beam forming
Comparison with existing technologies

**IRS vs Active Relay/Small Cell/DAS/Cell-free MIMO**

- **Network with active BS/AP/relay only**
- High cost, high energy consumption
- Backhaul issue
- Complicated interference management
- Low spectral efficiency due to half duplex (full-duplex radio needs costly self-interference cancelation)

- **Hybrid active-passive network**: fewer BSs with many passive IRSs
- Low cost, low energy consumption
- Low-rate wireless backhaul suffices (for control link only)
- Local coverage only **without the need of inter-IRS interference management**
- Full duplex **without self-interference**
A fundamental question for IRS:
- Can large-scale deployment of IRSs provide cost-effective & sustainable capacity growth in wireless network?

New hybrid active/passive network with IRS
- Randomly distributed active BSs and passive IRSs subjected to inter-cell interference
- Characterize network coverage probability and spatial throughput in terms of key system parameters including BS/IRS densities and network loading factor

Analytical framework based on stochastic geometry

Wireless Network with IRS vs w/o IRS: Simulation Results

- **Spatial throughput $\nu$ subject to total BS/IRS cost $C$**
  - IRS/BS density ratio: $\zeta \triangleq \lambda_I/\lambda_B$
  - Cost of each BS: $c_0$, BS/IRS cost ratio: $K_N$
  - Total cost $C$ per m$^2$ in the hybrid network:
    $$C \triangleq \lambda_B c_0 + \lambda_I c_0 / K_N = \lambda_B c_0 \left(1 + \zeta / K_N \right)$$

- **$\nu$ versus $\zeta$ under given total cost $C$**:
  - Optimal ratio $\zeta^*$ to achieve maximum $\nu^*$ exists
  - Significantly outperforms BS-only network ($\zeta=0$)
  - $\zeta$ too large: no enough signal power for effective IRS reflection and beamforming

- **$\nu$ versus $C$ under given density ratio $\zeta$**:
  - BS-only network: $\nu$ first increases then decreases due to more severe interference than improved signal power
  - Hybrid network with optimal $\zeta^*$: maximum $\nu^*$ increases almost linearly with $C \rightarrow$ cost-effective and sustainable capacity growth
Comparison with existing technologies

IRS vs Massive MIMO/Active Large Surface

Massive MIMO

- (Non-scalable with increased frequency)
- More RF chains needed for more active elements used
- Increased energy consumption, hardware cost, and processing complexity at higher frequencies (mmWave, THz)

IRS-aided Small MIMO

- (Scalable at any frequency)
- No RF chains needed for IRS due to passive reflection only
- Low energy consumption, scalable cost/complexity
- Compatible with cellular/WiFi and can be densely deployed
Comparison with existing technologies

IRS vs Massive MIMO: Simulation Setup

- IRS-aided small MIMO vs massive MIMO without IRS, both TDD-based
- 8 users randomly distributed within 60 m from AP and 8 users randomly distributed within 6 m from IRS

Transmission protocol for IRS-aided small MIMO

1) all users send orthogonal pilot signals concurrently
2) AP and IRS estimate AP-user and IRS-user channels, respectively
3) AP starts to transmit data to users and in the meanwhile sends its estimated AP-user channels to IRS controller via a separate control link.
4) IRS controller sends optimized transmit beamforming vectors to AP and sets its phase shifts accordingly
5) AP and IRS start to transmit data to users jointly

Two transmission phases for IRS-aided small MIMO

- Small MIMO transmission of duration, \( \tau \)
- IRS-aided joint MIMO transmission of duration, \( T_c - \tau \)

Delay ratio: \( \rho = \frac{\tau}{T_c} \)

Comparison with existing technologies

IRS vs Massive MIMO: Simulation Results

- **M**: # of active antennas at AP
- **N**: # of reflecting units at IRS
- Passive IRS helps reduce # of active antennas (see M=20 with N=80 vs M=50 without IRS)
- This also holds considering delay due to IRS channel estimation (compare M=20 with N=80 vs M=40 without IRS)

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Outline

- Part 1: Introduction of Intelligent Reflecting Surface (IRS)

- Part 2: Overview of IRS Communication Design Challenges
  - IRS reflection optimization
  - IRS channel estimation
  - IRS deployment

- Part 3: Selected Results for IRS-aided Wireless Network

- Part 4: Conclusions and Future Directions
Joint Active and Passive Beamforming: Single-user Case

- AP: active (transmit) beamforming
- IRS: passive (reflect) beamforming with maximum reflection amplitude ($\beta_n = 1$)
- Objective: maximize the received signal power via joint transmit and reflect beamforming optimization
- Establish a local “signal hotspot” in the vicinity of IRS
- Received SNR scaling order: $O(N^2)$
  - Thanks to the dual role of “receive” and “reflect” (full-duplex, noise-free), in contrast to $O(N)$ of massive MIMO (limited by sum-power constraint at Tx), and $O(N)$ of MIMO AF relay (due to relay noise)
  - Hold even for practical IRS with discrete phase shifts

Minimum AP transmit Power vs AP-user Distance

- Transmit beamforming: $\mathbf{w}$
- Reflect beamforming: $\mathbf{\Theta}$

Problem formulation (suboptimal solutions obtained via SDR or alternating optimization)

$$\min_{\mathbf{w}, \mathbf{\Theta}} \| \mathbf{w} \|^2$$

s.t. $$| (\mathbf{h}_r^H \mathbf{\Theta} \mathbf{G} + \mathbf{h}_d^H) \mathbf{w} |^2 \geq \gamma \sigma^2,$$

$$0 \leq \theta_n \leq 2\pi, \forall n = 1, \ldots, N.$$
Minimum AP transmit Power vs No. of IRS Elements (1)

\( d = 50 \text{ m} \)

- SNR scaling law \( O(N^2) \) for sufficiently large \( N \), near IRS

- Increasing \( N \) from 30 to 60 results in 6 dB power gain/saving

\( d = 41 \text{ m} \)

\( d = 15 \text{ m} \)
Suboptimal solution obtained via uniformly quantizing the continuous-phase solution
SNR scaling law, i.e., $O(N^2)$, still holds with finite-level phase shifters
IRS with 1-bit (2-bit) phase-shifters suffers a power loss of 3.9 dB (0.9 dB)

Objective: minimize total transmit power at the AP subject to individual user SINR constraints via joint transmit and reflect beamforming optimization

Establish a “signal hotspot” as well as an “interference-free zone” near IRS

Reflect beamforming by IRS
  ✓ help enhance SINR of the users near IRS
  ✓ Enable more flexible AP transmit beamforming toward users outside IRS coverage
  ✓ Thereby improve the overall network SINR performance

Effective Channel Power vs No. of IRS Elements

- **Small No. of IRS elements**: Minimizing end-to-end path-loss is optimal
- **Large No. of IRS elements**: Maximizing the cooperative passive beamforming gain is optimal
- **In general**, need to optimally balance the above two objectives

No. of IRS elements: 400, 700, 1500 (top to bottom)
Selected Work on IRS Reflection Optimization

- **Power minimization, energy efficiency/rate maximization**

- **IRS-aided OFDM/MIMO**

- **IRS optimization with practical phase shifters**

- **Multi-IRS optimization/cooperative beam routing**
IRS Reflection Optimization: Other Setups/Extensions
(to be continued in Part 3)

- IRS-aided multiuser MISO optimization
- IRS optimization under practical phase-shift models
- IRS-aided MIMO/OFDM
- IRS-aided multiple access
- IRS optimization with statistical/imperfect CSI
- Other applications (PHY-layer security, SWIPT, UAV, etc.)
IRS Channel Estimation

Channel estimation in IRS-aided wireless network
- BS-user links (existing): estimated by conventional methods and switching off IRS
- BS-IRS link (new): quasi-static with fixed BS and IRS
- IRS-user links (new): vary with user location, needs to be estimated in real time

Main challenges in IRS channel acquisition
- Passive IRS (no Tx RF chains): IRS cannot send pilot signals for channel estimation
- Large number of extra channel coefficients: $O(MN+NK)$. $M$: # of BS antennas; $N$: # of IRS elements; $K$: # of users
- IRS performance gains critically depend on the CSI in general

Three general approaches
- Equip IRS with active elements/sensors (semi-passive IRS)
- Estimate BS-IRS-user cascaded channels (fully-passive IRS)
- Beam searching without explicit channel estimation (fully-passive IRS)

Channel Estimation with Semi-Passive IRS

- IRS with active elements /sensing devices
  - Channels estimated by IRS leveraging TDD and channel reciprocity
  - Signal processing required for reconstructing the IRS-BS/user channels with limited/low-cost sensors

Channel Estimation with Fully-Passive IRS

IRS w/o active elements and sensing devices

- More challenging case (as compared to semi-passive IRS)
- Cascaded channel (BS-IRS-user) estimation by varying IRS reflection and exploiting the static/sparse BS-IRS channel (common for all users): an active area of research!

Cascaded Channel Estimation: Useful Techniques

- **Orthogonal IRS training reflection design**: Use designs like DFT/Hadamard matrix to resolve different user channels, nearly orthogonal for practical discrete phase shifts.

- **IRS elements grouping**: Divide IRS elements into adjacent groups with common phase shift per group to exploit channel correlation and reduce training/beamforming complexity: $O(N) \rightarrow O(M)$, with $M$ groups.

- **Common BS-IRS channel exploitation**: Estimate first the cascaded channel for a reference user and then resolve those of the other users more efficiently.

- **Progressive channel estimation**: Start with coarse channel estimation with large-size groups (for initial connection) and gradually refine channel estimation with smaller-size groups to improve beamforming gains (for high-rate data transmission).

- **Anchor-assisted channel estimation**: Exploit near-IRS static anchor nodes to assist in the cascaded channel estimation for reducing on-line training overhead and improving performance.

(More details are given in Part 3)
Beam Searching without Explicit Channel Estimation

- **Codebook-based IRS beam searching**
  - **Multi-beam training (new):** divide IRS reflecting elements into sub-arrays and design their simultaneous multi-beam steering over time
  - More efficient than conventional single-beam training

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Selected Work on IRS Channel Estimation

- **Semi-passive IRS**

- **Fully-passive IRS**
  - **IRS elements grouping and channel estimation in OFDM/OFDMA**
  - **IRS channel estimation in massive MIMO**
  - **Progressive IRS channel estimation with discrete phase**
  - **Anchor-assisted channel estimation**

- **IRS beam searching**
IRS Deployment: Single-User Case

- Consider one single IRS with \( N \) reflecting elements, assume no direct link

- **Double path loss (product distance)**
  - Received SNR:
    \[
    \rho_S = \frac{P \beta_0^2 N^2}{(d^2 + H^2)((D - d)^2 + H^2)\sigma^2}
    \]
  - IRS-AP distance generally increases as the user-IRS distance decreases

- **Optimal deployment strategy to maximize received SNR (minimize product distance):**
  - \( d = 0 \) (IRS near user) or \( d = D \) (IRS near AP), different from active relay (\( d = D/2 \))
  - Maximum received SNR:
    \[
    \rho_S^* = \frac{P \beta_0^2 N^2}{H^2(D^2 + H^2)\sigma^2} \approx \frac{P \beta_0^2 N^2}{H^2 D^2 \sigma^2}
    \]
IRS Deployment: Cooperative/Double IRSs

- Given $N$ IRS reflecting elements, forming them as two cooperative IRSs

- Pros: Cooperative beamforming gain with order $O((N/2)^4)$ (vs. $O(N^2)$ for single-IRS case)

- Cons: Double reflection, more path loss

- Received SNR:

$$\rho_D = \frac{P \beta_0^3 N^4}{16H^4 D^2 \sigma^2}$$

- Two cooperative IRSs outperform one single IRS if

$$N > \frac{4H}{\sqrt{\beta_0}}$$

General Channel Case: Single or Double IRSs?

- Consider multi-antenna BS, all single- and double-reflection links

- Double IRS generally outperforms single IRS at any SNR (theoretically proved if K=1 or single-user case)
- Double IRS also provides larger effective channel rank than single IRS (thus, higher spatial multiplexing gain)

IRS Deployment: Centralized IRS or Distributed IRSs?

- **Centralized deployment:** Deploy all \( N \) reflecting elements near the AP

- **Distributed deployment:** Deploy \( N_k \) elements near each user \( k \), \( \sum_{k=1}^{K} N_k = N \)

- Both users are served by the centralized IRS with \( N \) elements
  - Pros: Larger beamforming gain \( \mathcal{O}(N^2) \)
  - Cons: Beamforming gain needs to be shared by the two users

- Each user is only served by its nearby IRS with \( N_k \) (\( N_k < N \)) elements
  - Pros: Beamforming gain is maximized for each user
  - Cons: Only \( \mathcal{O}(N_k^2) \) beamforming gain for each user

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IRS Deployment: Centralized IRS or Distributed IRSs?

- Capacity region comparison for a two-user multiple access channel (MAC):

- Under symmetric channel condition, centralized deployment outperforms distributed deployment in terms of capacity region, due to more flexibility in trading off users’ individual reflected channels as compared to distributed IRSs.

- In practice, other factors need to be taken into account, such as space constraint, LoS availability, etc.

Selected Work on IRS Deployment

**Double/cooperative IRS**

**Double-IRS channel estimation**

**Centralized vs distributed IRS**

**IRS deployment in large network based on stochastic geometry**

**IRS deployment based on machine learning**
Outline

- Part 1: Introduction of Intelligent Reflecting Surface (IRS)
- Part 2: Overview of IRS Communication Design Challenges
- Part 3: Selected Results for IRS-aided Wireless Network
  - IRS reflection optimization
  - IRS cascaded channel estimation
  - Other IRS applications (security, SWIPT, UAV)
- Part 4: Conclusions and Future Directions
Selected Work for IRS Reflection Optimization

- **IRS-aided multiuser MISO optimization**

- **IRS optimization under practical phase-shift models**

- **IRS-aided OFDM/MIMO**

- **IRS-aided multiple access**

- **IRS optimization with statistical/imperfect CSI**
IRS-aided Multiuser MISO Optimization

Joint Active and Passive Beamforming: Multi-user Case

- **Objective**: minimize total transmit power at the AP subject to individual user SINR constraints via joint transmit and reflect beamforming optimization
- Establish a "signal hotspot" as well as an "interference-free zone" near IRS
- Reflect beamforming by IRS
  - help enhance SINR of the users near IRS
  - Enable more flexible AP transmit beamforming toward users outside IRS coverage
  - Thereby improve the overall network SINR performance

Problem Formulation and Algorithm Design

- Multi-user problem formulation

\[
\begin{align*}
\min_{w, \theta} & \quad \sum_{k=1}^{K} \|w_k\|^2 \\
\text{s.t.} & \quad \left| (h_{r,k}^H \theta G + h_{d,k}^H) w_k \right|^2 \\
& \quad \frac{1}{\sum_{j \neq k}^K \left| (h_{r,k}^H \theta G + h_{d,k}^H) w_j \right|^2 + \sigma_k^2} \geq \gamma_k, \forall k, \\
& \quad 0 \leq \theta_n \leq 2\pi, \forall n = 1, \ldots, N,
\end{align*}
\]

- Two challenges in algorithm design
  - Coupling between active BF and passive BF
  - Unit-modulus constraint of phase shifters

- Iterative algorithm design: Alternating optimization
  - Most commonly adopted approach in literature

\[(P3): \quad \min_{W} \quad \sum_{k=1}^{K} \|w_k\|^2 \text{ s.t. } \frac{\left| h_k^H w_k \right|^2}{\sum_{j \neq k}^K \left| h_j^H w_j \right|^2 + \sigma_k^2} \geq \gamma_k, \forall k, \quad (44)\]

\[(P4): \quad \text{Find } V \text{ s.t. } \text{tr}(R_{k,k}V) + |b_{k,k}|^2 \geq \gamma_k \sum_{j \neq k}^K \text{tr}(R_{k,j}V) \]
\[+ \gamma_k \left( \sum_{j \neq k}^K |b_{k,j}|^2 + \sigma_k^2 \right), \forall k, \quad (45)\]
\[V_{n,n} = 1, n = 1, \ldots, N + 1, \quad (46)\]
\[V \geq 0. \quad (47)\]

- Heuristic algorithm design: Two-stage algorithm
  - Maximize weighted user effective channel gain with IRS BF, followed by AP/BS MMSE BF
Minimum AP transmit Power vs User SINR Target

Simulation setup

- Special two-user case: one user near IRS and the other user far from IRS
  - $d_1=20$ m, $d_2=3$ m

- Significant power saving at AP with vs. w/o IRS
- Two-stage algorithm performs well for the case of high user SINR targets
- Setting random phase shift may even perform worse than the case w/o IRS
IRS provides not only signal power gain, but also interference mitigation gain for near user (user 2), which also benefits for far user (user 1)

User 1: far from IRS, served by AP transmit BF only
User 2: near IRS, served by both AP BF and IRS (reflect) BF
Impact of IRS on AP Active Beamforming

- **Without IRS**
  - From MRT BF to ZF BF
- **With IRS**
  - No need for ZF BF at high SINR

User 1: far from IRS, served by AP transmit BF only

- **Without IRS**
  - From MRT BF to ZF BF
- **With IRS**
  - No need for ZF BF at high SINR

User 2: near IRS, served by both AP BF and IRS (reflect) BF

- **Without IRS**
  - From MRT BF to ZF BF
- **With IRS**
  - No need for MRT BF at low SINR
IRS Optimization under Practical Phase-shift Models

Objective: minimize total transmit power at the AP subject to individual user SINR constraints via joint transmit and reflect beamforming optimization

- Discrete phase shift in $[0, 2\pi]$: $b$-bit phase shifters
  - Uniform quantization
    $$\mathcal{F} = \{0, \Delta \theta, \cdots, (L - 1)\Delta \theta\}, \quad \Delta \theta = \frac{2\pi}{L}, \quad L = 2^b$$
    - $b=1 \rightarrow \theta_n = \{0, \pi\}$

IRS: Discrete Phase Shift Model

- Problem formulation

\[(P1): \min_{W, \theta} \sum_{k=1}^{K} ||w_k||^2\]

\[\text{s.t.} \quad \frac{|(h^H_{r,k} G + h^H_{d,k})w_k|^2}{\sum_{j \neq k} |(h^H_{r,k} G + h^H_{d,k})w_j|^2 + \sigma_k^2} \geq \gamma_k, \forall k \in K,\]

\[\theta_n \in \mathcal{F} = \{0, \Delta \theta, \cdots, (L - 1)\Delta \theta\}, \forall n \in \mathcal{N}.\]

- Single-user case

  - Power loss analysis

- Multiuser case

  - ZF transmit BF

  - Successive refinement for phase shifts

- Coupled optimization variables

- Discrete optimization variables

- MINLP, thus NP-hard

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AP Transmit Power vs No. of Users/IRS elements

- Less transmit power required for adding additional users
- Hybrid system using low-resolution and low-cost IRS with less active antennas
- Trade off N, b, and M to minimize total hardware cost and energy consumption
IRS: Amplitude Dependent Phase Shift Model

Reflection coefficient at each IRS element

\[ v_n = \frac{Z_n(C_n, R_n) - Z_0}{Z_n(C_n, R_n) + Z_0} \]

where \( Z_n(C_n, R_n) \) : element impedance
\( Z_0 \) : free space impedance

- Ideal model: maximum (unit) reflection amplitude regardless of phase shift (widely used in the literature, but difficult to realize in practice)
- Practical model: minimum amplitude occurs near zero phase shift and approaches unity (maximum) at \( \pi \) or \(-\pi\)
- Reason: when phase shift approaches zero, image currents become in-phase with reflecting element currents, thus more energy loss and hence low reflection amplitude
- \( R_n \) cannot be zero in practice (varactor diodes \( R_n = 2.5 \, \Omega \))
- Implication: IRS passive beamforming needs to balance between reflection amplitude and phase alignment

Analytical IRS Model with Phase Shift Dependent Amplitude

- Generally applicable to a variety of semiconductor devices used for implementing the IRS

Reflection coefficient at each IRS element

\[ u_n = \beta_n(\theta_n) e^{j\theta_n} \]

\( n = 1, ..., N \)

where

- phase shift: \( \theta_n \in [-\pi, \pi) \)
- reflection amplitude:
  \[ \beta_n(\theta_n) = (1 - \beta_{\text{min}}) \left( \frac{\sin(\theta_n - \phi) + 1}{2} \right)^k + \beta_{\text{min}} \]
Single-user problem formulation

 Transmit beamforming: $\mathbf{w}$; Reflect beamforming: $\mathbf{v}$

 Suboptimal solution obtained via alternating optimization (AO)
IRS-aided OFDM/MIMO

IRS-aided OFDM

- BS & User: single-antenna
- IRS: passive beamforming with reflection coefficient \( \phi_m = \beta_m e^{j\theta_m}, m = 1 \ldots M \)
- BS-user direct link: \( h_d \) with \( L \) multipath
- BS-IRS-user link: \( h_r \) with \( L_0 \) multipath
- Power ratio of per element BS-IRS-user link to \( h_d \): \( \alpha \)

Main challenges:
- More channel coefficients to estimate as compared to narrow-band channels
  - Solution: IRS elements grouping, \( K = M/B \)
- Design (frequency-flat) IRS reflection to cater to frequency-selective OFDM channels
- Jointly optimize IRS reflection coefficients and OFDM power allocation for rate maximization
Phase II: Optimization

- Transmit power allocation: $p$
- IRS group coefficient: $\Phi$
- Composite BS-IRS & IRS-user channel: $V'$
- BS-IRS-user link: $h_r = V' \Phi$

$$r(p, \Phi) = \frac{1}{N + N_{cp}} \sum_{n=0}^{N-1} \log_2 \left( 1 + \frac{|f_n^H h_d + f_n^H V' \Phi|^2 p_n}{\Gamma \sigma^2} \right)$$

Phase I: Training & Channel Estimation

- On/off control of IRS elements groups, $K + 1$ OFDM symbols for training
- Obtain $\hat{h}_d$ and $\hat{V}'$

Phase III: Transmission

- $\Phi^*$ and $p^*$ from Phase II
- Actual achievable rate

$$R = \left( 1 - \frac{T_P + \tau_D}{T_c} \right) r(p^*, \Phi^*)$$

Transmission Protocol

- Pilot Transmission and Channel Estimation $T_p$
- Processing and Feedback
- Data Transmission $T_d$

Coherence Time $T_c$
IRS-aided OFDM

- With perfect channel information: \( K = M \) and ignore training overhead
  - Proposed solutions for Phase II: Iterative (alternating optimization) with CPM initialization
  - Performance gain over random phase design, without IRS

- With imperfect channel estimation: (various \( K \) and include training overhead)
  - Grouping ratio \( \rho = K / M \),
  - Trade-off between channel estimation overhead and IRS beamforming gain
    -> optimal \( \rho \)

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Graphs showing achievable rates for different scenarios:
- Iterative and CPM with varying coherence times and grouping ratios.
- Comparisons between iterative, CPM, and random phase methods.

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Qingqing Wu, University of Macau
IRS-aided MIMO Capacity

- Conventional MIMO channel without IRS
  - Fixed channel $H = \tilde{H}$
  - Capacity-achieving transmit covariance matrix $Q$:
    Eigenmode transmission with water-filling power allocation

- IRS-aided MIMO channel
  - Effective channel $\tilde{H}$ tunable by designing IRS reflection coefficients $\phi$
  - Optimal transmit covariance matrix $Q$ dependent on $\phi$

- Fundamental capacity limit characterization: Joint optimization of channel (IRS reflection coefficients) and transmit covariance matrix
IRS-aided MIMO Capacity

Problem formulation:

\[(P1) \max_{\phi, Q} \log_2 \det \left( I_{N_r} + \frac{1}{\sigma^2} \tilde{H}Q\tilde{H}^H \right) \]

\[\text{s.t. } \phi = \text{diag}\{\alpha_1, \ldots, \alpha_M\} \]
\[|\alpha_m| = 1, \quad m = 1, \ldots, M \]
\[\text{tr}(Q) \leq P \]
\[Q \succeq 0. \]

- Non-convex uni-modular constraints on IRS reflection coefficients
- Coupling between \(Q\) and \(\phi\)

Explicit channel expression in terms of each \(\alpha_m\):
\[\tilde{H} = H + \sum_{m=1}^{M} \alpha_m r_m t_m^H \]

Alternating optimization framework:

- Iteratively optimize each \(\alpha_m\) or \(Q\) with other variables being fixed
- With given \(\{\alpha_i, i \neq m\}, Q\), optimize \(\alpha_m\):
\[
\max_{\alpha_m} \log_2 \det(A_m + \alpha_m B_m + \alpha_m^* B_m^H) \\
\text{s.t. } |\alpha_m| = 1.
\]

Closed-form optimal solution
\[\alpha_m^* = \begin{cases} 
    e^{-j \arg \{\lambda_m\}}, & \text{if } \text{tr}(A_m^{-1} B_m) \neq 0 \\
    1, & \text{otherwise.}
\end{cases} \]

- With given \(\phi\), optimal \(Q\) given by eigenmode transmission & water-filling
- Locally optimal solution in polynomial time
- Extendible to MIMO-OFDM systems
IRS-aided MIMO Capacity

- Low-SNR regime:
  - MIMO capacity can be enhanced by deploying IRS (both narrowband and MIMO-OFDM systems), capacity gain increases with number of IRS reflecting elements.

- High-SNR regime:
  - Various critical channel parameters can be improved by IRS, including channel power, rank, and condition number.
IRS-aided Multiple Access

IRS-aided Multiple Access: OMA vs NOMA

- **Conventional multiple access without IRS**
  - NOMA is always superior to OMA (TDMA/FDMA)
  - TDMA and FDMA achieve the same theoretical performance

- **IRS-aided multiple access**
  - Setup: two users share two given adjacent time-frequency resource blocks (RBs)
  - TDMA is always superior to the FDMA (due to passive IRS reflection that can be time-selective, but cannot be frequency-selective)
  - NOMA is always superior to the FDMA (due to the higher spectrum efficiency of NOMA with any passive IRS reflection)
  - NOMA may perform worse than TDMA for near-IRS users with symmetric rates
IRS-aided Multiple Access: OMA versus NOMA

Problem formulation for NOMA:

- $\lambda_i(\theta)$: Channel power gain of user $i$
- $P_i$: Transmit power for user $i$
- $\sigma^2$: Noise variance

\[
\begin{align*}
(N1): P_{N1} & \triangleq \min_{\theta, P_1, P_2} \quad P_1 + P_2 \\
\text{s.t.} \quad & \log_2 \left( 1 + \frac{P_1 \lambda_i(\theta)}{\sigma^2} \right) \geq \gamma_1 \\
& \log_2 \left( 1 + \frac{P_2 \lambda_2(\theta)}{\sigma^2} \right) \geq \gamma_2 \\
& \theta_m \in F, \forall m = 1, \ldots, M \\
(N2): P_{N2} & \triangleq \min_{\theta, P_1, P_2} \quad P_1 + P_2 \\
\text{s.t.} \quad & \log_2 \left( 1 + \frac{P_1 \lambda_i(\theta)}{\sigma^2} \right) \geq \gamma_1 \\
& \log_2 \left( 1 + \frac{P_2 \lambda_2(\theta)}{\sigma^2} \right) \geq \gamma_2 \\
& \theta_m \in F, \forall m = 1, \ldots, M.
\end{align*}
\]

Problem formulation for FDMA:

- Frequency-flat IRS reflection

\[
(F1): P_F \triangleq \min_{\theta_1, \theta_2, P_1, P_2} \quad P_1 + P_2 \\
\text{s.t.} \quad \frac{1}{2} \log_2 \left( 1 + \frac{P_1 \lambda_1(\theta_1)}{\frac{1}{2} \sigma^2} \right) \geq \gamma_1 \\
& \frac{1}{2} \log_2 \left( 1 + \frac{P_2 \lambda_2(\theta_2)}{\frac{1}{2} \sigma^2} \right) \geq \gamma_2 \\
& \theta_{k,m} \in F, \forall m \in F, k \in \{1, 2\}
\]

Problem formulation for TDMA:

- Time-selective IRS reflection

\[
(T1): P_T \triangleq \min_{\theta_1, \theta_2, P_1, P_2} \quad P_1 + P_2 \\
\text{s.t.} \quad \frac{1}{2} \log_2 \left( 1 + \frac{2P_1 \lambda_1(\theta_1)}{\sigma^2} \right) \geq \gamma_1 \\
& \frac{1}{2} \log_2 \left( 1 + \frac{2P_2 \lambda_2(\theta_2)}{\sigma^2} \right) \geq \gamma_2 \\
& \theta_{k,m} \in F, \forall m = 1, \ldots, M, k \in \{1, 2\}
\]

- The user decoding order of NOMA can be permuted by adjusting the IRS reflection

- Symmetric user deployment: two near-IRS users

- Asymmetric user deployment: one near-IRS user and one far-IRS user

The graphs show the performance of different multiple access methods with and without IRS. The graphs are labeled as follows:

(a) AP transmit power versus the common target rate $\gamma_0$.
(b) AP transmit power versus user 1’s target rate $\gamma_1$, with the two users’ sum rate fixed as $\gamma_1 + \gamma_2 = 4$ bps/Hz.

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IRS-enhanced OFDMA: Dynamic Passive Beamforming

- BS & \( K \) Users: single-antenna
- Resource allocation of \( N \) sub-bands over \( Q \) time slots
- \( M \) dynamic IRS passive beamforming reflection coefficients \( \{\phi_{q,m}\} \)
- BS-user direct link: \( h_d^{k} \) with \( L_{0,k} \) taps
- BS-IRS-user link: \( h_r^{k,q} = V_k \phi_q \) with \( L_1 + L_2,k - 1 \) taps

\[
R_k = \frac{1}{NQ} \sum_{q=1}^{Q} \sum_{n=1}^{N} \alpha_{k,q,n} \log_2 \left( 1 + \frac{|f_n h_d^k + f_n^H V_k \phi_q|^2 p_{q,n}}{\Delta^2} \right)
\]

\[
\begin{align*}
\text{(P1)} & \quad \max_{\{\alpha_{k,q,n},\phi_q\},\{p_{q,n}\}} R \\
\text{s.t.} & \quad R_k \geq R, \quad \forall k \in K \\
& \quad \sum_{k=1}^{K} \alpha_{k,q,n} \leq 1, \quad \forall q \in Q, \forall n \in N \\
& \quad \alpha_{k,q,n} \in \{0, 1\}, \quad \forall k \in K, \forall q \in Q, \forall n \in N \\
& \quad \sum_{n=1}^{N} p_{q,n} \leq P, \quad \forall q \in Q \\
& \quad p_{q,n} \geq 0, \quad \forall q \in Q, \forall n \in N \\
& \quad |\phi_{q,m}| \leq 1, \quad \forall q \in Q, \forall m \in M.
\end{align*}
\]
IRS-aided Spectrum Sharing: A Cognitive Radio Approach

- **Challenging scenarios** (limited SU rate in conventional CR system without IRS):
  - Strong cross-link interference when the SU is located nearby the PU
  - The asymmetric interference scenarios (c, d) is even more challenging than symmetric ones (a, b)

- **Objective**: maximize the SU rate via joint power control and passive beamforming

- **Problem formulation**:

  \[
  \max_{p_{s}, v} \log(1 + \gamma_s) \\
  \text{s.t.} \quad \gamma_p \geq \gamma_{th}, \\
  p_s \geq P_{\max}, |v_n| = 1, n = 1, \ldots, N.
  \]

  \[
  \gamma_s = \frac{p_s |v^H h_{srs} + h_s|^2}{p_p |v^H h_{prs} + h_{ps}|^2 + \sigma_s^2}, \quad \gamma_p = \frac{p_s |v^H h_{srs} + h_s|^2}{p_p |v^H h_{prs} + h_{ps}|^2 + \sigma_s^2},
  \]

  \[
  h_{ij} = \text{diag}\left( h_{ij}^H \right) h_{ij}^*, i \in \{p, s\}, j \in \{p, s\}
  \]

  which is solved by using the alternating optimization technique

---

Qingqing Wu, University of Macau
IRS significantly improves the secondary user rates, especially in scenario (d), where ST and PR are near the IRS.
IRS Optimization with Statistical/Imperfect CSI

IRS Optimization with Statistical/Imperfect CSI

- Conventional instantaneous CSI based scheme
  - Design active and passive beamforming based on $G$, $h_{r,k}$, $h_{d,k}$ in each time slot
  - High signal processing complexity and large training/signaling overhead

- Two-timescale design with statistical CSI
  - Passive beamforming: long-term
  - Active beamforming: short-term
  - Phase 1: IRS -> sensing mode for statistical CSI estimation
  - Phase 2: passive beamforming design based on statistical CSI, and then fixed
  - Phase 3: IRS -> reflecting mode, AP serves the users using effective CSI (low dimension)

Transmission protocol
IRS Optimization with Statistical/Imperfect CSI

- **Problem formulation:**

  \[
  \max_{\Theta} \mathbb{E} \left\{ \max_{\{w_k\}} \sum_{k \in \mathcal{K}} \alpha_k \log_2 \left( \frac{1 + \frac{|(h_{r,k}^H \Theta G + h_{d,k}^H)w_k|^2}{\sum_{j \in \mathcal{K} \setminus k} |(h_{r,k}^H \Theta G + h_{d,k}^H)w_j|^2 + \sigma_k^2}}{\sum_{j \in \mathcal{K} \setminus k} |(h_{r,k}^H \Theta G + h_{d,k}^H)w_j|^2 + \sigma_k^2} \right) \right\}
  \]

  subject to \( \sum_{k \in \mathcal{K}} \|w_k\|^2 \leq P, \ \forall i \in \mathcal{F}, \ \forall i \in \mathcal{N} \).

- **Inner problem:** short-term design. **Outer problem:** long-term design
- **Non-convex uni-modular constraints on IRS reflection coefficients, can be discrete**
- **Coupling between \( \Theta \) and \( w_k \) in the objective function**

- **Single-user case:**

  \[
  \max_{v} v^H \Phi v + v^H b + b^H v
  \]

  subject to \( v_i \in \mathcal{F}, \ \forall i \in \mathcal{N} \).

  - The original stochastic optimization problem can be approximated by a deterministic problem
  - Solved by using the penalty dual decomposition method
  - Reflection coefficients are updated in parallel

- **Multiuser case:**

  \[
  \max_{v} f^t(v)
  \]

  subject to \( |v_i| \leq 1, \ \forall i \in \mathcal{N} \).

  - Short-term problem reduces to the conventional multiuser MISO downlink system, can be solved by the WMMSE method
  - Long-term problem is solved by iteratively constructing a concave surrogate objective function with generated channels

Qingqing Wu, University of Macau
IRS Optimization with Statistical/Imperfect CSI

- **Different Rician factor:**

- **Low-SNR regime:** transmit power is the performance bottleneck, larger channel correlation coefficient, better performance

- **High-SNR regime:** spatial multiplexing gain is the performance bottleneck, increasing the channel correlation coefficient improves the performance, but increasing it too much is adverse
IRS Optimization with Imperfect CSI

- **Conventional IRS optimization**
  - Design active and passive beamforming assuming **perfect CSI**
  - Full reflection at IRS is assumed (i.e., no reflection amplitude control)

- **Beamforming design with imperfect CSI and reflection amplitude control**
  - Channel estimation error is inevitable in practice and the user’s achievable rate under imperfect CSI needs to be analyzed
  - The distribution of CSI errors is required for rate analysis, but it depends on the channel estimation method adopted
  - In practice, due to hardware limitation, the amplitude and phase shift of each reflecting element can only take a finite number of discrete values
  - Full reflection for data transmission may not be optimal, under imperfect CSI
Assume full reflection during channel estimation

- Exploit uplink-downlink duality
- Employ the time-varying reflection pattern for channel estimation

\[
\tilde{H}_k = \left( \frac{1}{\sqrt{p_{u,k}s_{u,k}}} Y_k \bar{V} \bar{V}^H \right)^H \tilde{H}_k + \frac{1}{\sqrt{p_{u,k}s_{u,k}}} (\bar{V}^H)^H N_{u,k}^H,
\]

- \( s_{u,k} \): uplink training symbol
- \( p_{u,k} \): uplink training signal power
- \( N_{u,k} \): channel noise
- \( \tilde{H}_k \): estimated channel
- \( \bar{V} = [\tilde{v}_1, \cdots, \tilde{v}_{N_r}] \): reflection pattern

- Channel estimation error: \( \Delta H_k = \hat{H}_k - H_k \)

Correlated Gaussian distributed

\[
E\{\Delta \tilde{H}_k\} = 0 \quad E\{\Delta \tilde{H}_k \Delta \tilde{H}_k^H\} = \frac{M \varepsilon_k^2}{p_{u,k}} (\bar{V} \bar{V}^H)^\dagger
\]

Achievable rate subjected to channel estimation error

\[
\log \left( 1 + |(\bar{v}^H \hat{H}_k + \hat{h}_{d,k}^H) w_k|^2 / \Psi_k^d \right)
\]

\( \Psi_k^d \): multiuser interference + interference due to imperfect CSI + channel noise variance
Problem formulation:

- Non-convex optimization problem
- Unit-modular constraints on IRS reflection coefficients (discrete)
- Coupling between $\mathbf{v}$ and $\mathbf{w}$ in the objective function

Why amplitude control is helpful under imperfect CSI (Single-user case)?

- Focus on the $n$-th reflection coefficient $v_n = a_n e^{-j\theta_n}$

\[
\log \left(1 + \frac{a_n^2 A_{nn} + a_n e_n + d_n}{a_n^2 R_{nn} \| \mathbf{w} \|^2 + a_n e_n + f_n} \right)
\]

- $a_n = 1$ is not necessarily optimal for maximizing the achievable rate, especially when $R_{nn} \| \mathbf{w} \|^2 \gg A_{nn}$ and $e_n \gg c_n$, i.e., when the CSI error becomes large

Proposed algorithms:

- Single-user case: penalized Dinkelbach-BSUM algorithm
- Multiuser case: penalty dual decomposition algorithm
The proposed scheme with amplitude control outperforms that with full reflection in both continuous and discrete phase-shift cases.

The performance gain offered by amplitude control is more significant when uplink training power is lower.

Also outperform the case without IRS and the non-robust scheme.

Ignoring CSI errors in the non-robust scheme results in substantial performance degradation.
The performance gain of the proposed scheme with amplitude control is not sensitive to the value of \( N \).

- Amplitude beamforming > phase beamforming when \( N \) is small.
- It is more beneficial to employ amplitude beamforming for lower cost than phase beamforming when less accurate CSI is available.
Selected Work for IRS Cascaded Channel Estimation

- **IRS-aided OFDM/OFDMA channel estimation**

- **IRS channel estimation with discrete phase shift and progressive refinement**
IRS-aided OFDM/OFDMA Channel Estimation

IRS-aidered OFDM: Improved Channel Estimation

- Practical issues of the IRS elements/groups ON/OFF-based channel estimation
  - It requires on-off/amplitude control (in addition to phase shift)
  - The large aperture of IRS is not fully utilized to combat the interference and receiver noise, which degrades the channel estimation accuracy

- The mean-square error (MSE) of channel estimation using the DFT (full ON)-based IRS reflection pattern
  \[
  \varepsilon = \frac{1}{N} \cdot E \{ \| \mathbf{\hat{h}}_d \mathbf{V}' - [\mathbf{h}_d \mathbf{V}'] \|_F^2 \} \\
  = \frac{1}{(M+1)^2N} \cdot E \{ \| \mathbf{ZF}_{M+1}^H \|_F^2 \} \\
  = \frac{\sigma^2NL}{N_pP_t}
  \]
  - \( F_{M+1}^H \): \((M+1)\)-point DFT matrix as the full-ON IRS reflection pattern
  - \( \mathbf{Z} \): Received noise matrix with zero-mean and variance \( \sigma^2 \)
  - \( N \): Number of subcarriers
  - \( N_p \): Number of pilot tones
  - \( L \): Maximum delay spread
  - \( P_t \): Transmit power

- Consider practical channel estimation and low-complexity passive beamforming
  - IRS passive beamforming design for OFDM
    1. Semidefinite relaxation (SDR) method:
      high complexity -> \( O((M+1)^{3.5}) \)
    2. New strongest-CIR maximization (SCM) method:
      low complexity -> phase alignment for the strongest path
  - Better trade-off than on/off for balancing training overhead with IRS beamforming gain for different grouping ratio \( \rho \)
IRS-aided OFDMA: Multiuser Channel Estimation

- AP & $K$ users: single-antenna
- IRS: passive beamforming with $M$ reflection coefficients
  \[ \theta_m = \beta_m e^{j\phi_m}, m = 1 \ldots, M \]
- AP-user direct link: $\vec{d}_k$ with $L_d$ multipaths, $k = 1, \ldots, K$
- AP-IRS link: $\vec{g}_m$ with $L_1$ multipaths, $m = 1 \ldots, M$
- IRS-user link: $\vec{u}_{m,k}$ with $L_2$ multipaths, $k = 1, \ldots, K$
- Cascaded AP-IRS-user link: $\vec{q}_m = \vec{g}_m \ast \vec{u}_{m,k}$ with $L_r = L_1 + L_2 - 1$ multipaths, $m = 1 \ldots, M$, $k = 1, \ldots, K$
- Maximum delay spread: $L = \max\{L_d, L_r\}$
- Number of OFDM subcarriers: $N$
- Main challenges:
  - The user-by-user successive channel estimation increases the total training overhead by $K$ times (as compared to the single-user case)
  - More channel coefficients to be estimated due to the multipaths and the convolution of the AP-IRS and IRS-user channels in each cascaded AP-IRS-user channel.
  - The channels are frequency-selective, but the IRS reflection coefficients are frequency-flat, i.e., independent reflection over sub-carriers is impossible.
OFDMA Channel Estimation via Time-Varying Reflection

- **Simultaneous-user channel estimation (SiUCE):** applies to arbitrary frequency-selective fading channels and estimates the CSI of all users in parallel simultaneously at the AP.

  - Maximum number of supportable users:
    \[ K_1 = \left\lfloor \frac{N}{L} \right\rfloor \]

- **Sequential-user channel estimation (SeUCE):** applies to LoS dominant user-IRS channels by exploiting the same (common) IRS-AP channel shared by all users. Estimate the CSI of an arbitrarily-selected reference user, based on which the CSI of the remaining \( K - 1 \) users can be recovered.

  - Maximum number of supportable users:
    \[ K_2 = \left\lfloor \frac{(M+1)(N-L)}{M+L} + 1 \right\rfloor \text{ and } K_2 \geq K_1 \]
IRS Channel Estimation with Discrete Phase Shift and Progressive Refinement

IRS Channel Estimation with Discrete Phase Shifts

**Setting:**
- One single block with $M$ symbols used for channel training
- IRS training reflection matrix $\Phi_s$ with discrete phase shift
  $b$: No. of phase-control bits

**Problem:** minimize MSE under discrete-phase shift and full rank constraints

**Issues:** Orthogonal DFT-based IRS training reflection matrix for continuous phase shifts is inapplicable due to discrete phase shifts (optimal solution requires an exhaustive search)

**Solution:** Low-complexity near-orthogonal IRS training matrix construction
- DFT-matrix nearest-phase quantization for $b \geq 2$
- Hadamard-matrix truncation for $b = 1$

**New observation:** Channel estimation error is correlated over IRS elements and depends on IRS training reflection matrix

\[
\min_{\Theta_s} \frac{\sigma^2}{P} \text{tr} \left( (\Theta_s^H \Theta_s)^{-1} \right)
\]

\[
\text{s.t.} \quad |[\Theta_s]_{\hat{m}, m}| = 1, \quad 1 \leq \hat{m}, m \leq M,
\]

\[
\angle[\Theta_s]_{\hat{m}, m} \in \mathcal{F}, \quad 1 \leq \hat{m}, m \leq M,
\]

\[
\text{rank}(\Theta_s) = M.
\]
Progressive IRS Channel Estimation

- All-at-once IRS channel estimation may not be feasible in practice
- Problem: How to progressively resolve more accurate CSI of IRS over $I_0$ blocks
- Solution: Hierarchical IRS training reflection
  - Per-group effective channel estimation with IRS element-grouping
  - Intra-group channel estimation with IRS group/subgroup partition
- Resolve $iM$ group/subgroup channels in block $i$
- MSE over blocks is correlated with training matrix
  \[
  \text{MSE}(\hat{g}^{(i)}) = \frac{\sigma^2}{P} \text{tr} \left( (\Theta_s^H \Theta_s)^{-1} \right) \text{tr} \left( (\Psi_a^{(i)})^H \Psi_a^{(i)} \right)^{-1}
  \]
- Advantages: adapt to the transmission requirement and channel coherence time
Progressive Passive Beamforming

- Progressively refine passive beamforming for data transmission with more resolved IRS CSI
- Should consider the correlated channel estimation error covariance matrix over blocks
- Solution: Successive refinement with different initializations
  - SDR-based initialization: high complexity -> $O((iM)^{3.5})$
  - Replication-based initialization: the first block use SDR-based, the subsequent blocks replicate passive beamforming in previous block and augment it -> $O(1)$
  - Channel-gain-maximization based initialization: phase alignment for the strongest path -> $O(iM^2b)$

$$R^{(i)} = E[g_e^{(i)H} g_e^{(i)}]$$
$$= \frac{\sigma^2}{P} \text{tr} \left( \left( \Theta_s^H \Theta_s \right)^{-1} \text{tr} \left( \left( \Psi_a^{(i)H} \Psi_a^{(i)} \right)^{-1} R_s^{(i)} \right) \right)$$

$$\gamma(\phi^{(i)}) = \frac{P(\phi^{(i)})^H \hat{G} \phi^{(i)}}{\sigma^2 (\phi^{(i)})^H R_a^{(i)} \phi^{(i)} + 1}, \quad \forall i \in \mathcal{I}.$$

$$\max_{\phi} \frac{\phi^H \hat{G} \phi}{\phi^H R_a \phi + 1}$$

s.t. $|\phi_\ell| = 1, \quad \ell = 1, 2, \ldots, iM,$

$\angle \phi_\ell \in \mathcal{F}, \quad \ell = 1, 2, \ldots, iM.$
Selected Work for Other IRS Applications

IRS-aided PHY security

IRS-aided SWIPT

UAV-mounted IRS
IRS-aided PHY Security

Challenging scenarios (zero secrecy rate in conventional system without IRS):

- Eavesdropping channel is stronger than legitimate channel
- Two channels are highly correlated (aligned) in space

Objective: maximize the secrecy rate for the user via joint transmit and reflect beamforming optimization

- Reflected signal by IRS is added constructively with non-reflected signal at the user, while being destructively added with that at the eavesdropper
- Exploit AP's transmit beamforming to strike a balance between the signal power beamed towards IRS and that to the user/eavesdropper for signal enhancement/cancellation
Problem Formulation and Alternating Optimization Solution

- Problem formulation
- AP transmit beamforming: $w$
- IRS reflect beamforming: $q$

$Q \triangleq \text{diag}(q)$

Suboptimal alternating optimization method

Sub-problem 1: (optimal solution)

$$\max_{w, q} \log_2 \left( 1 + \frac{|(h_{IU}QH_{AI} + h_{AU})w|^2}{\sigma_U^2} \right)$$

$$- \log_2 \left( 1 + \frac{|(h_{IE}QH_{AI} + h_{AE})w|^2}{\sigma_E^2} \right)$$

s.t. $\|w\|^2 \leq P_{AP}$

$|q_n| = 1, \ \forall n.$

Sub-problem 2: (approximate solution via SDR)

$$\max_{w, q} \frac{w^HAw + 1}{w^HBw + 1}$$

s.t. $w^Hw \leq P_{AP}.$

$$A = \frac{1}{\sigma_U^2} (h_{IU}QH_{AI} + h_{AU})^H(h_{IU}QH_{AI} + h_{AU}),$$

$$B = \frac{1}{\sigma_E^2} (h_{IE}QH_{AI} + h_{AE})^H(h_{IE}QH_{AI} + h_{AE}),$$

$$\max_{q} \frac{1}{\sigma_U^2} |(h_{IU}QH_{AI} + h_{AU})w|^2 + 1$$

$$\max_{q} \frac{1}{\sigma_E^2} |(h_{IE}QH_{AI} + h_{AE})w|^2 + 1$$

s.t. $|q_n| = 1, \ \forall n.$
The AP, the user, the eavesdropper, and the IRS are located at (0,0), (150,0), (145,0), and (145,5) in meter, respectively. Spatial correlation matrix $R$, where $[R]_{i,j} = r^{|i-j|}$ with $r = 0.95$

- AP transmit beamforming alone can only achieve very limited secrecy rate
- Joint design achieves constructive/destructive signal superposition at user/eavesdropper, thus providing a new DoF to enhance secrecy rate
- With more reflecting elements, IRS beamforming becomes more flexible and achieves higher gains
IRS-aided PHY Security: Is Artificial Noise Helpful or not?

- **Challenge**: lack of transmit DoF due to increasing number of eavesdroppers
  - Conventional system without IRS: AN is helpful
  - IRS-aided secrecy communication: Is AN still helpful?

- **Objective**: maximize the achievable secrecy rate via a joint design of transmit/reflect beamforming with AN and investigate
  - whether IRS can have any impact on the necessity of using AN
  - under what conditions AN is most helpful
Problem Formulation and Solution

- Problem formulation
  - Transmit beamforming: $f_1$
  - Jamming with AN: $f_2$
  - IRS reflect beamforming: $v$
  - IRS reflected channel: $H_{ari} = \text{diag}(h_{ri}^H)H_{ar}$

- Alternating optimization

\[ R_i = \log \left( 1 + \frac{\gamma_0 \left( v^H H_{ari} + h_{ai}^H \right) f_1^2}{\gamma_0 \left( v^H H_{ari} + h_{ai}^H \right) f_2^2 + 1} \right), i \in \{b, e_k\} \]

\[ \max_{f_1, f_2, v} \left\{ R_b - \max_k R_{ek} \right\} \]
\[ \text{s.t. } f_1^H f_1 + f_2^H f_2 \leq P_{\text{max}}, \]
\[ |v_n| = 1, \forall n. \]

Sub-problem 1: optimizing $(f_1, f_2)$ for given $v$

\[ \max_{f_1, f_2} \log \left[ 1 + \gamma_b (f_1, f_2) \right] - \max_k \log \left[ 1 + \gamma_{ek} (f_1, f_2) \right] \]
\[ \text{s.t. } f_1^H f_1 + f_2^H f_2 \leq P_{\text{max}}. \]

\[ \gamma_i (f_1, f_2) = \frac{\gamma_0 \left( v^H H_{ari} + h_{ai}^H \right) f_1^2}{\gamma_0 \left( v^H H_{ari} + h_{ai}^H \right) f_2^2 + 1}, i \in \{b, e_k\} \]

Sub-problem 2: optimizing $v$ for given $(f_1, f_2)$

\[ \max_v \log \left[ 1 + \gamma_b (v) \right] - \max_k \log \left[ 1 + \gamma_{ek} (v) \right] \]
\[ \text{s.t. } |v_n| = 1, \forall n. \]

\[ \gamma_i (v) = \frac{\gamma_0 \left( v^H H_{ari} f_1 + h_{ai}^H f_1 \right)^2}{\gamma_0 \left( v^H H_{ari} f_2 + h_{ai}^H f_2 \right)^2 + 1}, i \in \{b, e_k\} \]

Solve the sub-problems by applying SDR with SCA.
Consider two setups, corresponding to the cases with local and remote Eves from IRS.

As $P_{\text{max}}$ increases, the AN-aided designs outperform their counterparts without AN.

Using AN is still helpful with IRS, especially for the case of local Eves (setup (a)).
IRS-aided SWIPT

IRS-aided SWIPT

- IRS controller
- Information flow
- Energy flow
- Wireless control link

- AP
- IDR
- IRS

- Information signals can be exploited for energy harvesting
- Fundamental question: dedicated energy beamforming or not?

- SWIPT bottleneck: low energy efficiency of far-field WPT
- Compensate high RF signal attenuation over long distance with IRS’s intelligent signal reflection using a large aperture
  - Create an effective energy harvesting/charging zone
- Objective: maximize the weighted sum received RF power at EHRs subject to SINR constraints at IDR via joint transmit and reflect beamforming optimization
Problem Formulation and Fundamental Result

- **Special case: WPT only**

\[
\begin{aligned}
\max_{\{v_j\}, \theta} & \quad \sum_{j \in \mathcal{K}_E} v_j^H S v_j \\
\text{s.t.} & \quad \sum_{j \in \mathcal{K}_E} \|v_j\|^2 \leq P, \\
& \quad 0 \leq \theta_n \leq 2\pi, \forall n \in \mathcal{N}.
\end{aligned}
\]

\[S = \sum_{j \in \mathcal{K}_E} \alpha_j g_j g_j^H\]

- **General case: SWIPT**

\[
\begin{aligned}
\max_{\{w_i\}, \{v_j\}, \theta} & \quad \sum_{i \in \mathcal{K}_I} w_i^H S w_i + \sum_{j \in \mathcal{K}_E} v_j^H S v_j \\
\text{s.t.} & \quad \text{SINR}_i \geq \gamma_i, \forall i \in \mathcal{K}_I, \\
& \quad \sum_{i \in \mathcal{K}_I} \|w_i\|^2 + \sum_{j \in \mathcal{K}_E} \|v_j\|^2 \leq P, \\
& \quad 0 \leq \theta_n \leq 2\pi, \forall n \in \mathcal{N}.
\end{aligned}
\]

\[\text{SINR}_i = \frac{|h_i^H w_i|^2}{\sum_{k \neq i, k \in \mathcal{K}_I} |h_i^H w_k|^2 + \sum_{j \in \mathcal{K}_E} |h_i^H v_j|^2 + \sigma_i^2}\]

- **Alternating optimization with SCA or SDR**

- **General result for SWIPT:** Dedicated energy signals are not required, for arbitrary user channels, i.e., \(v_j = 0, \forall j \in \mathcal{K}_E\)
Deploying IRS in line-of-sight with AP is beneficial for improving WPT efficiency

- Different from IRS deployment for information transmission, DoF vs beamforming gain

- Significantly improve the achievable power-SINR (energy-rate) region for SWIPT

- Sending dedicated energy beam suffers considerable performance loss
IRS-aided SWIPT: QoS-Constrained Beamforming Design

- **Smart IoT networks**
  - Establish both communication and energy hot spots by using multiple IRSs
  - Guarantee QoS for both IUs and EUs
- **Objective:** minimize the transmit power at the AP subject to both SINR constraints at IUs and energy harvesting constraints at EUs via joint transmit and reflect beamforming optimization

- Strong coupling between optimization variables in QoS constraints
- Many QoS constraints render alternating optimization easily get stuck at local optimum
Problem Formulation and Penalty-based Algorithm

- **Optimization problem**

\[
\begin{align*}
\min_{\{w_i\},\{v_j\},\theta} & \sum_{i \in \mathcal{K}_I} \|w_i\|^2 + \sum_{j \in \mathcal{K}_E} \|v_j\|^2 \\
\text{s.t.} & \frac{|(h_{r,i}^H \Theta F + h_{d,i}^H) w_i|^2}{\sum_{k \neq i, k \in \mathcal{K}_I} |(h_{r,k}^H \Theta F + h_{d,k}^H) w_k|^2 + \sigma_i^2} \geq \gamma_i, \forall i \in \mathcal{K}_I, \\
& \sum_{i \in \mathcal{K}_I} |(g_{r,j}^H \Theta F + g_{d,j}^H) v_i|^2 + \sum_{m \in \mathcal{K}_E} |(g_{r,j}^H \Theta F + g_{d,j}^H) v_m|^2 \geq E_j, \forall j \in \mathcal{K}_E, \\
& 0 \leq \theta_n \leq 2\pi, \forall n \in \mathcal{N},
\end{align*}
\]

- **Equivalent transformation**

\[
\begin{align*}
\min_{\{w_i\},\{v_j\},\theta} & \sum_{i \in \mathcal{K}_I} \|w_i\|^2 + \sum_{j \in \mathcal{K}_E} \|v_j\|^2 \\
\text{s.t.} & \frac{|x_{i,i}|^2}{\sum_{k \neq i, k \in \mathcal{K}_I} |x_{i,k}|^2 + \sigma_i^2} \geq \gamma_i, \forall i \in \mathcal{K}_I, \quad (1) \\
& \sum_{i \in \mathcal{K}_I} |s_{j,i}|^2 + \sum_{m \in \mathcal{K}_E} |t_{j,m}|^2 \geq E_j, \forall j \in \mathcal{K}_E, \quad (2) \\
& h_i^H w_k = x_{i,k}, i, k \in \mathcal{K}_I, \\
& g_j^H w_i = s_{j,i}, g_j^H v_m = t_{j,m}, i \in \mathcal{K}_I, j, m \in \mathcal{K}_E, \quad (3)
\end{align*}
\]

- New penalty-based method to decouple QoS constraints
- Block coordinate descent
- (Semi) closed-form solutions for variables in each block
Simulation Setup and Convergence

- 3D coordinate system
- Spherical-wave model
- IU cluster and EU cluster
- Converged solution satisfies all the QoS constraints
### IRS-aided WPT

- As $K_E$, i.e., number of QoS constraints increases, **proposed penalty method** achieves higher gain than alternating optimization
- Favorable high user channel correlation achieved by
  - Tuning IRS phase shifts
  - Proper IRS deployment, LoS better than Rayleigh fading
- IRS helps
  - reduce the transmit power
  - reduce the number of energy beams and simplify AP transmission

#### TABLE I

**RESULTS ON THE NUMBER OF ENERGY BEAMS REQUIRED: WITH (W/) IRS VERSUS WITHOUT (W/O) IRS**

<table>
<thead>
<tr>
<th></th>
<th>w/ IRS (LoS $F$)</th>
<th>w/ IRS (Rayleigh-fading $F$)</th>
<th>w/o IRS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$d_E = 1$</td>
<td>$d_E = 1$</td>
<td>$d_E = 1$</td>
</tr>
<tr>
<td>$K_E = 10$</td>
<td>500</td>
<td>499</td>
<td>73</td>
</tr>
<tr>
<td>$K_E = 30$</td>
<td>500</td>
<td>205</td>
<td>0</td>
</tr>
<tr>
<td>$K_E = 40$</td>
<td>500</td>
<td>62</td>
<td>0</td>
</tr>
</tbody>
</table>

- W/O IRS
  - more EUs ➔ more energy beams
- W/ IRS
  - only one beam!
- IRS acts as a master EU

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Without IRS: dedicated energy beamforming is effective

With IRS: dedicated energy beamforming gain is marginal (thus not needed)

- exploit information beamforming leakage to the IRS for WPT
- simplify the transmitter (energy beamforming) and receiver (energy signal cancellation) operations for implementing dedicated energy beamforming
UAV-mounted IRS

Aerial IRS vs Terrestrial IRS

**Terrestrial IRS**
- 180 half-space reflection only
- Multiple reflections required due to NLoS
- Constrained deployment

**Aerial IRS**
- 360° panoramic full-angle reflection
- One reflection suffices due to LoS
- Flexible deployment

360° panoramic full-angle reflection by AIRS

Reduced number of reflections by AIRS
The placement of AIRS can be flexibly optimized to further improve the communication performance.

**Objective:** maximize the minimum SNR within the rectangular area by jointly optimizing the transmit beamforming of the source node, the placement and phase shifts of the AIRS.

- The objective function is the minimum SNR over a 2D area, which is difficult to be expressed in terms of the optimization variables.
- The optimization problem is highly non-convex and the optimization variables are intricately coupled with each other in the objective function.
Problem Formulation and Solution

Problem formulation

- Transmit beamforming at the source node: \( \mathbf{v} \)
- AIRS placement: \( \mathbf{q} \)
- AIRS phase shifts: \( \theta \)
- Destination node location: \( \mathbf{w} \)

Two-step optimization

First step:

\[
\max_{\theta} \min_{\mathbf{w} \in \mathcal{A}} f_1(\mathbf{q}, \theta, \mathbf{w})
\]  
\[
\text{s.t. } 0 \leq \theta_n \leq 2\pi, \; n = 1, \cdots, N.
\]

\[
f_1(\mathbf{q}, \theta, \mathbf{w}) \triangleq \left| \sum_{n=1}^{N} e^{j(\theta_n + 2\pi (n-1)d(\phi_T(\mathbf{q}, \mathbf{w}) - \phi_R(\mathbf{q})))} \right|^2 \quad \text{Array gain}
\]

Second step:

\[
\max_{\mathbf{q}} \min_{\mathbf{w} \in \mathcal{A}} \frac{f_1(\mathbf{q}, \theta^*(\mathbf{q}), \mathbf{w})}{f_2(\mathbf{q}, \mathbf{w})}
\]

\[
f_2(\mathbf{q}, \mathbf{w}) \triangleq \left( H^2 + \|\mathbf{q} - \mathbf{w}\|^2 \right) \left( H^2 + \|\mathbf{w}\|^2 \right) \quad \text{Concatenated path loss}
\]
Outline

- Part 1: Introduction of Intelligent Reflecting Surface (IRS)
- Part 2: Overview of IRS Communication Design Challenges
- Part 3: Selected Results for IRS-aided Wireless Network
- Part 4: Conclusions and Future Directions
Conclusions

- IRS: a new and disruptive technology to achieve smart and reconfigurable propagation environment for future wireless network

- Achieve high spectral/energy efficiency with low-cost passive reflecting elements

- A paradigm shift of wireless communication from traditional “active component solely” to the new “active and passive” hybrid network

- Main challenges (from the communications perspective):
  - IRS reflection optimization
  - IRS channel estimation
  - IRS deployment
Promising Directions for Future Work

- IRS hardware design/prototype
- IRS reflection/channel modeling
- IRS reflection optimization for more general setups (e.g., with partial/imperfect CSI, under hardware imperfections) and other applications (spatial modulation, localization, etc.)
- Capacity and performance analysis of IRS-aided system/network
- Practical IRS channel estimation and low-complexity passive beamforming designs
- IRS deployment/association/multiple access in multi-cell network
- IRS meets massive MIMO, mmWave/THz, energy harvesting, UAV, security, wireless power transfer, etc.
- IRS integration to WiFi/Cellular
- ......