IEEE GLOBECOM 2021

Intelligent Reflecting Surfaces and Classical Relays: Coexistence and Co-Design

Te-Yi Kan[1], Ronald Y. Chang[1], and Feng-Tsun Chien[2]

[1]Research Center for Information Technology Innovation, Academia Sinica, Taiwan
[2]Institute of Electronics, National Yang Ming Chiao Tung University, Taiwan

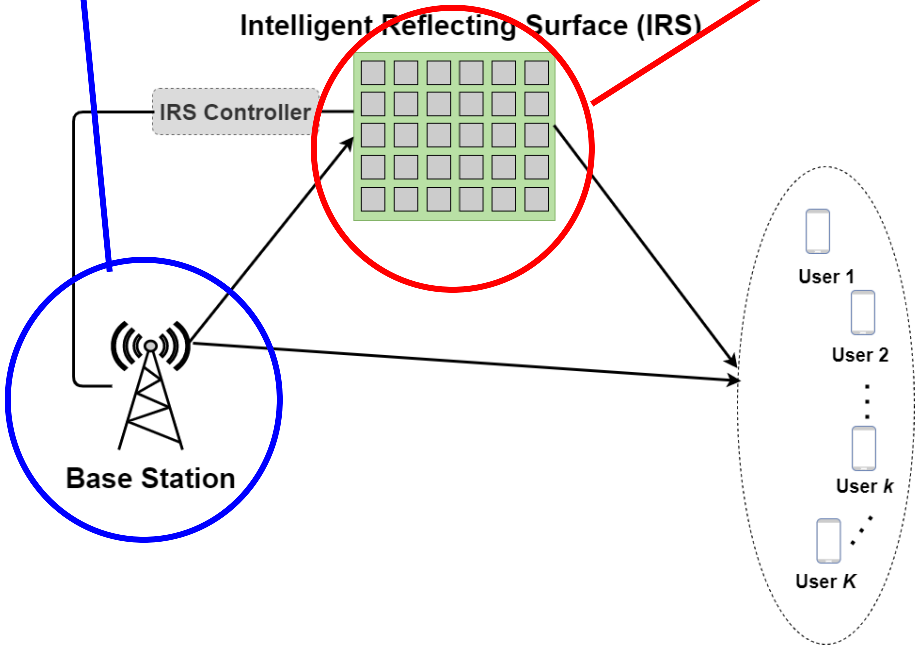
What is *Intelligent Reflecting Surfaces (IRSs)* ?

- IRSs employ low-cost ***passive*** elements to ***reflect*** signals.
- IRSs operate in a ***full-duplex*** manner.
- Operating IRSs eases ***signal processing*** and ***interference management*** requirements.

Key Limitations – existing works

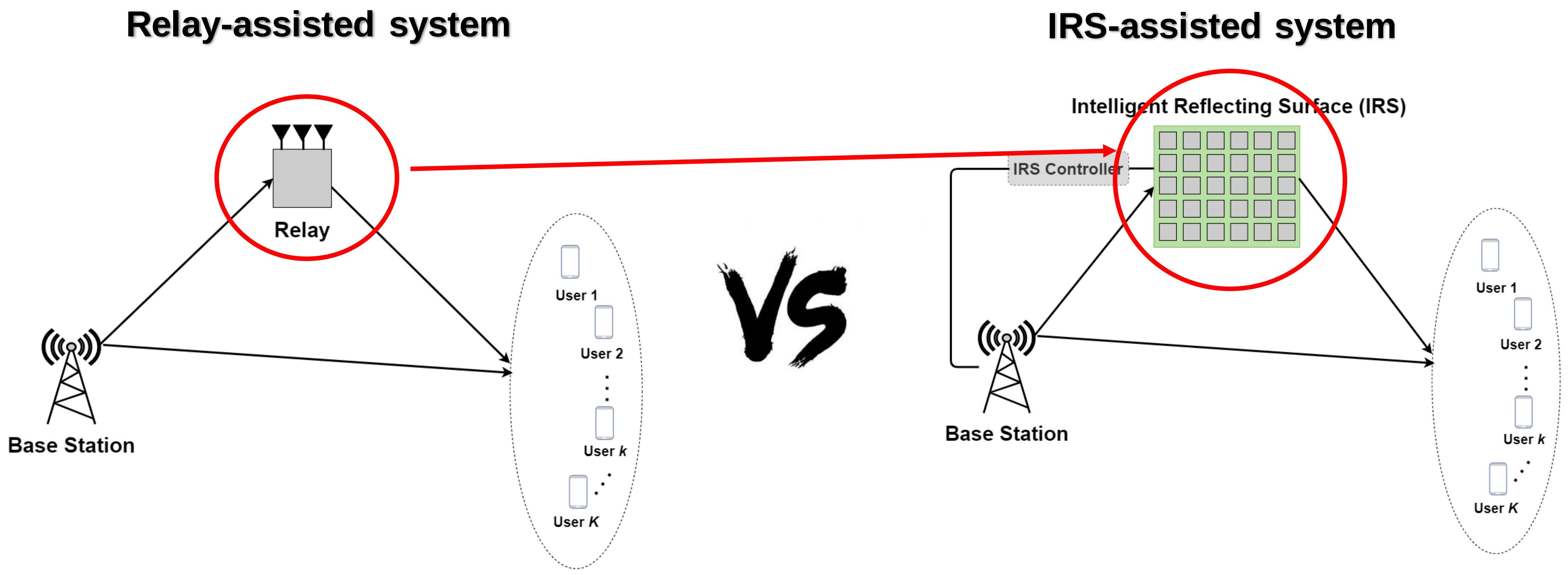
Joint Beamforming Design

transmit beamforming & IRS phase shifts



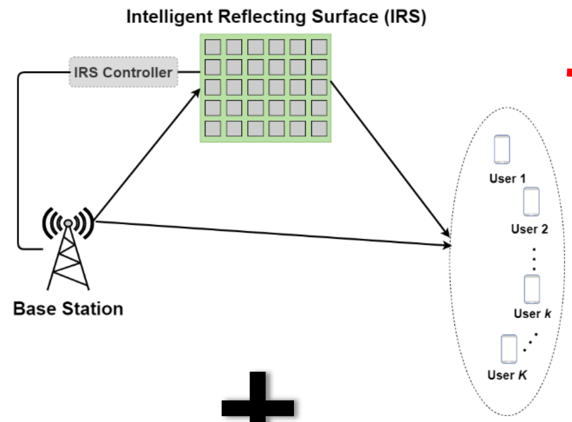
Key Limitations – existing works (cont.)

Differences? Similarities?

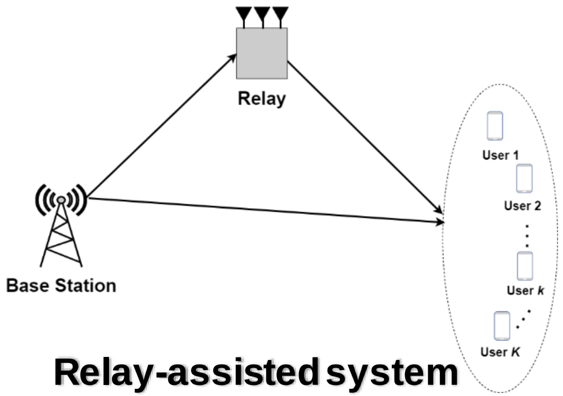


Motivations

IRS-assisted system



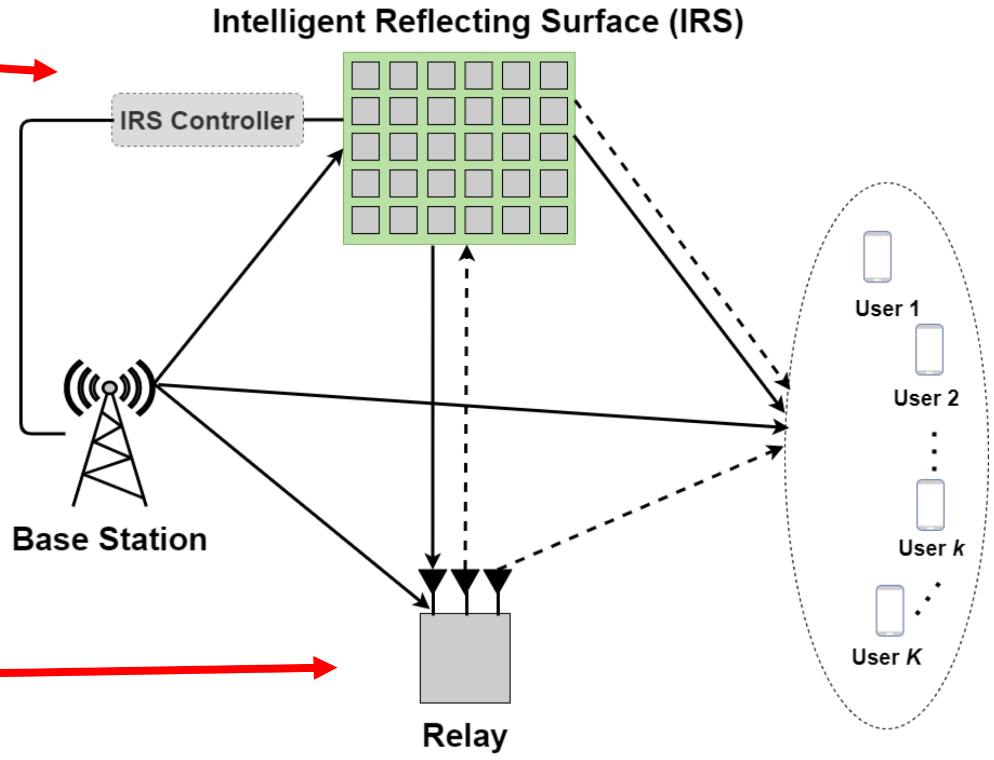
+



Relay-assisted system

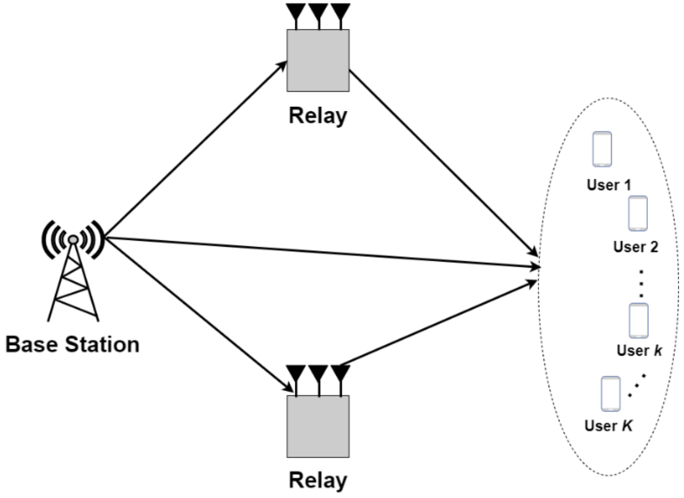
Sounds interesting!
Give it a try!

Coexisting IRS-relay assisted system

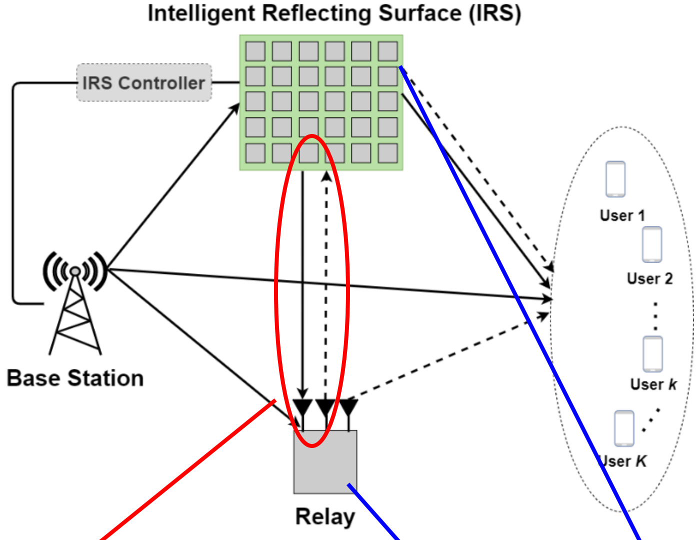


What's new?

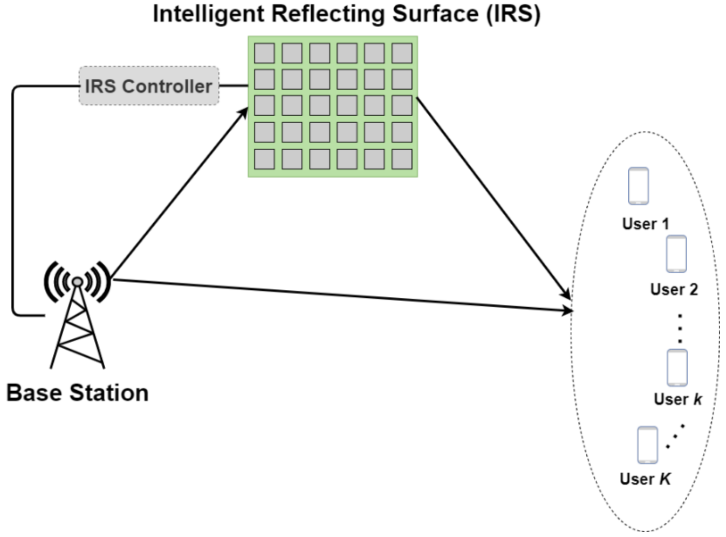
multi-relay system | **coexistence system** | **IRS-assisted system**



VS



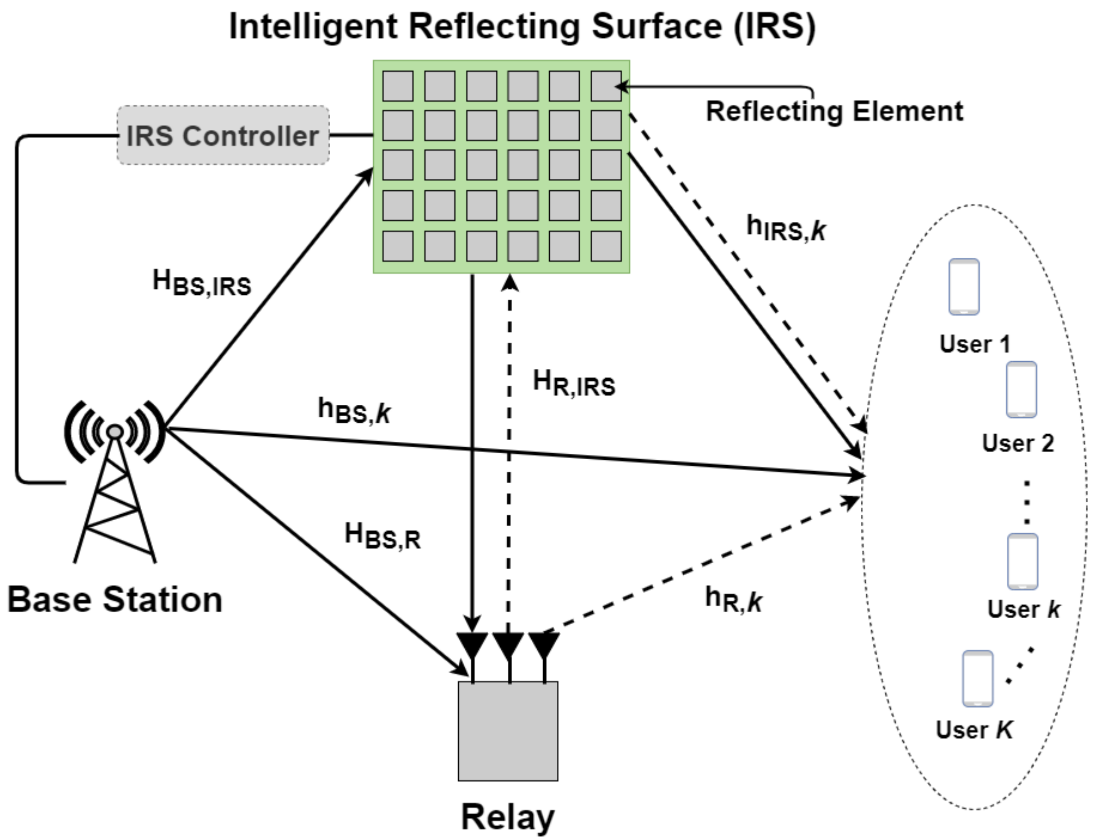
VS



interaction between IRS and relay

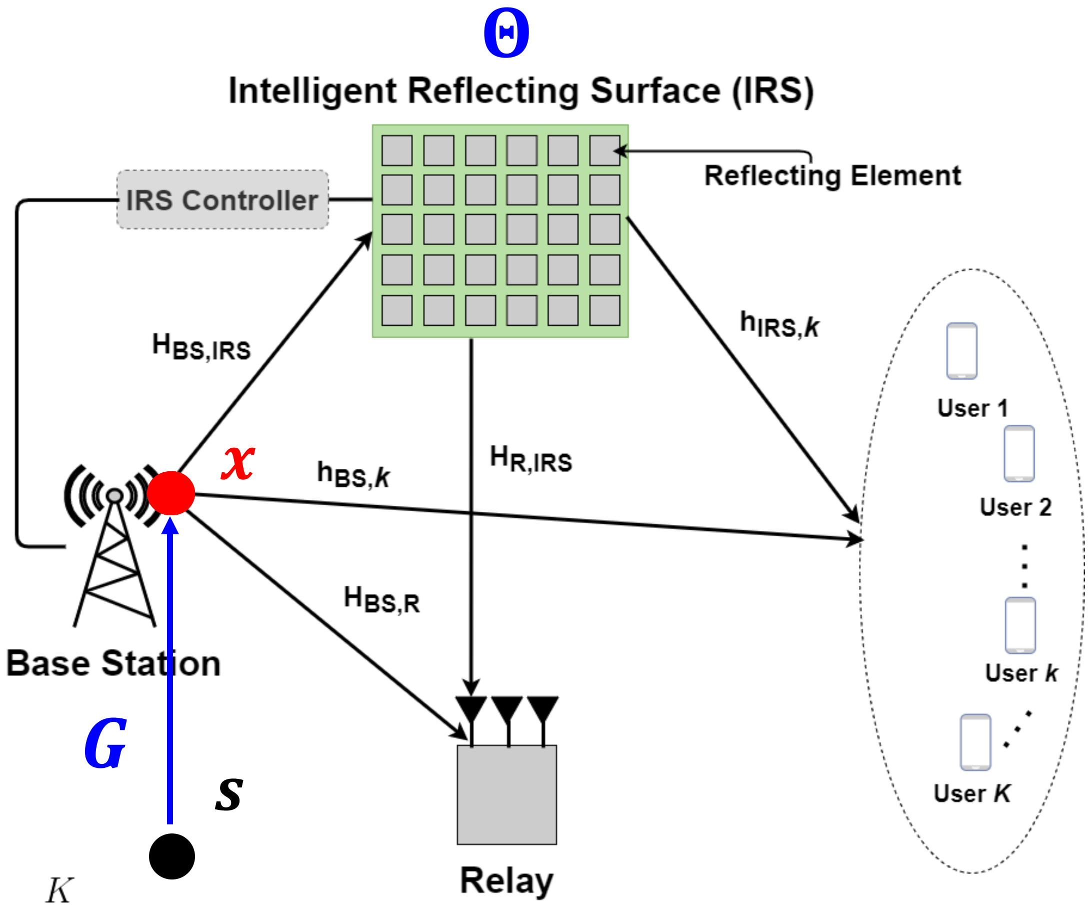
full-duplex relaying
+
half-duplex relaying

Coexisting IRS and relay assisted system



- Base station (BS) with ***M*** antennas
- DF relay with ***L*** antennas
- Ideal IRS with ***N*** reflecting elements
- ***K*** single-antenna end users
- IRS controller

Transmission – Phase I



$$\mathbf{x} = \sum_{k=1}^{K} \mathbf{g}_k s_k = \mathbf{G} \cdot \mathbf{s}$$

first phase received signal

IRS-assisted link · noise · direct link

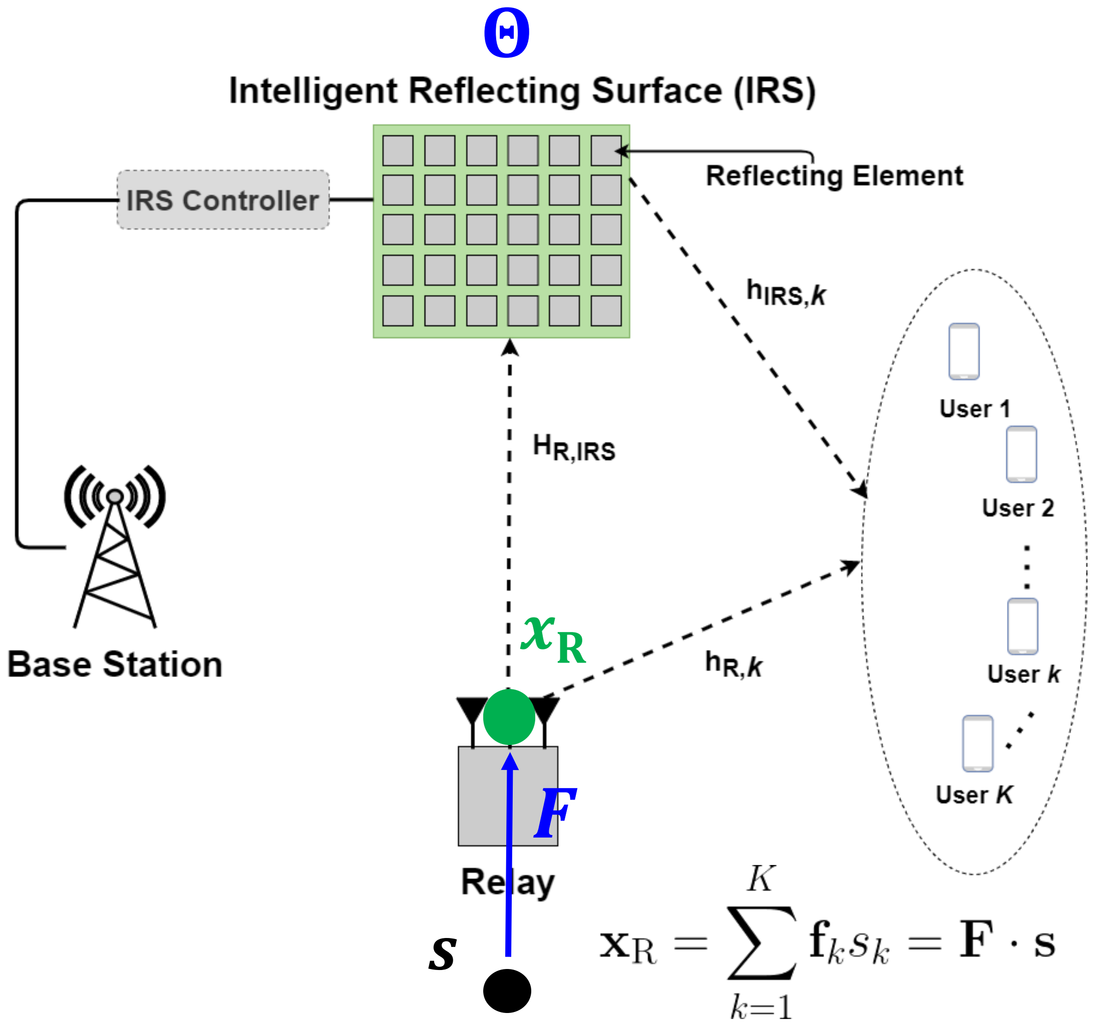
$$y_k^{\mathrm{I}} = \mathbf{h}_{\mathrm{IRS},k}\mathbf{\Theta}\mathbf{H}_{\mathrm{BS,IRS}}\mathbf{x} + \mathbf{h}_{\mathrm{BS},k}\mathbf{x} + w_k^{\mathrm{I}}$$
$$= \mathbf{h}'_{\mathrm{BS},k}\mathbf{x} + w_k^{\mathrm{I}}$$

Relay received signal

IRS-assisted link · noise · direct link

$$y_{\mathrm{R}} = \mathbf{H}_{\mathrm{R,IRS}}{}^{\mathrm{H}}\mathbf{\Theta}\mathbf{H}_{\mathrm{BS,IRS}}\mathbf{x} + \mathbf{H}_{\mathrm{BS,R}}\mathbf{x} + \mathbf{w}_{\mathrm{R}}$$
$$= \mathbf{H}'_{\mathrm{BS,R}}\mathbf{x} + \mathbf{w}_{\mathrm{R}}$$

Transmission – Phase II



$$\mathbf{x}_\mathrm{R} = \sum_{k=1}^{K} \mathbf{f}_k s_k = \mathbf{F} \cdot \mathbf{s}$$

Second phase received signal

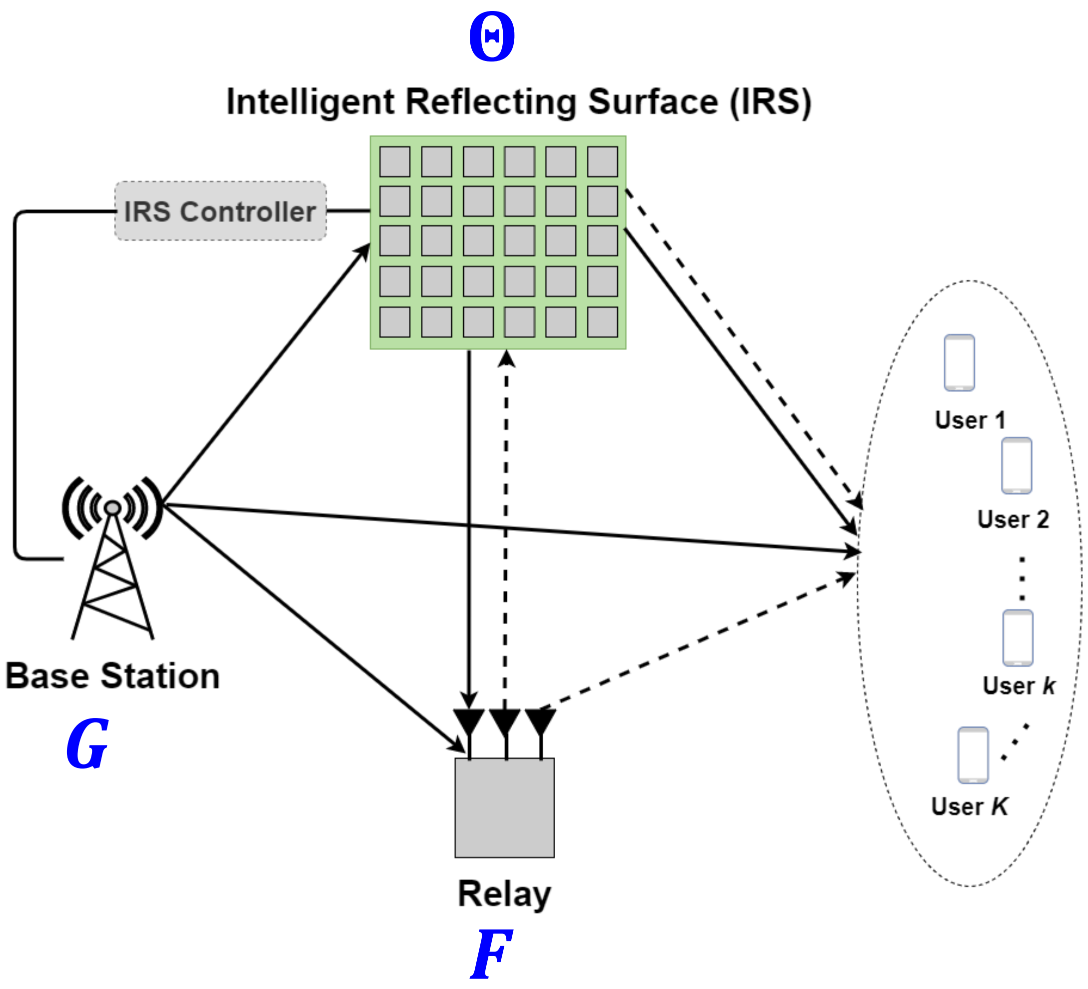
IRS-assisted link

noise

$$y_k^{\mathrm{II}} = \mathbf{h}_{\mathrm{IRS},k} \mathbf{\Theta} \mathbf{H}_{\mathrm{R,IRS}} \mathbf{x}_\mathrm{R} + \mathbf{h}_{\mathrm{R},k} \mathbf{x}_\mathrm{R} + w_k^{\mathrm{II}}$$
$$= \mathbf{h}'_{\mathrm{R},k} \mathbf{x}_\mathrm{R} + w_k^{\mathrm{II}}$$

direct link

Joint beamforming design Problem



Sum-rate maximization:

$$\max \sum_{k=1}^{K} \log_2 (1 + \gamma_k), \quad \gamma_k = \gamma_k^{\mathrm{I}} + \gamma_k^{\mathrm{II}}$$

second phase SINR

k-th user's SINR

first phase SINR

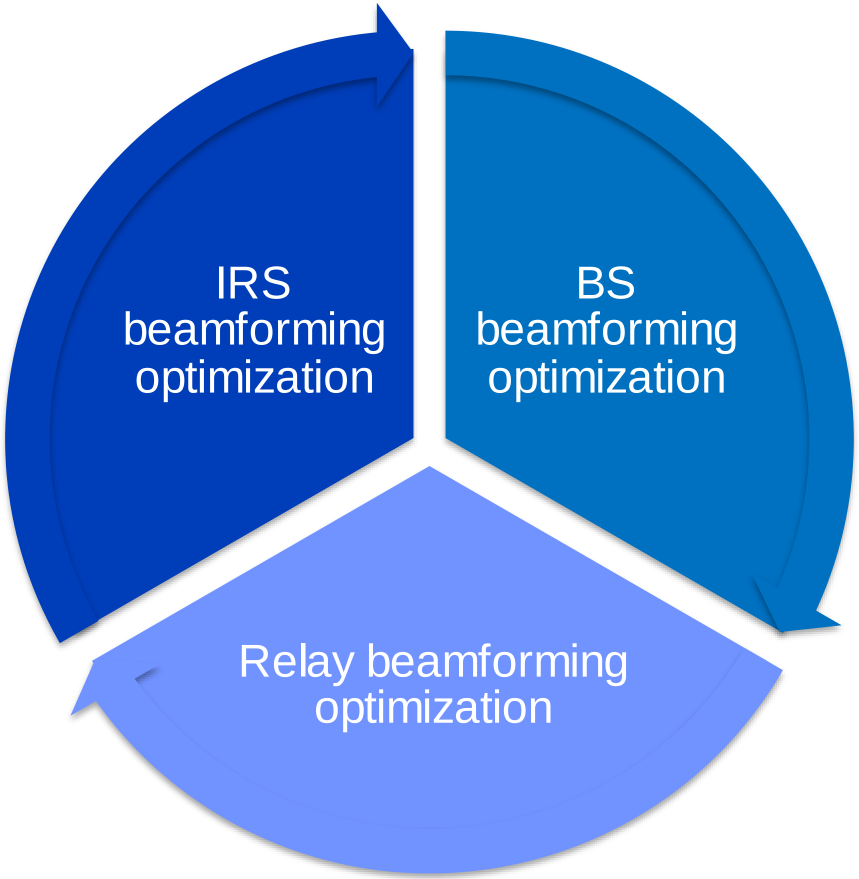
Variables:

- BS beamformer $\boldsymbol{G}$
- Relay beamformer $\boldsymbol{F}$
- IRS beamformer $\boldsymbol{\Theta}$

Constraints:

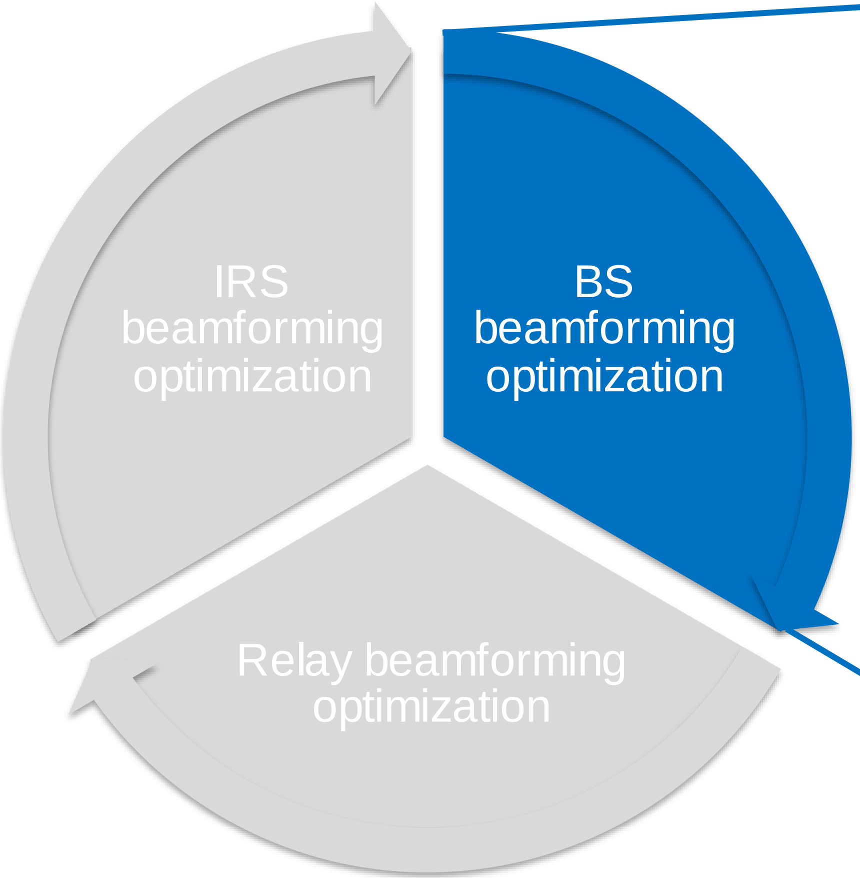
- BS power constraint
- Relay power constraint
- IRS reflection constraints $\mathrm{IRS}_{\mathrm{ideal}} \triangleq \{|\theta_n| \leq 1\}$
- Decoding SINR requirements (matched filter)

Proposed method



- Alternating optimization (AO)-based method
- Joint beamforming design is decoupled into 3 subproblems
  - BS beamforming
    - Optimizing BS beamformer $\boldsymbol{G}$
    - BS power constraint & decoding SINR requirements
  - Relay beamforming
    - Optimizing relay beamformer $\boldsymbol{F}$
    - relay power constraint
  - IRS beamforming
    - Optimizing IRS beamformer $\boldsymbol{\Theta}$
    - IRS reflection constraints & decoding SINR requirements

BS Beamforming Optimization



Introducing Slack Variables

↓

First-order Taylor Approximation

↓

Semidefinite Relaxation

Introducing Slack Variables

Introducing Slack Variables

First-order Taylor Approximation

Semidefinite Relaxation

$$\max \sum_{k=1}^{K} \log_2\left(1+\frac{\left|\mathbf{h}_{\mathrm{BS},k}'\mathbf{g}_k\right|^2}{\sum_{j=1,j\neq k}^{K}\left|\mathbf{h}_{\mathrm{BS},k}'\mathbf{g}_j\right|^2+\sigma_k^2}+\gamma_k^{\mathrm{II}}\right)$$

$$\Big\downarrow \; \mathbf{G}_k=\mathbf{g}_k\mathbf{g}_k^{\mathrm{H}}$$

$$\max \sum_{k=1}^{K} \log_2\left(1+\frac{\mathrm{tr}\left(\mathbf{h}_{\mathrm{BS},k}'^{\mathrm{H}}\mathbf{h}_{\mathrm{BS},k}'\mathbf{G}_k\right)}{\sum_{j=1,j\neq k}^{K}\mathrm{tr}\left(\mathbf{h}_{\mathrm{BS},k}'^{\mathrm{H}}\mathbf{h}_{\mathrm{BS},k}'\mathbf{G}_j\right)+\sigma_k^2}+\gamma_k^{\mathrm{II}}\right)$$

Introducing Slack Variables (cont.)

Introducing Slack Variables

First-order Taylor Approximation

Semidefinite Relaxation

$$\max \sum_{k=1}^{K} \log_2 \left(1 + \frac{\mathrm{tr}(\mathbf{h}'_{\mathrm{BS},k}{}^{\mathrm{H}} \mathbf{h}'_{\mathrm{BS},k} \mathbf{G}_k)}{\sum_{j=1,j\neq k}^{K} \mathrm{tr}(\mathbf{h}'_{\mathrm{BS},k}{}^{\mathrm{H}} \mathbf{h}'_{\mathrm{BS},k} \mathbf{G}_j) + \sigma_k^2} + \gamma_k^{\mathrm{II}}\right)$$

$$\downarrow$$

$$\max \sum_{k=1}^{K} R_{1,k}$$

$$R_{1,k} \leq \log_2 \left(1 + \frac{1}{\mathcal{S}_{1,k}\mathcal{I}_{1,k}} + \gamma_k^{\mathrm{II}}\right)$$

$$\frac{1}{\mathcal{S}_{1,k}} \leq \mathrm{tr}(\mathbf{h}'_{\mathrm{BS},k}{}^{\mathrm{H}} \mathbf{h}'_{\mathrm{BS},k} \mathbf{G}_k)$$

$$\mathcal{I}_{1,k} \geq \sum_{j=1,j\neq k}^{K} \mathrm{tr}(\mathbf{h}'_{\mathrm{BS},k}{}^{\mathrm{H}} \mathbf{h}'_{\mathrm{BS},k} \mathbf{G}_j) + \sigma_k^2$$

First-order Taylor Approximation

Introducing Slack Variables

First-order Taylor Approximation

Semidefinite Relaxation

$$R_{1,k} \leq \log_2\left(1 + \frac{1}{\mathcal{S}_{1,k}\mathcal{I}_{1,k}} + \gamma_k^{\mathrm{II}}\right)$$

Decoding SINR requirements

$$\frac{1}{\mathcal{S}_{\mathrm{R},k}\mathcal{I}_{\mathrm{R},k}} \geq \gamma_{\mathrm{R}}^{\mathrm{th}}$$

Convex function

- A convex function is ***lower bounded*** by its first-order Taylor approximation.
- We ***replace convex functions with thier first-order Taylor approximation*** to convexify constraints.

Semidefinite Relaxation

Introducing Slack Variables

↓

First-order Taylor Approximation

↓

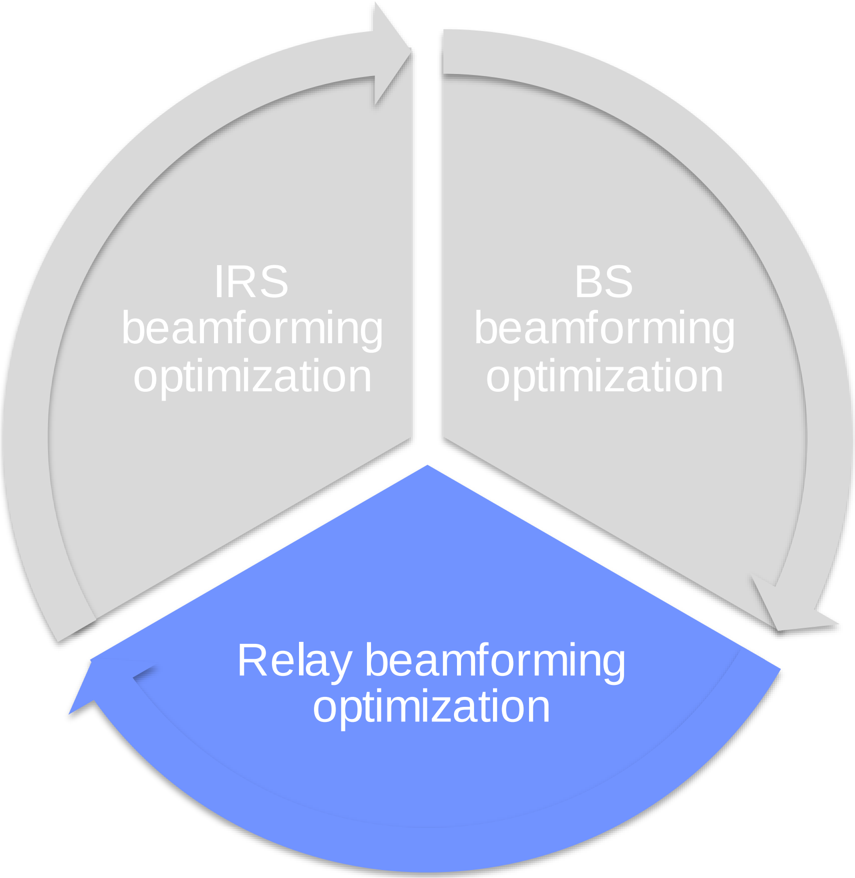
Semidefinite Relaxation

rank-one positive semidefinite matrix

$$\mathbf{G}_k = \mathbf{g}_k \mathbf{g}_k^{\mathrm{H}}$$

- The rank-one constraints are relaxed.
- The resulting SDP problem can be solved by CVX.
- Rank-one solution can be obtained by using the Randomization procedure.

Relay Beamforming Optimization



Introducing Slack Variables

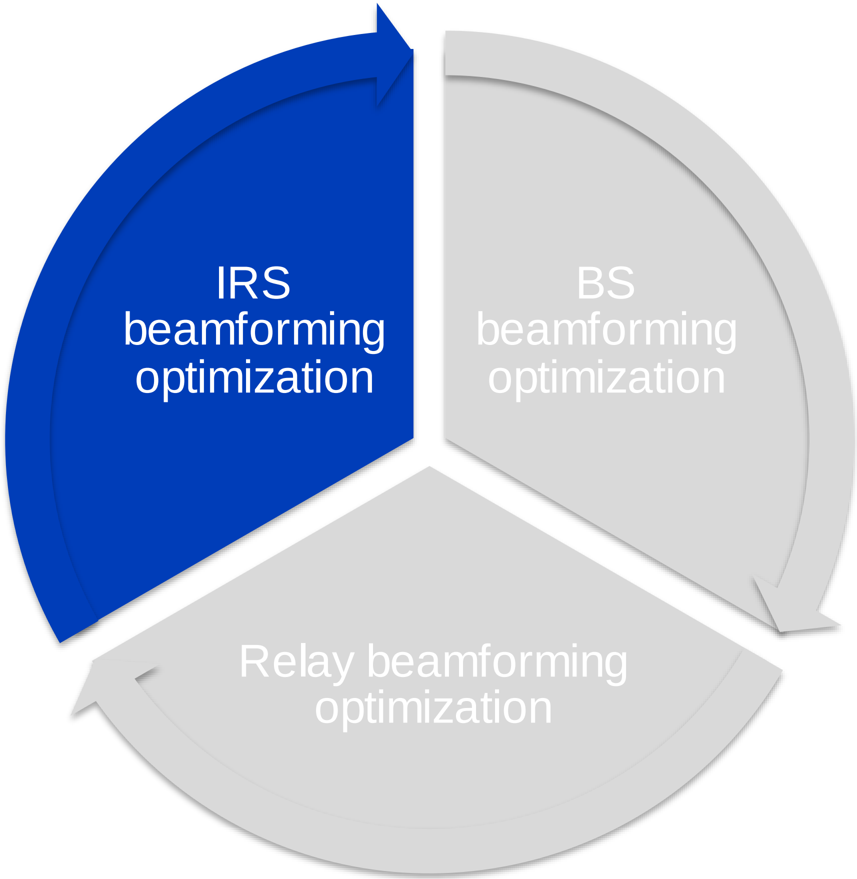
↓

First-order Taylor Approximation

↓

Semidefinite Relaxation

IRS Beamforming Optimization



Introducing Slack Variables

↓

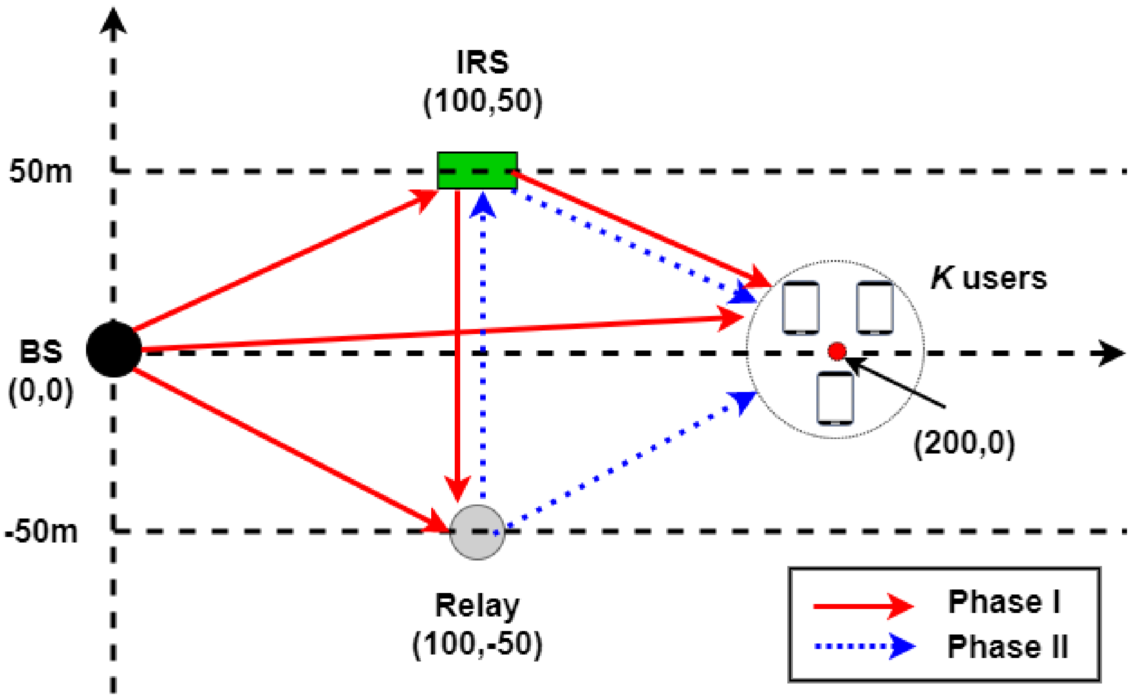
First-order Taylor Approximation

↓

Semidefinite Relaxation

Simulation Setup

System Topology



Channel Model

All channels follow Rayleigh flat-fading

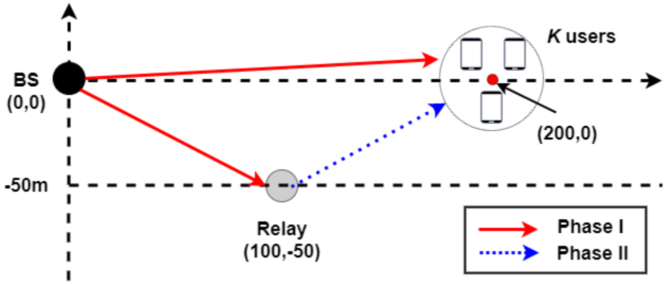
Small-scale fading: $\mathcal{CN}(0,1)$

Large-scale fading: $\kappa(d/d_0)^{-\varrho}$

	fading constant κ	path-loss exponent ϱ
$\mathbf{H}_{\mathrm{BS,R}}$	10^{-4}	3.5
$\mathbf{h}_{\mathrm{BS},k}$	10^{-4}	3.5
$\mathbf{h}_{\mathrm{R},k}$	10^{-4}	3.5
$\mathbf{H}_{\mathrm{BS,IRS}}$	$10^{-0.5}$	2
$\mathbf{H}_{\mathrm{R,IRS}}$	$10^{-0.5}$	2
$\mathbf{h}_{\mathrm{IRS},k}$	$10^{-0.5}$	2

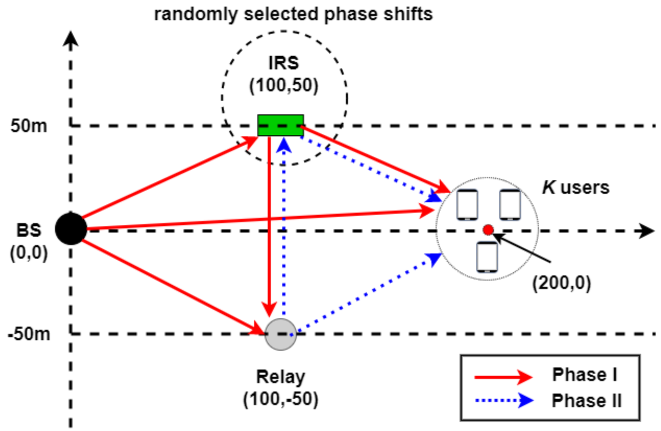
Benchmarks

Relay only scheme



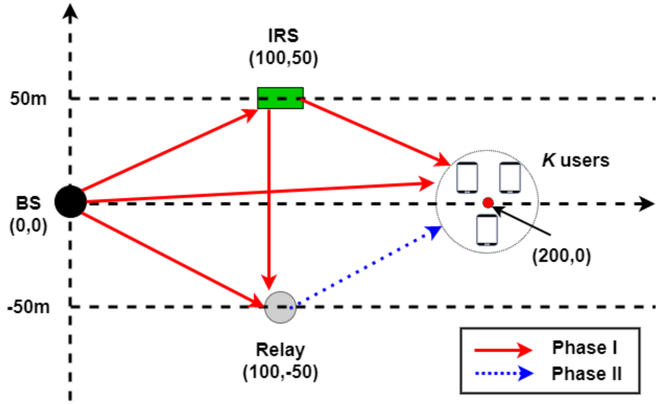
- There is ***no IRS***.
- BS and relay beamforming are optimized.

Random scheme



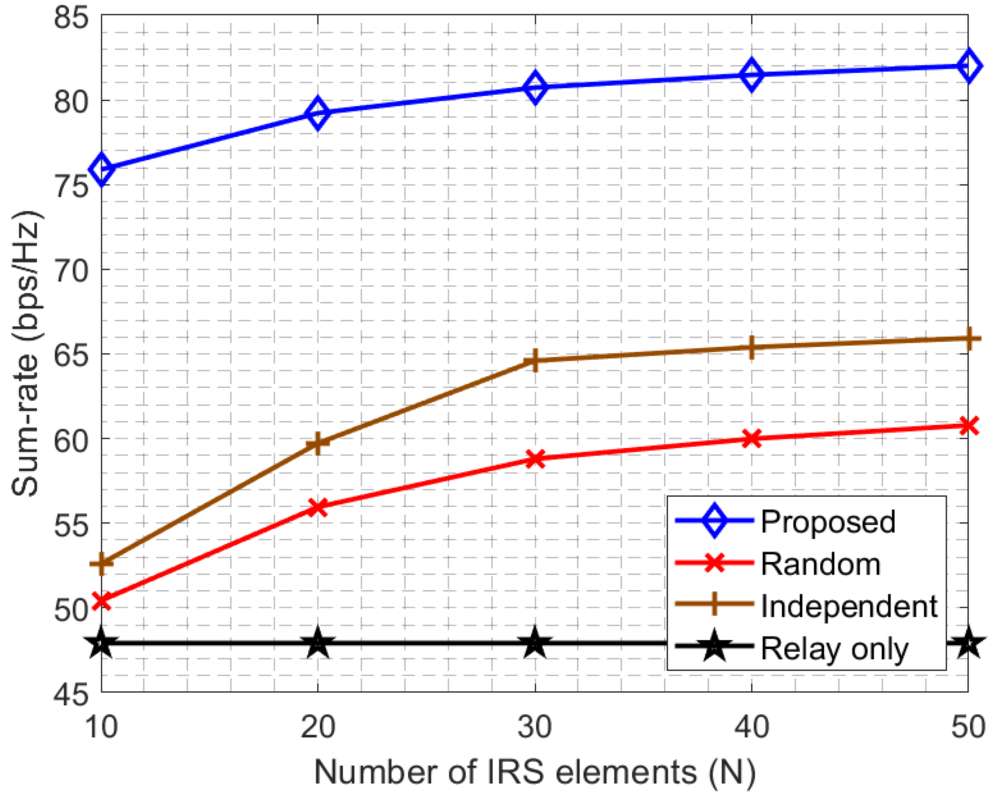
- IRS adopts ***random phase shifts*** and ***fixed amplitudes of one***.
- BS and relay beamforming are optimized.

Independent scheme



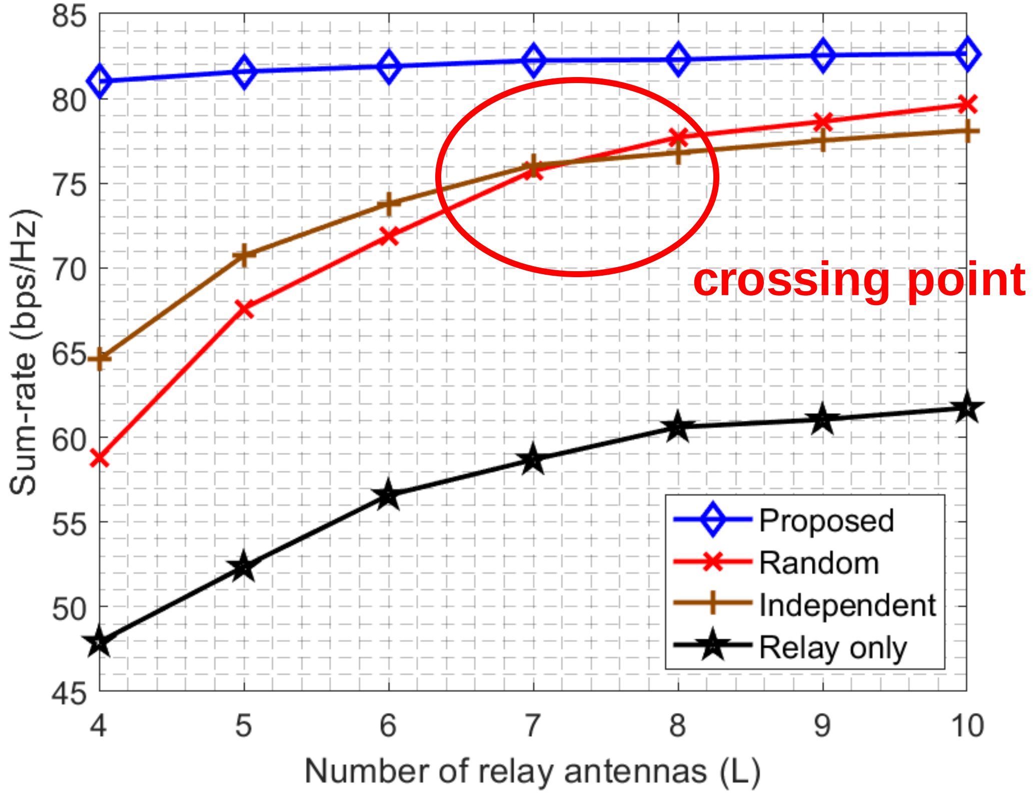
- IRS is ***turned off in the second phase***.
- BS, relay, and IRS beamforming are optimized in this case.

Impact of IRS elements



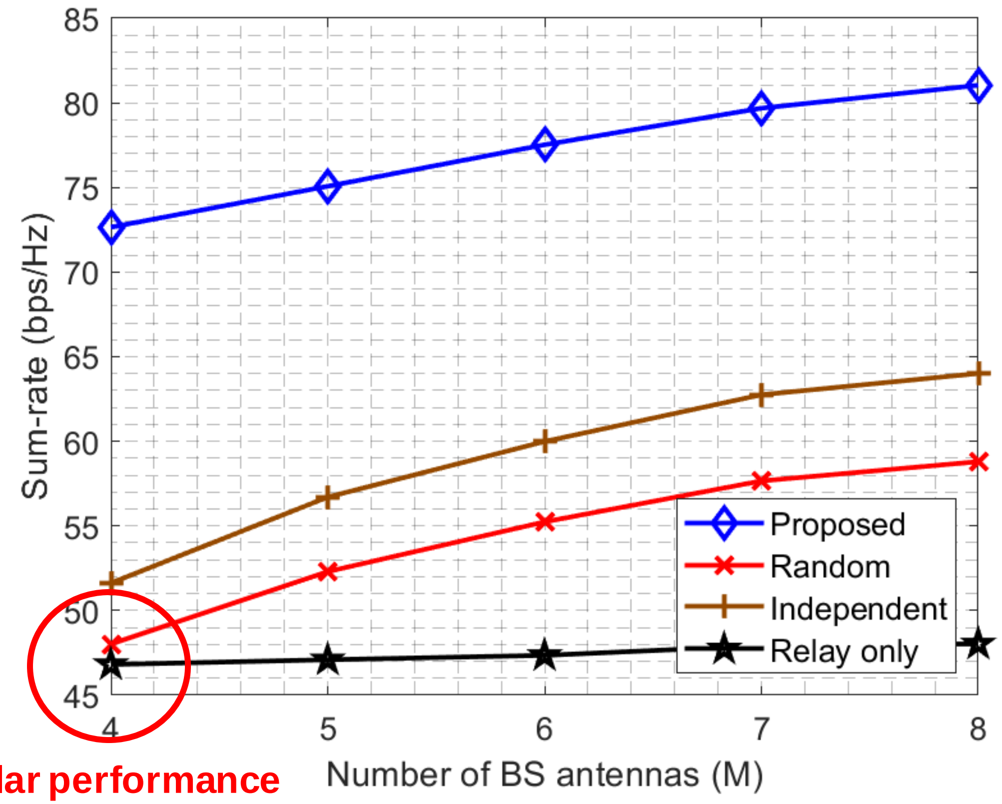
- The sum-rate of all IRS-assisted schemes increases as *N* increases.
- The proposed scheme provides the highest sum-rate.
- The Independent scheme achieves better performance than the Random scheme.
- The IRS-assisted schemes outperform the Relay only scheme.

Impact of relay antennas



- The sum-rates of all schemes increases with *L.*
- The performance gains of the proposed scheme ***diminish*** as *L* increases.
- The independent and Random schemes exhibit a ***crossing point***.

Impact of BS antennas



Similar performance

- The sum-rate of all schemes increases with *M*.
- The effect of *M* on sum-rate is ***moderate*** for the Relay only scheme.
- The Independent scheme achieves better performance than the Random scheme.
- The Random scheme achieves only a ***small performance gain*** in the small *M* region.

Key Takeaways

1. We have presented a joint beamforming design for a multiuser MISO system in which **an IRS and a decode-and-forward relay coexist and assist downlink transmission simultaneously**.

2. The proposed scheme significantly improves the sum-rate performance of end users by **jointly optimizing BS beamforming, relay beamforming, and IRS beamforming**.

3. **The interaction between the IRS and relay** brings great merits.

4. The coexistence of an IRS and a relay **requires a proper co-design** to benefit communications.

Thanks for your attention!

Q&A

Te-Yi Kan[1], Ronald Y. Chang[1], and Feng-Tsun Chien[2]

[1]Research Center for Information Technology Innovation (CITI), Academia Sinica, Taiwan
[2]Institute of Electronics, National Yang Ming Chiao Tung University (NYCU), Taiwan

E-mail: [tyk, rchang]@citi.sinica.edu.tw, and ftchien@mail.nctu.edu.tw