Intelligent Reflecting Surface Aided Wireless Communication: Opportunities and Challenges

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Outline

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

- Communication Design Challenges
  - IRS reflection optimization
  - IRS channel estimation
  - IRS deployment

- Other Applications/Extensions

- Conclusion and Future Work
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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 \( H \ll 1 \) to \( H \to 1 \)?
  - 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
\[ \beta_n \in [0, 1] : \text{reflection amplitude} \]
\[ \theta_n \in [0, 2\pi) : \text{phase shift} \]
\[ N : \text{No. of elements} \]

- In practice, both amplitude and phase shift need to be discretized

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

- **Baseband equivalent channel model (narrow-band)**
  - Assume isotropic reflection, and no mutual coupling among reflecting elements
  
  \[
  y = \left( \sum_{n=1}^{N} h_n g_n e^{j\theta_n} \right) x + z
  \]

- **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**

  - $x$: transmitted signal
  - $y$: received signal
  - $h_n$: first link channel
  - $g_n$: second link channel
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 beamforming
- Interference nulling/cancellation
- ...

IRS functions

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-enabled Passive Beamforming

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

IRS-assisted Interference Nulling/Cancelation

- Enhance desired signal power while nulling the reflected 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
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
Wireless Network with IRS vs w/o IRS: System Setup

- 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: \( \zeta \triangleq \frac{\lambda_I}{\lambda_B} \)
  - Cost of each BS: \( C_0 \), BS/IRS cost ratio: \( \frac{K_N}{K_N} \)
  - Total cost \( C \) per \( m^2 \) in the hybrid network:
    \[
    C \triangleq \lambda_B c_0 + \frac{\lambda I c_0}{K_N} = \lambda B c_0 \left(1 + \frac{\zeta}{K_N}\right)
    \]

- **\( \nu \) 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 \( C \to \) cost-effective and sustainable capacity growth
Comparison with existing technologies

IRS vs Massive MIMO/Active Large Surface

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**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)

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**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

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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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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**: $\mathcal{O}(N^2)$
  - Thanks to the dual role of “receive” and “reflect” (full-duplex, noise-free), in contrast to $\mathcal{O}(N)$ of massive MIMO (limited by sum-power constraint at Tx), and $\mathcal{O}(N)$ 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: $w$
- Reflect beamforming: $\Theta$

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

$$\min_{w, \theta} \| w \|^2$$

s.t.  $$|(h_r^H \Theta G + h_d^H)w|^2 \geq \gamma \sigma^2,$$

$$0 \leq \theta_n \leq 2\pi, \forall n = 1, \cdots, N.$$

Simulation setup

- Significant power saving with IRS (vs w/o IRS)
- Performance gain of joint transmit and reflect beamforming design (vs AP-user MRT or AP-IRS MRT benchmarks)
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

Minimum AP transmit Power vs User SINR Target

- Multi-user problem formulation

\[
\min_{W, \theta} \sum_{k=1}^{K} \|w_k\|^2 \\
\text{s.t.} \quad \frac{|(h_{r,k}^H \Theta G + h_{d,k}^H)w_k|^2}{\sum_{j \neq k} |(h_{r,k}^H \Theta G + h_{d,k}^H)w_j|^2 + \sigma_k^2} \geq \gamma_k, \forall k; \\
0 \leq \theta_n \leq 2\pi, \forall n = 1, \cdots, N,
\]

Simulation setup

- Special two-user case: one user near IRS and the other user far from IRS

- Significant power saving at AP with vs. w/o IRS
- Two algorithms proposed: Alternating optimization or two-stage algorithm (details omitted here)
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).
IRS: Practical 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

- Reflection coefficient at each IRS element

\[ u_n = \beta_n(\theta_n)e^{j\theta_n} \quad n = 1, \ldots, N \]

where

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

- Generally applicable to a variety of semiconductor devices used for implementing the IRS
Achievable Rate with Practical vs Ideal Model

- Single-user problem formulation
- Transmit beamforming: $\mathbf{w}$; Reflect beamforming: $\mathbf{v}$
- Suboptimal solution obtained via alternating optimization (AO)

\[
\max_{\mathbf{w}, \mathbf{v}, \{\theta_n\}} \left| (\mathbf{h}_r^H \text{diag}(\mathbf{v}) \mathbf{G} + \mathbf{h}_d^H) \mathbf{w} \right|^2 \\
\text{s.t. } \|\mathbf{w}\|_2^2 \leq P_T, \\
\quad v_n = \beta_n(\theta_n)e^{j\theta_n}, \forall n = 1, \ldots, N, \\
\quad -\pi \leq \theta_n \leq \pi, \forall n = 1, \ldots, N,
\]
Selected Work on IRS Reflection Optimization

- **Power minimization**

- **Energy efficiency maximization**

- **Rate maximization**

- **IRS-aided OFDM**

- **IRS-aided MIMO**

- **IRS optimization with discrete phase/hardware imperfection**
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 (codebook-based)

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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 reflection design** for training (e.g., DFT/Hadamard matrix) to resolve different user channels, nearly orthogonal for practical discrete phase

- **IRS elements grouping**: divide IRS elements into adjacent groups with common phase shift per group to exploit channel correlation and reduce training/passive 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 for large-size groups (for initial connection) and gradually refine channel estimation for smaller-size groups to improve beamforming gains (for high-rate data transmission)
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

- **IRS beamforming searching**
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:
  \[ \rho_D = \frac{P \beta_0^3 N^4}{16 H^4 D^2 \sigma^2} \]

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

- **Distributed deployment**: Deploy $N_k$ elements near each user $k$, $\sum_{k=1}^{K} N_k = N$
  - 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 $O(N_k^2)$ beamforming gain for each user

**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.

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Selected Work on IRS Deployment

- **Double/cooperative IRS**

- **Centralized vs distributed IRS**

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

- **IRS deployment based on machine learning**
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Conclusions and Future Work
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:
  \[
  \begin{align*}
  \text{(N1): } & \min_{\theta, P_1, P_2} P_1 + P_2, \\
  & \text{s.t. } \log_2 (1 + \frac{P_1 \lambda_1(\theta)}{\sigma^2}) \geq \gamma_1 \\
  & \log_2 (1 + \frac{P_2 \lambda_2(\theta)}{\sigma^2}) \geq \gamma_2 \\
  & \theta_m \in \mathcal{F}, \forall m = 1, \ldots, M \\
  \end{align*}
  \]
  \[
  \begin{align*}
  \text{(N2): } & \min_{\theta, P_1, P_2} P_1 + P_2, \\
  & \text{s.t. } \log_2 (1 + \frac{P_1 \lambda_1(\theta)}{\sigma^2}) \geq \gamma_1 \\
  & \log_2 (1 + \frac{P_2 \lambda_2(\theta)}{\sigma^2}) \geq \gamma_2 \\
  & \theta_m \in \mathcal{F}, \forall m = 1, \ldots, M \\
  \end{align*}
  \]

- 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

- Problem formulation for FDMA:
  \[
  \begin{align*}
  \text{(F1): } & \min_{\theta, P_1, P_2} P_1 + P_2, \\
  & \text{s.t. } \frac{1}{2} \log_2 (1 + \frac{P_1 \lambda_1(\theta)}{\sigma^2}) \geq \gamma_1 \\
  & \frac{1}{2} \log_2 (1 + \frac{P_2 \lambda_2(\theta)}{\sigma^2}) \geq \gamma_2 \\
  & \theta_m \in \mathcal{F}, \forall m = 1, \ldots, M \\
  \end{align*}
  \]

- Frequency-flat IRS reflection

- Problem formulation for TDMA:
  \[
  \begin{align*}
  \text{(T1): } & \min_{\theta_1, \theta_2, P_1, P_2} P_1 + P_2, \\
  & \text{s.t. } \frac{1}{2} \log_2 (1 + \frac{2P_1 \lambda_1(\theta_1)}{\sigma^2}) \geq \gamma_1 \\
  & \frac{1}{2} \log_2 (1 + \frac{2P_2 \lambda_2(\theta_2)}{\sigma^2}) \geq \gamma_2 \\
  & \theta_{k,m} \in \mathcal{F}, \forall m = 1, \ldots, M, k \in \{1, 2\} \\
  \end{align*}
  \]

- Time-selective IRS reflection

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

Mathematical formulation:

$$R_k = \frac{1}{NQ} \sum_{q=1}^{Q} \sum_{n=1}^{N} \alpha_{k,q,n} \log_2 \left( 1 + \frac{\|f_n h^d_k + f_n V_k \phi_q\|^2 p_{q,n}}{\Gamma \sigma^2} \right)$$

$$\begin{align*}
(P1) \quad & \max_{\{\alpha_{k,q,n}\}, \{p_{q,n}\}, \{\phi_q\}} R_k \\
\text{s.t.} & \quad R_k \geq R, \quad \forall k \in K \\
& \quad \sum_{k=1}^{K} \alpha_{k,q,n} \leq 1, \quad \forall q \in Q, \forall n \in N \\
& \quad \alpha_{k,q,n} \in \{0, 1\}, \quad \forall k \in K, \forall q \in Q, \forall n \in N \\
& \quad \sum_{n=1}^{N} p_{q,n} \leq P, \quad \forall q \in Q \\
& \quad p_{q,n} \geq 0, \quad \forall q \in Q, \forall n \in N \\
& \quad |\phi_{q,m}| \leq 1, \quad \forall q \in Q, \forall m \in M.
\end{align*}$$

Graphs and diagrams illustrate the comparison between dynamic beamforming, fixed beamforming, and random phase, as well as the common rate (bps/Hz) variations with different numbers of reflecting elements ($M$) and time slots ($Q$).
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**:

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

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

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

  which is solved by using the alternating optimization technique.
IRS-aided Spectrum Sharing: Simulation Results

- IRS significantly improves the secondary user rates, especially in scenario (d), where ST and PR are near the IRS.
IRS-aided PHY Security

IRS-aided Secure Wireless Communication

- **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: $q$

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

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

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

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

Suboptimal alternating optimization method

Sub-problem 1:
(optimal solution)

$$\max_w \frac{w^H Aw + 1}{w^H Bw + 1}$$

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

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

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

Sub-problem 2:
(approximate solution via SDR)

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

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

$$\frac{1}{\sigma_E^2}|(h_{IE}QH_{AI} + h_{AE})w|^2 + 1$$
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: \( \mathbf{f}_1 \)
- Jamming with AN: \( \mathbf{f}_2 \)
- IRS reflect beamforming: \( \mathbf{v} \)
- IRS reflected channel: \( \mathbf{H}_{ari} = \text{diag}\left( \mathbf{h}_{ri}^H \right) \mathbf{H}_{ar} \)

\[
R_i = \log \left( 1 + \frac{\gamma_0 \left( \mathbf{v}^H \mathbf{H}_{ari} + \mathbf{h}_{ai}^H \right) \mathbf{f}_1^2}{\gamma_0 \left( \mathbf{v}^H \mathbf{H}_{ari} + \mathbf{h}_{ai}^H \right) \mathbf{f}_2^2 + 1} \right), i \in \{b, e_k\}
\]

\[
\max_{\mathbf{f}_1, \mathbf{f}_2, \mathbf{v}} \left\{ R_b - \max_k R_{e_k} \right\}
\]

s.t. \( \mathbf{f}_1^H \mathbf{f}_1 + \mathbf{f}_2^H \mathbf{f}_2 \leq P_{\text{max}}, \) \( |\mathbf{v}_n| = 1, \forall n. \)

❑ Alternating optimization

Sub-problem 1: optimizing \( (\mathbf{f}_1, \mathbf{f}_2) \) for given \( \mathbf{v} \)

\[
\max_{\mathbf{f}_1, \mathbf{f}_2} \log \left[ 1 + \gamma_b \left( \mathbf{f}_1, \mathbf{f}_2 \right) \right] - \max_k \log \left[ 1 + \gamma_{ek} \left( \mathbf{f}_1, \mathbf{f}_2 \right) \right]
\]

s.t. \( \mathbf{f}_1^H \mathbf{f}_1 + \mathbf{f}_2^H \mathbf{f}_2 \leq P_{\text{max}}. \)

\[
\gamma_i (\mathbf{f}_1, \mathbf{f}_2) = \frac{\gamma_0 \left( \mathbf{v}^H \mathbf{H}_{ari} + \mathbf{h}_{ai}^H \right) \mathbf{f}_1^2}{\gamma_0 \left( \mathbf{v}^H \mathbf{H}_{ari} + \mathbf{h}_{ai}^H \right) \mathbf{f}_2^2 + 1}, i \in \{b, e_k\}
\]

Sub-problem 2: optimizing \( \mathbf{v} \) for given \( (\mathbf{f}_1, \mathbf{f}_2) \)

\[
\max_{\mathbf{v}} \log \left[ 1 + \gamma_b (\mathbf{v}) \right] - \max_k \log \left[ 1 + \gamma_{ek} (\mathbf{v}) \right]
\]

s.t. \( |\mathbf{v}_n| = 1, \forall n. \)

\[
\gamma_i (\mathbf{v}) = \frac{\gamma_0 \left( \mathbf{v}^H \mathbf{H}_{ari} \mathbf{f}_1 + \mathbf{h}_{ai}^H \mathbf{f}_1 \right)^2}{\gamma_0 \left( \mathbf{v}^H \mathbf{H}_{ari} \mathbf{f}_2 + \mathbf{h}_{ai}^H \mathbf{f}_2 \right)^2 + 1}, i \in \{b, e_k\}
\]

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

- 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 s via joint transmit and reflect beamforming optimization
Problem Formulation and Fundamental Result

- Special case: WPT only

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

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

- General case: SWIPT

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

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

- 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**

\[
\min_{\{w_i\},\{v_j\},\theta} \sum_{i \in \mathcal{K}_I} \|w_i\|^2 + \sum_{j \in \mathcal{K}_E} \|v_j\|^2 \\
\text{s.t.} \left(\begin{array}{l}
\sum_{k \neq i, k \in \mathcal{K}_I} |(h_{r,i}^H \Theta F + h_{d,i}^H)w_i|^2 \\
\sum_{i \in \mathcal{K}_I} |(g_{r,j}^H \Theta F + g_{d,j}^H)w_i|^2 \\
0 \leq \theta_n \leq 2\pi, \forall n \in \mathcal{N},
\end{array}\right)
\]

- **Equivalent transformation**

\[
\min_{\{w_i\},\{v_j\},\theta,\{x_{i,k}, s_{j,i}, t_{j,m}\}} \sum_{i \in \mathcal{K}_I} \|w_i\|^2 + \sum_{j \in \mathcal{K}_E} \|v_j\|^2 \\
\text{s.t.} \left(\begin{array}{l}
\sum_{k \neq i, k \in \mathcal{K}_I} |x_{i,k}|^2 + \sigma_i^2 \geq \gamma_i, \forall i \in \mathcal{K}_I, \quad (1) \\
\sum_{j \in \mathcal{K}_E} |s_{j,i}|^2 + \sum_{m \in \mathcal{K}_E} |t_{j,m}|^2 \geq E_j, \forall j \in \mathcal{K}_E, \quad (2) \\
h_i^H w_k = x_{i,k}, i, k \in \mathcal{K}_I, \\
g_j^H w_i = s_{j,i}, g_j^H v_m = t_{j,m}, i \in \mathcal{K}_I, j, m \in \mathcal{K}_E, \\
0 \leq \theta_n \leq 2\pi, \forall n \in \mathcal{N}. \quad (3)
\right)
\]

- **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**

<table>
<thead>
<tr>
<th>$K_E$</th>
<th>$d_E = 1$</th>
<th>$d_E = 2$</th>
<th>$d_E = 3$</th>
<th>$d_E = 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_E = 10$</td>
<td>500</td>
<td>499</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$K_E = 30$</td>
<td>500</td>
<td>205</td>
<td>294</td>
<td>1</td>
</tr>
<tr>
<td>$K_E = 40$</td>
<td>500</td>
<td>62</td>
<td>415</td>
<td>23</td>
</tr>
</tbody>
</table>

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

- 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
Optimal Aerial IRS Placement

- AIRS-assisted communication system: enabling intelligent reflection from the sky
- Enhance signal coverage over a given target area

- 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:**
  \[
  \max_{\theta} \min_{\mathbf{w} \in \mathcal{A}} f_1 (\mathbf{q}, \theta, \mathbf{w})
  \]
  \[
  \text{s.t. } 0 \leq \theta_n \leq 2\pi, \ n = 1, \cdots, N.
  \]
  \[
  f_1 (\mathbf{q}, \theta, \mathbf{w}) \triangleq \left| \sum_{n=1}^{N} e^{j(\theta_n + 2\pi(n-1)d(\phi_T(q, w) - \phi_R(q)))} \right|^2 \text{ Array gain}
  \]

  **Second step:**
  \[
  \max_{\mathbf{q}} \min_{\mathbf{w} \in \mathcal{A}} \frac{f_1 (\mathbf{q}, \theta^* (\mathbf{q}), \mathbf{w})}{f_2 (\mathbf{q}, \mathbf{w})}
  \]
  \[
  f_2 (\mathbf{q}, \mathbf{w}) \triangleq \left( H^2 + \|\mathbf{q} - \mathbf{w}\|^2 \right) \left( H^2 + \|\mathbf{q}\|^2 \right) \text{ Concatenated path loss}
  \]
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
- ......