Joint Transceiver Design for QoS-Constrained MIMO Two-Way Non-Regenerative Relaying

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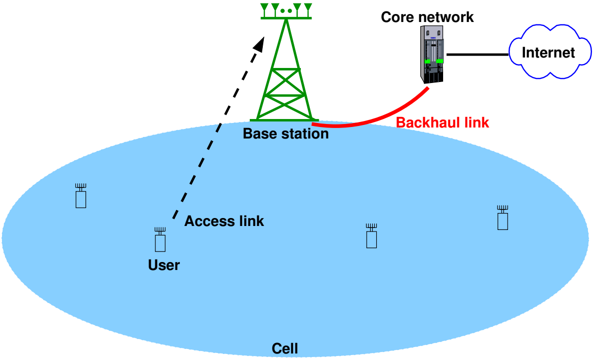
Brief architecture of cellular systems



Three different nodes:

- Users who communicate via base station with wireless access links.
- Core n/w – e.g., billing; connected to base station with wired backhaul links.

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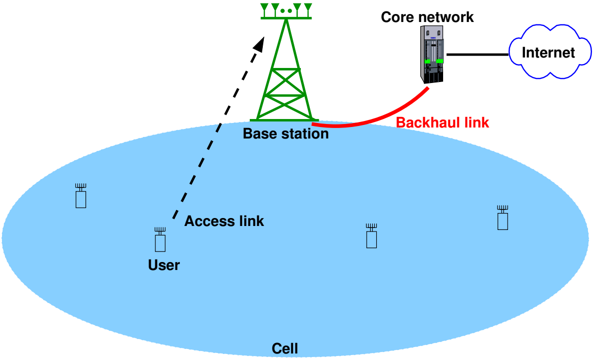
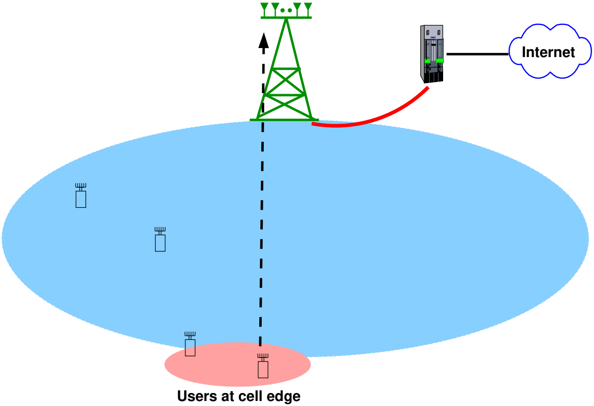


Three different nodes:

- Users who communicate via base station with wireless access links.
- Core n/w – e.g., billing; connected to base station with wired backhaul links.

Architecture works well if wireless access links are strong.

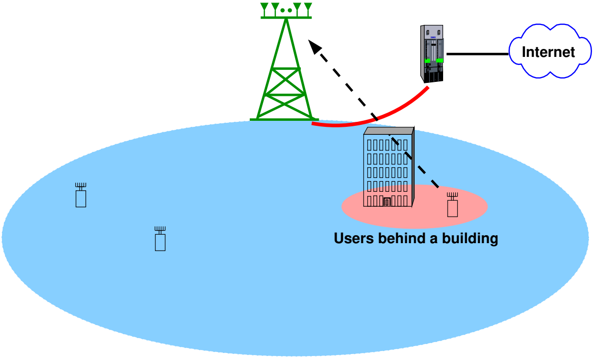
Cellular scenarios with weak direct links



High attenuation due to large distance between base station and users.

- Scenario usually observed in rural areas with large cell sizes.

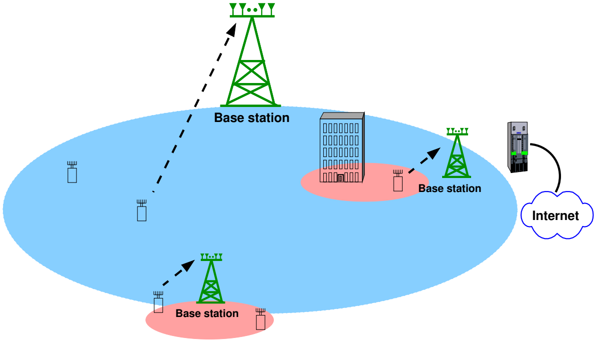
Cellular scenarios with weak direct links



High attenuation due to multiple walls between base station and users.

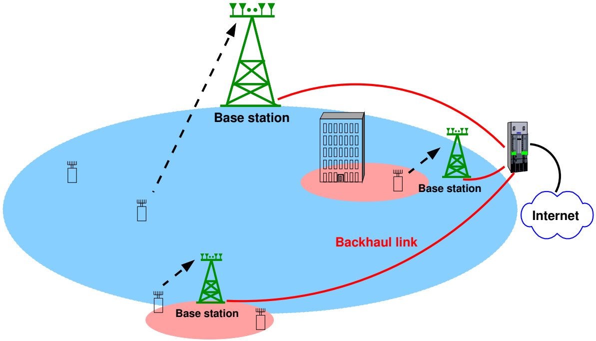
- Scenario usually observed in urban areas with high-rise apartments.

Serve weak users with proximate base stations



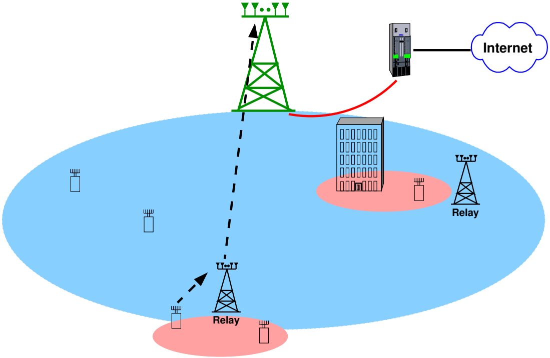
Advantage: Users will now observe strong signals from the base station.

Serve weak users with proximate base stations



Limitation: Backhaul links make base station installation for few users costly.

Serve weak users with relays



Relay is a base station with wireless backhaul – cheaper than base station.

Relay amplifies signal before retransmitting – improves signal strength.

Two different relaying protocols.

Half-duplex one-way relaying

Half-duplex relays – cannot receive and transmit at same time on same frequency.

Time slot 1:

Half-duplex one-way relaying

Half-duplex relays – cannot receive and transmit at same time on same frequency.

Time slot 1:

Time slot 2:

Half-duplex one-way relaying

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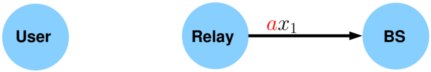

User needs two orthogonal time slots to send one data packet to base station.

- Twice the number of slots when user and base station communicate direcly.

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Half-duplex two-way relaying

Requires two orthogonal time slots to transmit two data units.

Assumes a user wants to simultaneously exchange data with base station.

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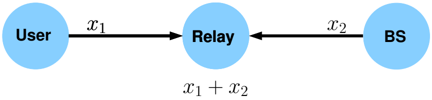

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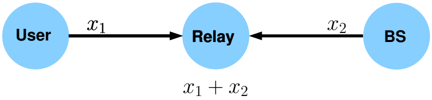

Time slot 2:

Half-duplex two-way relaying

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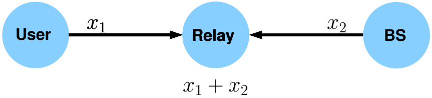

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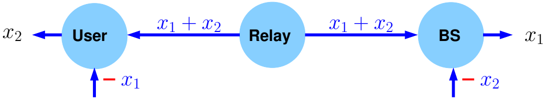

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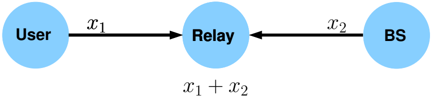

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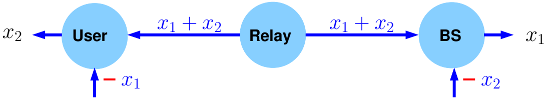
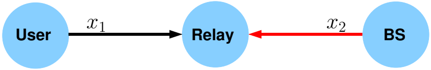


[Rankov et. al, 2007]: Twice spectrally-efficient than one-way relaying.

Basic assumption in two-way relaying

Assumption: user wants to simultaneously exchange data with base station.

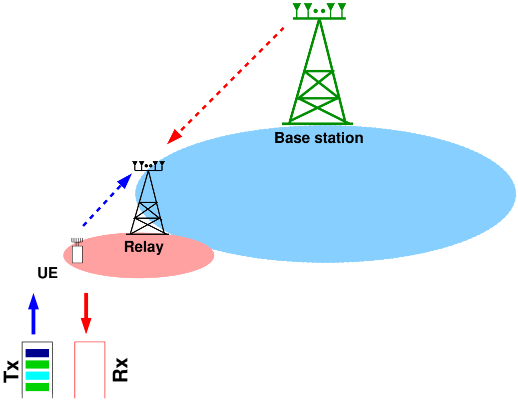


First time slot of two-way relaying

Strong assumption!

Two-way relaying in cellular systems

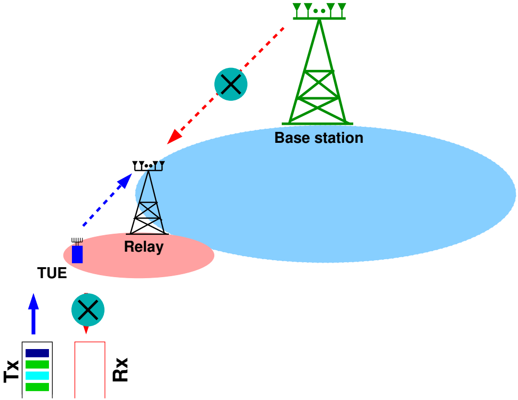
User simultaneously sends and receives data from base station.



First time slot of two-way relaying

Simultaneously send and receive data in cellular systems

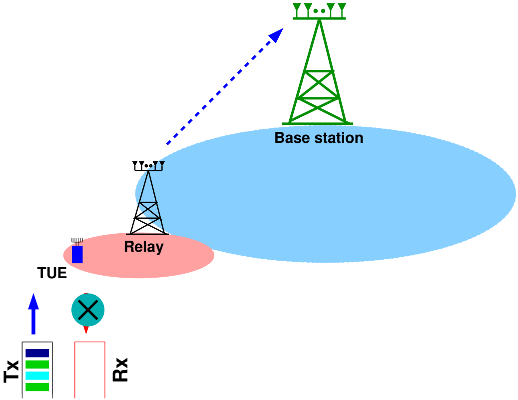
Usually does not happen. E.g., a user TUE uploading a video on facebook.



First time slot of two-way relaying

Simultaneously send and receive data in cellular systems

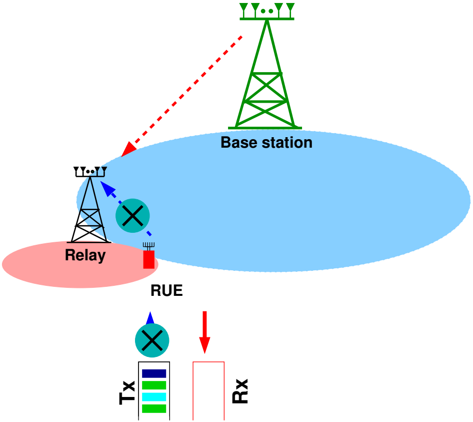
Two-way relaying reduces to one way relaying.



Second time slot of two-way relaying

Simultaneously send and receive data in cellular systems

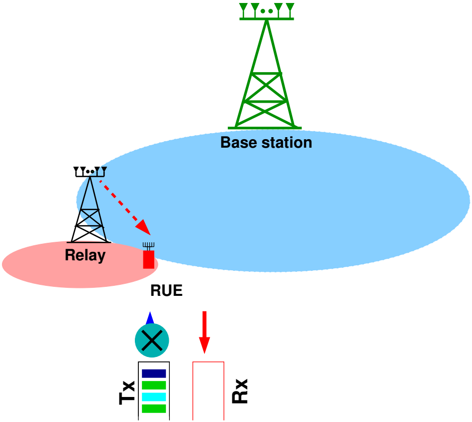
Another example: a receive-only user RUE watching a youtube video.



First time slot of two-way relaying

Simultaneously send and receive data in cellular systems

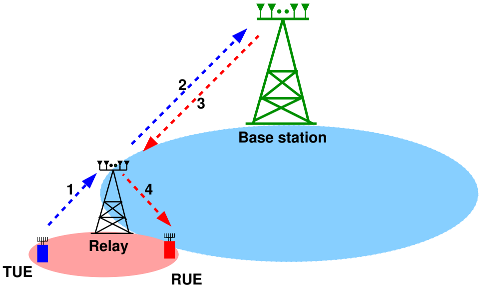
Two-way relaying again reduces to one-way relaying.



Second time slot of two-way relaying

To summarize: two-way relaying for asymmetric traffic

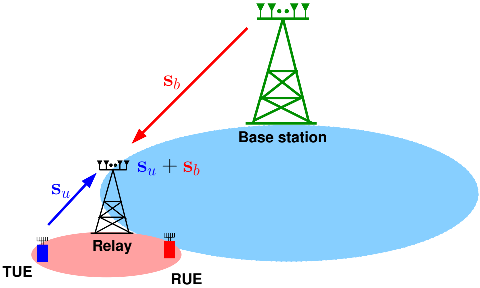
Is equivalent to one-way relaying.



Requires four orthogonal time slots. Two end-to-end non-interfering links.

Proposed asymmetric two-way relaying (1)

Protocol solves considered problem using only two time slots.

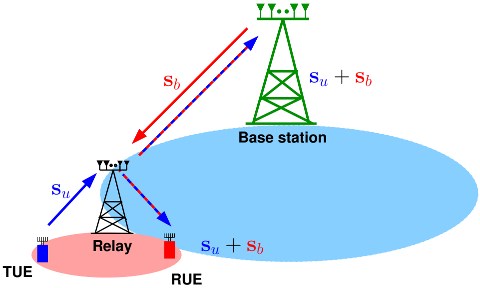


Time slot 1: Both base station and TUE transmit to relay.

Remember – links/data are color-coded.

Proposed asymmetric two-way relaying (2)

Protocol solves considered problem using only two time slots.



Time slot 2: Both base station and RUE receive the sum-signals.

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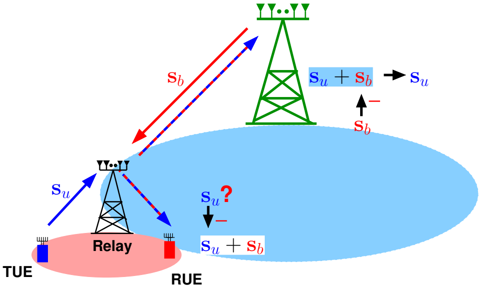


Base station alone can cancel the interference while RUE cannot!

Objective of the work

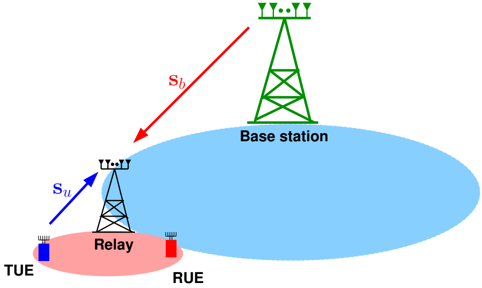
To establish two interference-free channels as in one-way relaying by using only two time slots.

- Performs better than one-way relaying due to reduced number of time slots.
- Requires additional antennas at relay.

Optimal power allocation to maximize the system sum rate.

- Problem is hard-to-solve non-convex signomial program.

State-of-the-art to cancel interference



[Carvalho 2013] assumes RUE overhears TUE in first time slot.

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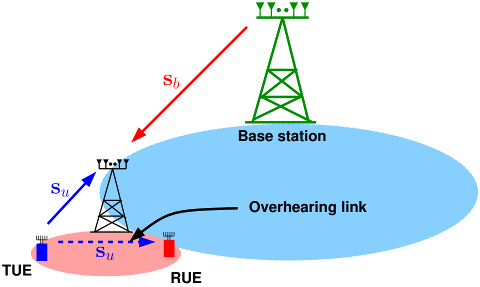

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- Time slot 1 rx signal: $y_1 = s_u$

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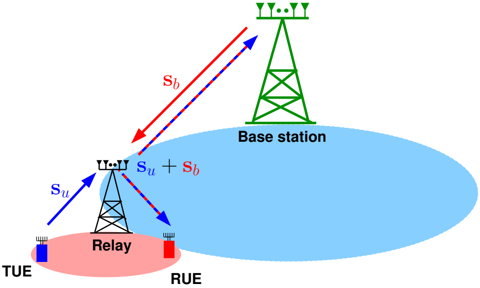

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- Time slot 1 rx signal: $y_1 = s_u$
- Time slot 2 rx signal: $y_2 = s_u + s_b$.

[Sun 2013], [Paulraj 2014] – diversity-multiplexing tradeoff and sum rate.

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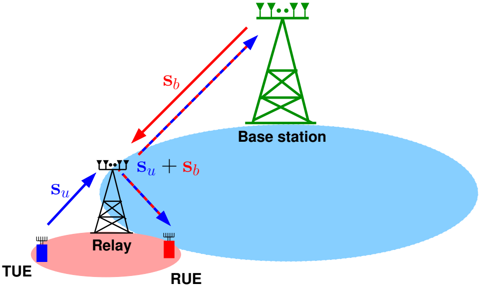

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State-of-the-art to cancel interference

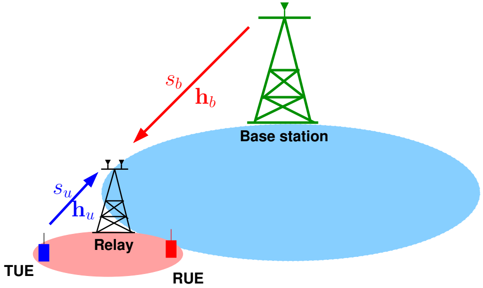
Limitations of overhearing approach

- Practical – in a cellular system, two users do not overhear each other.
- Analytical – consider single-antenna nodes.
  - ⋆ Difficult to extend optimization techniques for MIMO systems.

Our approach:

- Do not assume overhearing.
- Consider MIMO nodes.
  - ⋆ Geometric programming framework for sum rate optimization.

System model and solution – first time slot



We limit discussion to single-antenna base station and users.

- Relay has two antennas; requires twice the number of TUE antennas.

Papers extend the work to multi-antenna base station and users.

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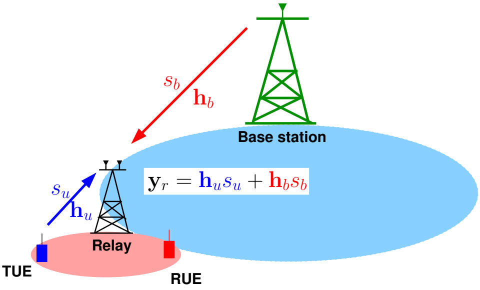

Relay receive signal: $\mathbf{y}_r = \mathbf{h}_u s_u + \mathbf{h}_b s_b$.

- $\begin{bmatrix} y_{r1} \\ y_{r2} \end{bmatrix} = \underbrace{[\mathbf{h}_u \ \mathbf{h}_b]}_{\mathbf{H}} \begin{bmatrix} s_u \\ s_b \end{bmatrix}$; two equations with two variables.

Relay spatially separates s_u and s_b using receiver matrix $\mathbf{H}^{-1}$:

- $\mathbf{H}^{-1}\mathbf{y}_r = \begin{bmatrix} s_u \\ s_b \end{bmatrix}$.

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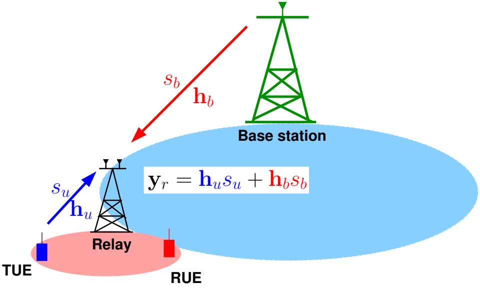

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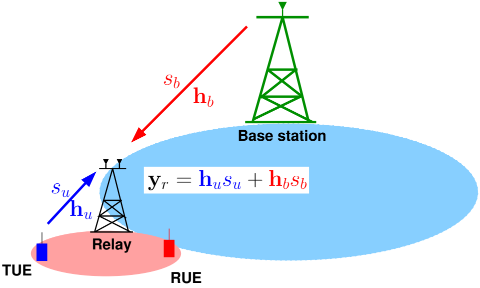

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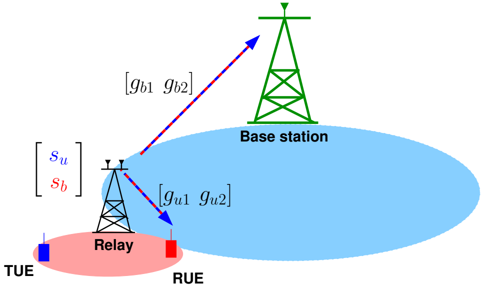

Relay has to broadcast $\begin{bmatrix} s_u \\ s_b \end{bmatrix}$ to RUE and BS in second time slot.

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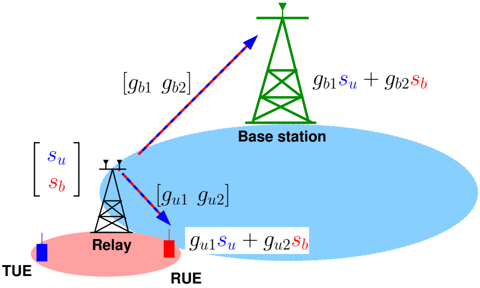

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RUE still experiences interference from s_u.

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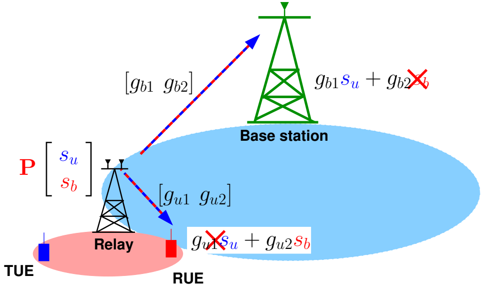

Before broadcasting, relay multiplies $\begin{bmatrix} s_u \\ s_b \end{bmatrix}$ with $\mathbf{P}$ to cancel s_u at RUE.

Signals received by RUE and base station

- $\begin{bmatrix} y_u \\ y_b \end{bmatrix} = \underbrace{\begin{bmatrix} g_{u1} & g_{u2} \\ g_{b1} & g_{b2} \end{bmatrix}}_{\mathbf{G}} \mathbf{P} \begin{bmatrix} s_u \\ s_b \end{bmatrix}$; two equations with two variables.

Set $\mathbf{P} = \mathbf{G}^{-1}\mathbf{\Delta}$; where $\mathbf{\Delta}$ is anti-diagonal power allocation matrix.

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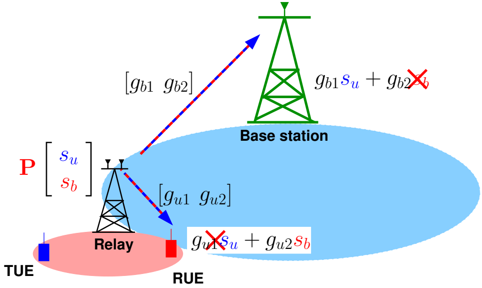

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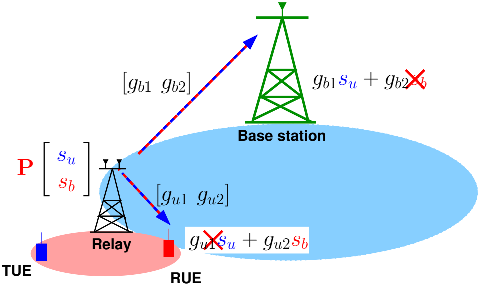

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System model and solution – second time slot

RUE and BS receive signals become

- $$\begin{bmatrix} y_u \\ y_b \end{bmatrix} = \mathbf{G}\mathbf{G}^{-1}\boldsymbol{\Delta} \begin{bmatrix} s_u \\ s_b \end{bmatrix} = \begin{bmatrix} 0 & \delta_u \\ \delta_b & 0 \end{bmatrix} \begin{bmatrix} s_u \\ s_b \end{bmatrix} = \begin{bmatrix} \delta_u s_b \\ \delta_b s_u \end{bmatrix}.$$

Sub-optimal approach as it cancels interference for base station also.

End-to-end input-output system

- $$\begin{bmatrix} y_u \\ y_b \end{bmatrix} = \mathbf{G}\underbrace{\mathbf{G}^{-1}}_{\mathbf{P}_2}\boldsymbol{\Delta}\underbrace{\mathbf{H}^{-1}}_{\mathbf{P}_1}\mathbf{H} \begin{bmatrix} s_u \\ s_b \end{bmatrix}.$$

Design constructs $\mathbf{P}_2$ and $\mathbf{P}_1$ such that $\mathbf{G}\mathbf{P}_2 = \mathbf{P}_1\mathbf{H} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$.

System model and solution – second time slot

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Approach to cancel interference for RUE alone

Theorem

Design $\mathbf{P}_2$ and $\mathbf{P}_1$ such that $\mathbf{G}\mathbf{P}_2 = \begin{bmatrix} \times & 0 \\ \times & \times \end{bmatrix}$ and $\mathbf{P}_1\mathbf{H} = \begin{bmatrix} \times & \times \\ 0 & \times \end{bmatrix}$.

Receive signals in second time slot

- RUE: $y_u = ()\delta_u s_b$.
- BS: $y_b = ()\delta_b s_u + ()s_b$.

$\mathbf{P}_1$ and $\mathbf{P}_2$ are designed using LQ and QR decompositions of $\mathbf{G}$ and $\mathbf{H}$.

SNR observed by RUE and BS:

$$\mathrm{SNR}_i = \frac{a_i \delta_i^2}{\sigma_r^2(b_i\delta_u^2 + c_i\delta_b^2) + \sigma^2}, \text{ where } a_i, b_i, c_i \geq 0.$$

- This fact will be used to prove convexity of optimization programs.

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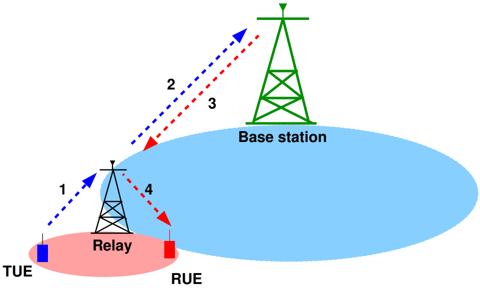
Comparison with one-way relaying

Proposed protocol and one-way relaying establish two interference-free channels.

- Proposed protocol requires only two time slots and two relay antennas.
- In contrast, one-way relaying requires four time slots and single relay antenna.



Optimal power allocation

Maximize system sum rate; cast as a geometric program.

Geometric program terminology

- A monomial is a function $f : \mathbf{R}^n_{++} :\to \mathbf{R}$ of the form

$$f(\mathbf{x}) = cx_1^{a_1} x_2^{a_2} \cdots x_n^{a_n}, \text{ where } c > 0 \text{ and } a_j \in \mathbf{R}.$$

- A posynomial is a positive sum of monomials; not closed under division.
- Objective in a geometric program is a posynomial.
- Inequality constraints are upper-bounded posynomials.

Sum rate maximization

$$\begin{aligned} \underset{\boldsymbol{\delta} \succeq 0}{\text{Max.}} \quad & \log\{1 + \mathsf{SNR}_u(\boldsymbol{\delta})\} + \log\{1 + \mathsf{SNR}_b(\boldsymbol{\delta})\} \\ \text{subject to} \quad & P_{\text{relay}}(\boldsymbol{\delta}) \leq p_r \end{aligned}$$

$P_{\text{relay}}(\boldsymbol{\delta})$ is a posynomial [Budhiraja 2014] while objective isn't. We show why.

Recall $\mathsf{SNR}_i = \frac{a_i \delta_i^2}{\sigma_r^2 (b_i \delta_u^2 + c_i \delta_b^2) + \sigma^2}$; where $a_i, b_i, c_i \geq 0$.

- $\{1 + \mathsf{SNR}_i(\boldsymbol{\delta})\}$ is a ratio of two posynomials due to term 1.
- Sum rate maximization is a non-convex signomial program.
- Note that $\mathsf{ISNR}_i = 1/\mathsf{SNR}_i$ is a posynomial.

Sum rate maximization

$$\begin{aligned} \underset{\boldsymbol{\delta}\succeq 0}{\text{Max.}} \quad & \log\{1+\mathsf{SNR}_u(\boldsymbol{\delta})\}+\log\{1+\mathsf{SNR}_b(\boldsymbol{\delta})\} \\ \text{subject to} \quad & P_{\text{relay}}(\boldsymbol{\delta}) \leq p_r \end{aligned}$$

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- $\{1+\mathsf{SNR}_i(\boldsymbol{\delta})\}$ is a ratio of two posynomials due to term 1.
- Sum rate maximization is a non-convex signomial program.
- Note that $\mathsf{ISNR}_i = 1/\mathsf{SNR}_i$ is a posynomial.

Sum rate maximization

$$\max_{\boldsymbol{\delta}\succeq 0} \quad \log\{1+\mathrm{SNR}_u(\boldsymbol{\delta})\}+\log\{1+\mathrm{SNR}_b(\boldsymbol{\delta})\}$$
$$\text{subject to} \quad P_{\mathrm{relay}}(\boldsymbol{\delta}) \leq p_r$$

$P_{\mathrm{relay}}(\boldsymbol{\delta})$ is a posynomial [Budhiraja 2014] while objective isn't. We show why.

Recall $\mathrm{SNR}_i = \frac{a_i\delta_i^2}{\sigma_r^2(b_i\delta_u^2+c_i\delta_b^2)+\sigma^2}$; where $a_i, b_i, c_i \geq 0$.

- $\{1+\mathrm{SNR}_i(\boldsymbol{\delta})\}$ is a ratio of two posynomials due to term 1.
- Sum rate maximization is a non-convex signomial program.
- Note that $\mathrm{ISNR}_i = 1/\mathrm{SNR}_i$ is a posynomial.

Sum rate maximization at high SNR

Use high SNR approximation: $\log(1+\mathrm{SNR}) \simeq \log(\mathrm{SNR})$.

- $R_{\mathrm{sum}}^{\mathrm{approx}} \simeq \frac{1}{2}\log\{\mathrm{SNR}_u(\boldsymbol{\delta}) \cdot \mathrm{SNR}_b(\boldsymbol{\delta})\} = -\log\{\mathrm{ISNR}_u(\boldsymbol{\delta}) \cdot \mathrm{ISNR}_b(\boldsymbol{\delta})\}$.
- Note that $\mathrm{ISNR}_u(\boldsymbol{\delta})\cdot\mathrm{ISNR}_b(\boldsymbol{\delta})$ is a posynomial.

Sum rate can now be maximized as a geometric program:

$$\begin{aligned} \underset{\boldsymbol{\delta}\succeq 0}{\text{Min.}} \quad & \mathrm{ISNR}_u(\boldsymbol{\delta}) \cdot \mathrm{ISNR}_b(\boldsymbol{\delta}) \\ \text{subject to} \quad & P_{\mathrm{relay}}(\boldsymbol{\delta}) \leq p_r . \end{aligned}$$

At low SNR, sum rate is maximized using successive convex approximation.

Sum rate maximization at high SNR

Use high SNR approximation: $\log(1 + \text{SNR}) \simeq \log(\text{SNR})$.

- $R_{\text{sum}}^{\text{approx}} \simeq \frac{1}{2} \log\{\text{SNR}_u(\boldsymbol{\delta}) \cdot \text{SNR}_b(\boldsymbol{\delta})\} = -\log\{\text{ISNR}_u(\boldsymbol{\delta}) \cdot \text{ISNR}_b(\boldsymbol{\delta})\}$.
- Note that $\text{ISNR}_u(\boldsymbol{\delta}) \cdot \text{ISNR}_b(\boldsymbol{\delta})$ is a posynomial.

Sum rate can now be maximized as a geometric program:

$$\begin{aligned} \underset{\boldsymbol{\delta} \succeq 0}{\text{Min.}} \quad & \text{ISNR}_u(\boldsymbol{\delta}) \cdot \text{ISNR}_b(\boldsymbol{\delta}) \\ \text{subject to} \quad & P_{\text{relay}}(\boldsymbol{\delta}) \leq p_r. \end{aligned}$$

At low SNR, sum rate is maximized using successive convex approximation.

Sum rate maximization with user rate constraints

$$\begin{aligned} \underset{\boldsymbol{\delta} \succeq 0}{\text{Min.}} \quad & \mathrm{ISNR}_u(\boldsymbol{\delta}) \cdot \mathrm{ISNR}_b(\boldsymbol{\delta}) \\ \text{subject to} \quad & P_{\text{relay}}(\boldsymbol{\delta}) \leq p_r \\ & \log(1 + \mathrm{SNR}_u(\boldsymbol{\delta})) \geq r_u \\ & \log(1 + \mathrm{SNR}_b(\boldsymbol{\delta})) \geq r_b \end{aligned}$$

Cast as a geometric program by re-stating the rate constraints:

$$\begin{aligned} \underset{\delta \succeq 0}{\text{Min.}} \quad & \mathrm{ISNR}_u(\delta) \cdot \mathrm{ISNR}_b(\delta) \\ \text{subject to} \quad & P_{\text{relay}}(\delta) \leq p_r \\ & \mathrm{ISNR}_u(\delta) \leq 2^{-r_u} - 1 \\ & \mathrm{ISNR}_b(\delta) \leq 2^{-r_b} - 1 \end{aligned}$$

Used to analyze the effect of rate constraints on sum rate.

Sum rate maximization with user rate constraints

$$\begin{aligned}
\underset{\boldsymbol{\delta} \succeq 0}{\text{Min.}} \quad & \mathrm{ISNR}_u(\boldsymbol{\delta}) \cdot \mathrm{ISNR}_b(\boldsymbol{\delta}) \\
\text{subject to} \quad & P_{\text{relay}}(\boldsymbol{\delta}) \leq p_r \\
& \log(1 + \mathrm{SNR}_u(\boldsymbol{\delta})) \geq r_u \\
& \log(1 + \mathrm{SNR}_b(\boldsymbol{\delta})) \geq r_b
\end{aligned}$$

Cast as a geometric program by re-stating the rate constraints:

$$\begin{aligned}
\underset{\boldsymbol{\delta} \succeq 0}{\text{Min.}} \quad & \mathrm{ISNR}_u(\boldsymbol{\delta}) \cdot \mathrm{ISNR}_b(\boldsymbol{\delta}) \\
\text{subject to} \quad & P_{\text{relay}}(\boldsymbol{\delta}) \leq p_r \\
& \mathrm{ISNR}_u(\boldsymbol{\delta}) \leq 2^{-r_u} - 1 \\
& \mathrm{ISNR}_b(\boldsymbol{\delta}) \leq 2^{-r_b} - 1
\end{aligned}$$

Used to analyze the effect of rate constraints on sum rate.

Relay power minimization with user rate constraints

$$\begin{aligned} \underset{\boldsymbol{\delta} \succeq 0}{\text{Min.}} \quad & P_{\text{relay}}(\boldsymbol{\delta}) \\ \text{subject to} \quad & P_{\text{relay}}(\boldsymbol{\delta}) \leq p_r \\ & \log(1 + \text{SNR}_u(\boldsymbol{\delta})) \geq r_u \\ & \log(1 + \text{SNR}_b(\boldsymbol{\delta})) \geq r_b \end{aligned}$$

Cast as a geometric program by re-stating the rate constraints:

$$\begin{aligned} \underset{\boldsymbol{\delta} \succeq 0}{\text{Min.}} \quad & P_{\text{relay}}(\boldsymbol{\delta}) \\ \text{subject to} \quad & P_{\text{relay}}(\boldsymbol{\delta}) \leq p_r \\ & \text{ISNR}_u(\boldsymbol{\delta}) \leq 2^{-r_u} - 1 \\ & \text{ISNR}_b(\boldsymbol{\delta}) \leq 2^{-r_b} - 1 \end{aligned}$$

Decides relay transmit power to support user rates.

Maximize rate of the user with minimum SNR (max-min)

$$\begin{aligned} \underset{\boldsymbol{\delta} \succeq 0}{\text{Max.}} \quad & \text{Min.} \ \ (\text{SNR}_u(\boldsymbol{\delta}), \text{SNR}_b(\boldsymbol{\delta})) \\ \text{subject to} \quad & P_{\text{relay}}(\boldsymbol{\delta}) \leq p_r \end{aligned}$$

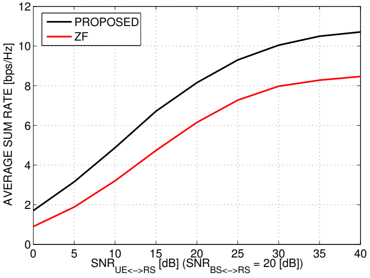
Cast as a geometric program by using epigraph form

$$\begin{aligned} \underset{\boldsymbol{\delta}, t}{\text{Min.}} \quad & 1/t \\ \text{subject to} \quad & t \cdot \text{ISNR}_u(\boldsymbol{\delta}) \leq 1, \ \ t \cdot \text{ISNR}_b(\boldsymbol{\delta}) \leq 1 \\ & P_{\text{relay}}(\boldsymbol{\delta}) \leq p_r \end{aligned}$$

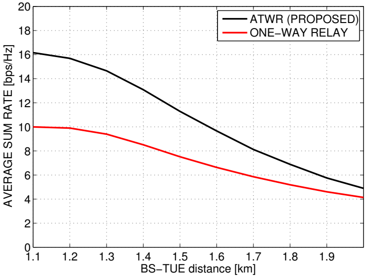
Enforces fairness among users.

Optimal power allocation for energy-efficient design, multi-user transmission.

Sum rate comparison of proposed precoders/protocols



Precoder comparison.



Protocol comparison.

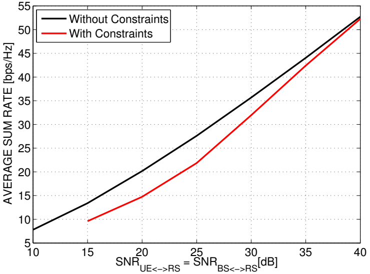
Assume 4 relay antennas and 2 antennas at the base station and users.

- Antenna configuration is same for all precoders and protocols.

Proposed precoder works better as it avoids matrix inversion.

- Both precoders have same computational complexity.

Sum rate maximization with user rate constraints



Sum-rate with rate constraints.

Assume 8 relay antennas and 4 antennas at the base station and users.

Rate-constrained sum rate is inferior.

Thank you

References

[1] **Rohit Budhiraja** and Ajit Chaturvedi "Common Transceiver Design for asymmetric and symmetric tw-way relaying", IEEE Trans. Vehicular Tech., accepted Jan. 2017.

[2] **Rohit Budhiraja** and Bhaskar Ramamurthi "Joint Precoder and Receiver Design for AF Non-Simultaneous Two-way MIMO Relaying", IEEE Trans. Wireless Commun., Jun. 2015.