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Transmit Power Optimization for Multiantenna Decode-and-Forward Relays with Loopback Self-Interference from Full-Duplex Operation

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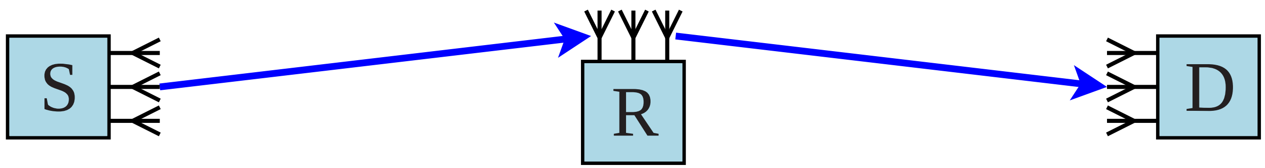
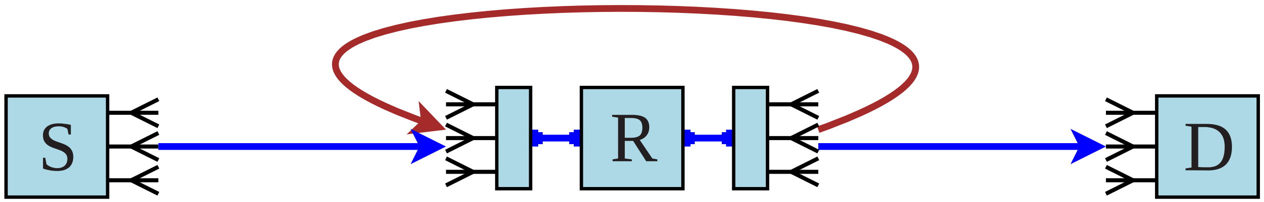
Introduction

Brief History of Full-Duplex Relaying (1)



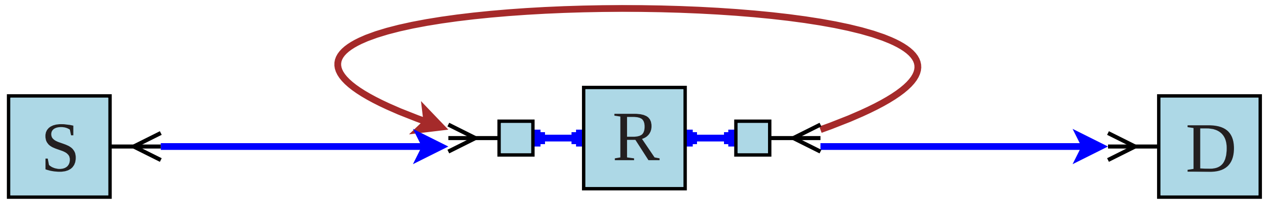
- The information theory of full-duplex MIMO relaying has been investigated extensively (2005–2007)
  - ▷ Implementation aspects are out of the scope of those studies
    - The limitations of transceiver electronics?
    - How to isolate the two hops?
    - Relay with a single antenna array?
  - ▷ In this work: A step to more practical direction
- First prototypes of full-duplex MIMO repeaters (2009–2010)
  - ▷ But the background theory still needs further development

Brief History of Full-Duplex Relaying (2)



- The existence of self-interference was recognized only recently
  - Ahead of their time: Bliss, Parker, and Margetts (Aug. 2007)
  - The relay must be equipped with separated Rx and Tx arrays
- Interference mitigation schemes for full-duplex MIMO relays
  - Our contributions: [ACSSC'09], [ACSSC'10], [CISS'11], [IEEE TSP 12/2011]
- Achievable transmission rates of full-duplex amplify-and-forward MIMO relay links with self-interference
  - In this work: Decode-and-forward relaying

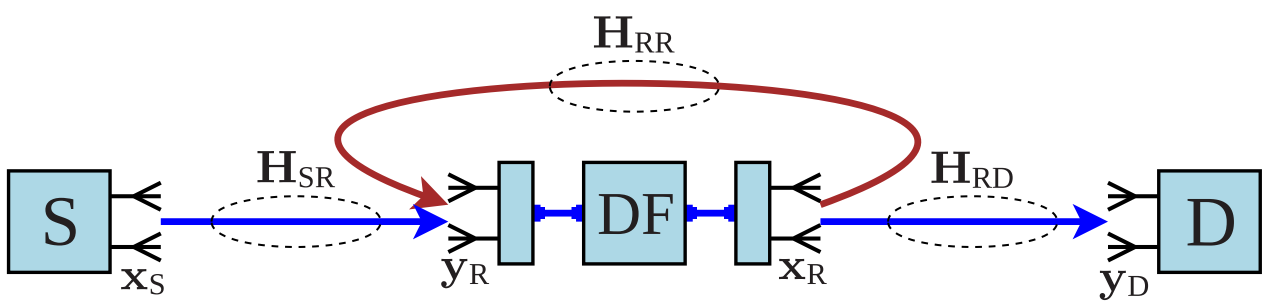
Brief History of Full-Duplex Relaying (3)



- Our earlier studies on full-duplex SISO relays
  - ▷ Transmit power adaptation (i.e., gain control in AF relaying) taking into account the self-interference
    - See [IEEE TWC 6/2009], [SPAWC'09], [PIMRC'10], [IEEE TWC 9/2011]
  - ▷ Comparison of full-duplex and half-duplex relaying in the presence of (residual) self-interference
    - See [WCNC'09], [SPAWC'09], [PIMRC'10], [IEEE TWC 9/2011]
- In this work: The above aspects generalized for the MIMO case

System Model

Full-Duplex Relay Link with Self-Interference



- Two-hop transmission through a full-duplex MIMO relay
  - The source (S) and the relay (R) transmit simultaneously

$$\mathbf{x}_{\mathrm{S}} \in \mathbb{C}^{N_{\mathrm{S}} \times 1} \quad \text{and} \quad \mathbf{x}_{\mathrm{R}} \in \mathbb{C}^{N_{\mathrm{tx}} \times 1}$$

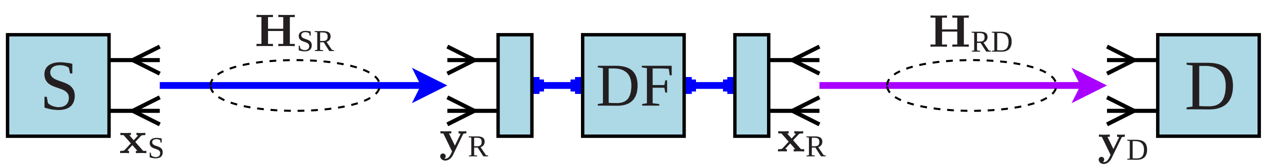
  - and the relay and the destination (D) receive

$$\mathbf{y}_{\mathrm{R}} = \mathbf{H}_{\mathrm{SR}}\mathbf{x}_{\mathrm{S}} + \mathbf{H}_{\mathrm{RR}}\mathbf{x}_{\mathrm{R}} + \mathbf{n}_{\mathrm{R}} \in \mathbb{C}^{N_{\mathrm{rx}} \times 1}$$

$$\mathbf{y}_{\mathrm{D}} = \mathbf{H}_{\mathrm{RD}}\mathbf{x}_{\mathrm{R}} + \mathbf{H}_{\mathrm{SD}}\mathbf{x}_{\mathrm{S}} + \mathbf{n}_{\mathrm{D}} \in \mathbb{C}^{N_{\mathrm{D}} \times 1}$$

- $\mathbf{H}_{\mathrm{RR}}$ represents the *residual* channel if mitigation is used
- The direct link is assumed to be blocked, i.e., $\mathbf{H}_{\mathrm{SD}} \approx \mathbf{0}$

The Reference System: Half-Duplex Relay Link



- Two-hop transmission through a half-duplex MIMO relay
  - 1st time slot (duration τ_S): The source transmits $\mathbf{x}_\mathrm{S} \in \mathbb{C}^{N_\mathrm{S}\times 1}$ and the relay receives

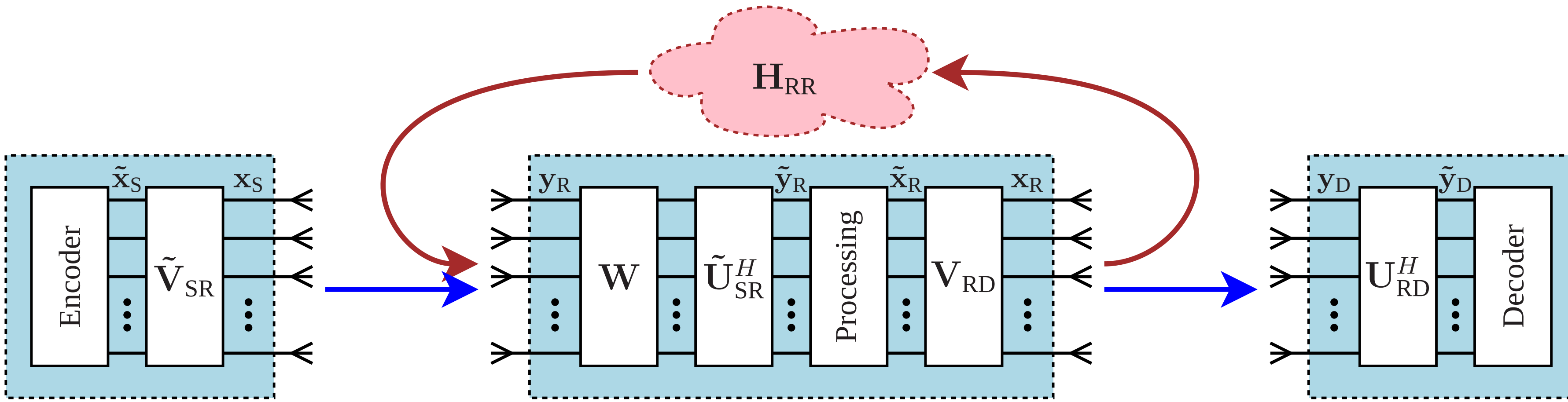
$$\mathbf{y}_\mathrm{R} = \mathbf{H}_\mathrm{SR}\mathbf{x}_\mathrm{S} + \mathbf{n}_\mathrm{R} \in \mathbb{C}^{N_\mathrm{rx}\times 1}$$

  - 2nd time slot (duration τ_R): The relay transmits $\mathbf{x}_\mathrm{R} \in \mathbb{C}^{N_\mathrm{tx}\times 1}$ and the destination receives

$$\mathbf{y}_\mathrm{D} = \mathbf{H}_\mathrm{RD}\mathbf{x}_\mathrm{R} + \mathbf{n}_\mathrm{D} \in \mathbb{C}^{N_\mathrm{D}\times 1}$$

- No self-interference ($\mathbf{H}_\mathrm{RR} = \mathbf{0}$) at the cost of using two time slots

Regenerative (DF) MIMO Relaying Protocol



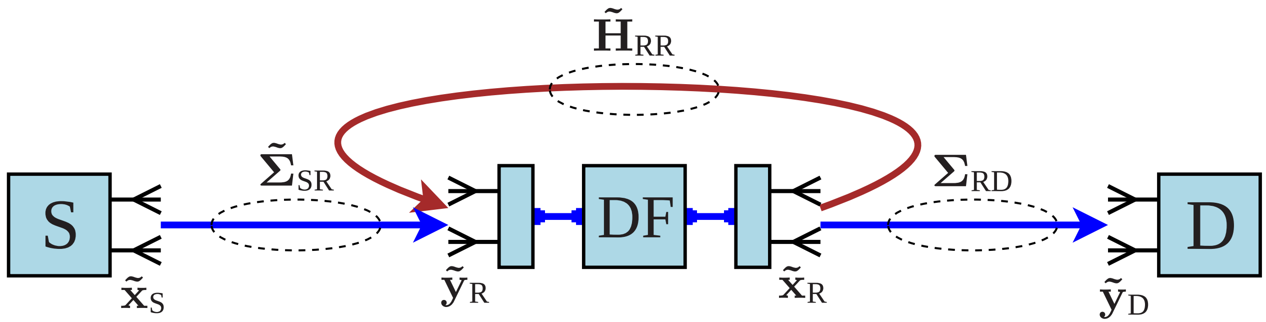
- Pre-whitening: $\mathbf{W} = (\mathbf{H}_{\mathrm{RR}}\mathbf{R}_{\mathbf{x}_{\mathrm{R}}}\mathbf{H}_{\mathrm{RR}}^{H} + \mathbf{I})^{-\frac{1}{2}}$ and $\tilde{\mathbf{H}}_{\mathrm{SR}} = \mathbf{W}\mathbf{H}_{\mathrm{SR}}$
- Spatial-division multiplexing transforms the signal model to

$$\tilde{\mathbf{y}}_{\mathrm{R}} = \tilde{\mathbf{\Sigma}}_{\mathrm{SR}}\tilde{\mathbf{x}}_{\mathrm{S}} + \tilde{\mathbf{n}}_{\mathrm{R}}$$

$$\tilde{\mathbf{y}}_{\mathrm{D}} = \mathbf{\Sigma}_{\mathrm{RD}}\tilde{\mathbf{x}}_{\mathrm{R}} + \tilde{\mathbf{n}}_{\mathrm{D}}$$

  - ▷ SVDs: $\tilde{\mathbf{H}}_{\mathrm{SR}} = \tilde{\mathbf{U}}_{\mathrm{SR}}\tilde{\mathbf{\Sigma}}_{\mathrm{SR}}\tilde{\mathbf{V}}_{\mathrm{SR}}^{H}$ and $\mathbf{H}_{\mathrm{RD}} = \mathbf{U}_{\mathrm{RD}}\mathbf{\Sigma}_{\mathrm{RD}}\mathbf{V}_{\mathrm{RD}}^{H}$
- The half-duplex link operates in the same way but with $\mathbf{H}_{\mathrm{RR}} = \mathbf{0}$

Transmitted Signals and Power Constraints



- Spatial-division multiplexing diagonalizes $\tilde{\mathbf{H}}_{\mathrm{SR}}$ and $\mathbf{H}_{\mathrm{RD}}$, but not the self-interference channel: $\tilde{\mathbf{H}}_{\mathrm{RR}} = \tilde{\mathbf{U}}_{\mathrm{SR}}^{H}\mathbf{W}\mathbf{H}_{\mathrm{RR}}\mathbf{V}_{\mathrm{RD}}$
  - ▷ Transmission of independent spatial streams with

$$\mathbf{P}_{\mathrm{S}} = \mathcal{E}\{\tilde{\mathbf{x}}_{\mathrm{S}}\tilde{\mathbf{x}}_{\mathrm{S}}^{H}\} = \mathrm{diag}\left\{p_{\mathrm{S}}[1], \ldots, p_{\mathrm{S}}[N_{\mathrm{S}}]\right\}$$

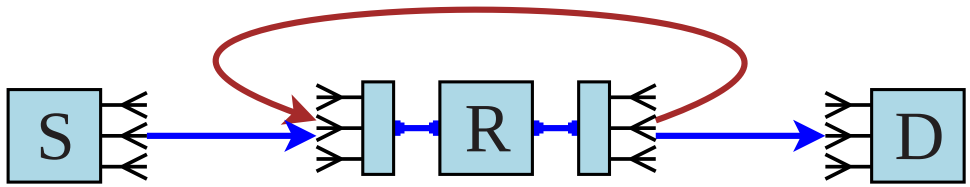
$$\mathbf{P}_{\mathrm{R}} = \mathcal{E}\{\tilde{\mathbf{x}}_{\mathrm{R}}\tilde{\mathbf{x}}_{\mathrm{R}}^{H}\} = \mathrm{diag}\left\{p_{\mathrm{R}}[1], \ldots, p_{\mathrm{R}}[N_{\mathrm{tx}}]\right\}$$

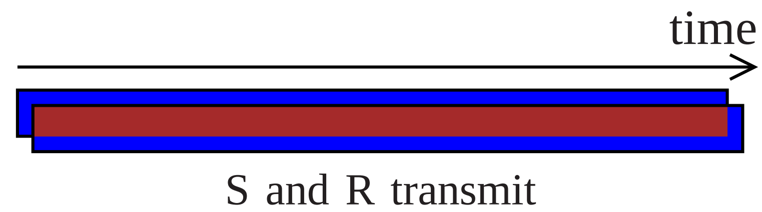
  - ▷ DF: The relay decodes $\tilde{\mathbf{y}}_{\mathrm{R}}$ and re-encodes the data into $\tilde{\mathbf{x}}_{\mathrm{R}}$
- Separate transmit power constraints:

$$p_{\mathrm{S}} = \mathrm{tr}\{\mathbf{P}_{\mathrm{S}}\} = \sum_{n=1}^{N_{\mathrm{S}}} p_{\mathrm{S}}[n] \leq 1, \qquad p_{\mathrm{R}} = \mathrm{tr}\{\mathbf{P}_{\mathrm{R}}\} = \sum_{n=1}^{N_{\mathrm{tx}}} p_{\mathrm{R}}[n] \leq 1$$

Transmission Rates

Transmission Rate: Full-Duplex Relay





- The rates of the two hops are given by

$$R_{\mathrm{SR}} = \log_2 \det\{\mathbf{I} + \tilde{\mathbf{\Sigma}}_{\mathrm{SR}} \mathbf{P}_{\mathrm{S}} \tilde{\mathbf{\Sigma}}_{\mathrm{SR}}^H\} = \sum_{n=1}^{\min\{N_{\mathrm{S}}, N_{\mathrm{rx}}\}} \log_2 \left(1 + p_{\mathrm{S}}[n] \tilde{\sigma}_{\mathrm{SR}}^2[n]\right)$$

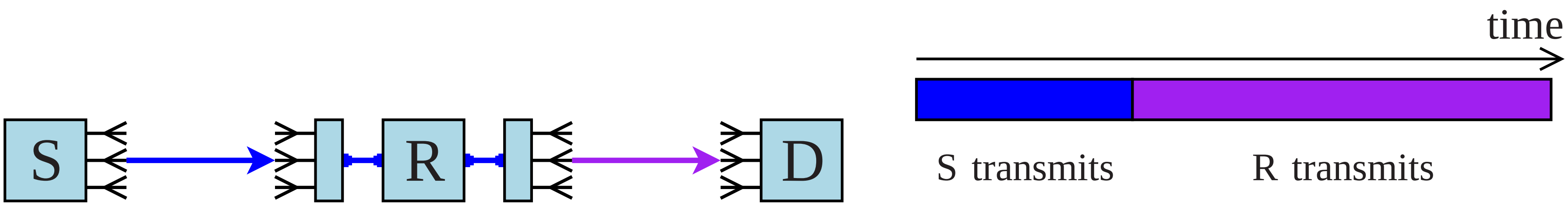
$$R_{\mathrm{RD}} = \log_2 \det\{\mathbf{I} + \mathbf{\Sigma}_{\mathrm{RD}} \mathbf{P}_{\mathrm{R}} \mathbf{\Sigma}_{\mathrm{RD}}^H\} = \sum_{n=1}^{\min\{N_{\mathrm{tx}}, N_{\mathrm{D}}\}} \log_2 \left(1 + p_{\mathrm{R}}[n] \sigma_{\mathrm{RD}}^2[n]\right)$$

- The end-to-end rate is given by

$$R_{\mathrm{FD}} = \min\{R_{\mathrm{SR}}, R_{\mathrm{RD}}\}$$

since data should not accumulate in the relay

Transmission Rate: Half-Duplex Relay



- By setting $\mathbf{H}_{\mathrm{RR}} = \mathbf{0}$, the rates of the two hops are given by R_{SR} and R_{RD} as shown in the previous slide
- The end-to-end rate is given by

$$R_{\mathrm{HD}} = \min\{\tau_{\mathrm{S}} R_{\mathrm{SR}}, \tau_{\mathrm{R}} R_{\mathrm{RD}}\}$$

  - ▷ The typical reference case is $\tau_{\mathrm{S}} = \tau_{\mathrm{R}} = \frac{1}{2}$
  - ▷ Optimal time shares are $\tau_{\mathrm{S}} = R_{\mathrm{RD}}/(R_{\mathrm{SR}} + R_{\mathrm{RD}})$, $\tau_{\mathrm{R}} = 1 - \tau_{\mathrm{S}}$:

$$R_{\mathrm{HD}} = \max_{\tau_{\mathrm{S}}+\tau_{\mathrm{R}} \leq 1} \min\{\tau_{\mathrm{S}} R_{\mathrm{SR}}, \tau_{\mathrm{R}} R_{\mathrm{RD}}\} = \frac{R_{\mathrm{SR}} R_{\mathrm{RD}}}{R_{\mathrm{SR}} + R_{\mathrm{RD}}}$$

Transmit Power Optimization

Separately Optimal Transmit Powers

- The reference case: Two-step approach for power allocation
  1. Maximize the second-hop rate:

$$C_{\mathrm{RD}} = \max_{\mathbf{P}_{\mathrm{R}}} R_{\mathrm{RD}} = \sum_{n=1}^{\min\{N_{\mathrm{tx}}, N_{\mathrm{D}}\}} \max\left\{0, \log_2\left(\mu_{\mathrm{R}} \sigma_{\mathrm{RD}}^2[n]\right)\right\}$$

  2. And then, given $\mathbf{P}_{\mathrm{R}}$, maximize the first-hop rate:

$$C_{\mathrm{SR}} = \max_{\mathbf{P}_{\mathrm{S}}} R_{\mathrm{SR}} = \sum_{n=1}^{\min\{N_{\mathrm{S}}, N_{\mathrm{rx}}\}} \max\left\{0, \log_2\left(\mu_{\mathrm{S}} \tilde{\sigma}_{\mathrm{SR}}^2[n]\right)\right\}$$

  Water-filling: $p_{\mathrm{S}}[n] = \max\{0, \mu_{\mathrm{S}} - \frac{1}{\tilde{\sigma}_{\mathrm{SR}}^2[n]}\}$, $p_{\mathrm{R}}[n] = \max\{0, \mu_{\mathrm{R}} - \frac{1}{\sigma_{\mathrm{RD}}^2[n]}\}$

- This approach is optimal for half-duplex relaying:

$$R_{\mathrm{HD}} = \frac{1}{2}\min\{C_{\mathrm{SR}}, C_{\mathrm{RD}}\}, \qquad C_{\mathrm{HD}} = \frac{C_{\mathrm{SR}} C_{\mathrm{RD}}}{C_{\mathrm{SR}} + C_{\mathrm{RD}}}$$

Jointly Optimal Transmit Powers

- Separate power adaptation is suboptimal for full duplex relaying, because the hops are coupled:

$$R_{\mathrm{FD}} = \min\{C_{\mathrm{SR}}, C_{\mathrm{RD}}\}$$

- Single-step approach for jointly optimal power allocation:

$$C_{\mathrm{FD}} = \max_{\mathbf{P}_{\mathrm{S}}, \mathbf{P}_{\mathrm{R}}} \min\{R_{\mathrm{SR}}, R_{\mathrm{RD}}\} = \max_{\mathbf{P}_{\mathrm{R}}} \min\{C_{\mathrm{SR}}, R_{\mathrm{RD}}\}$$

  - ▷ Only numerical solution available except for the SISO case
  - ▷ The solution lies in the subspace for which $C_{\mathrm{SR}} = R_{\mathrm{RD}}$

- Two-fold benefit from jointly optimal power allocation

  1. Interference is directed to the least harmful spatial dimensions
  2. End-to-end rate improvement by decreasing relay's Tx power

Numerical Results

Example System Setup

- Let us illustrate next power allocation in the simplest MIMO case, i.e., $N_{\mathrm{S}} = N_{\mathrm{rx}} = N_{\mathrm{tx}} = N_{\mathrm{D}} = 2$
- and choose randomized example channels as

$$\mathbf{H}_{\mathrm{SR}} = \sqrt{\gamma_{\mathrm{SR}}} \left(\begin{bmatrix} 0.5036 & 0.4348 \\ -0.5794 & 0.8751 \end{bmatrix} + \jmath \begin{bmatrix} 0.7546 & 0.8125 \\ 1.1061 & 0.0528 \end{bmatrix} \right)$$

$$\mathbf{H}_{\mathrm{RR}} = \sqrt{\gamma_{\mathrm{RR}}} \left(\begin{bmatrix} 0.5387 & 0.3153 \\ 0.7987 & -0.7633 \end{bmatrix} + \jmath \begin{bmatrix} -1.3410 & 0.2403 \\ -0.6481 & 0.3370 \end{bmatrix} \right)$$

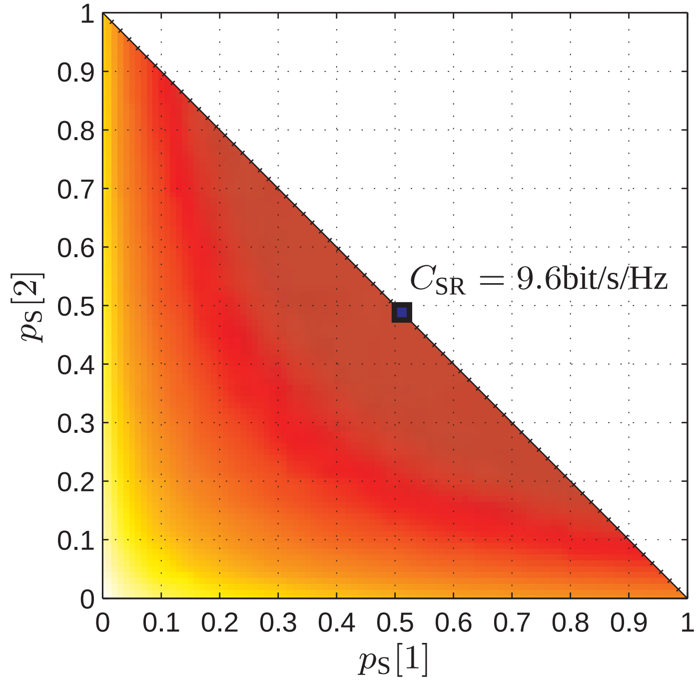
$$\mathbf{H}_{\mathrm{RD}} = \sqrt{\gamma_{\mathrm{RD}}} \left(\begin{bmatrix} 0.0281 & 0.7647 \\ -0.2892 & -0.5713 \end{bmatrix} + \jmath \begin{bmatrix} 0.4119 & -0.1978 \\ -1.2992 & 1.0524 \end{bmatrix} \right)$$

where γ_{SR}, γ_{RR}, and γ_{RD} represent the channel SNRs

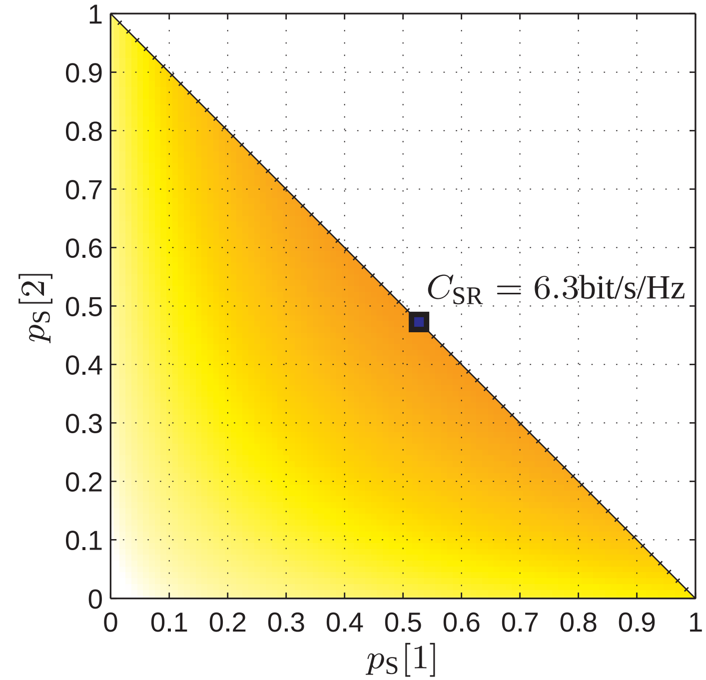
– Next slides: $\gamma_{\mathrm{SR}} = 15\mathrm{dB}$, $\gamma_{\mathrm{RR}} = 5\mathrm{dB}$, and $\gamma_{\mathrm{RD}} = 20\mathrm{dB}$

Effect of Self-Interference at First Hop

(a) R_{SR} when $p_{\mathrm{R}}[1] = p_{\mathrm{R}}[2] = 0$

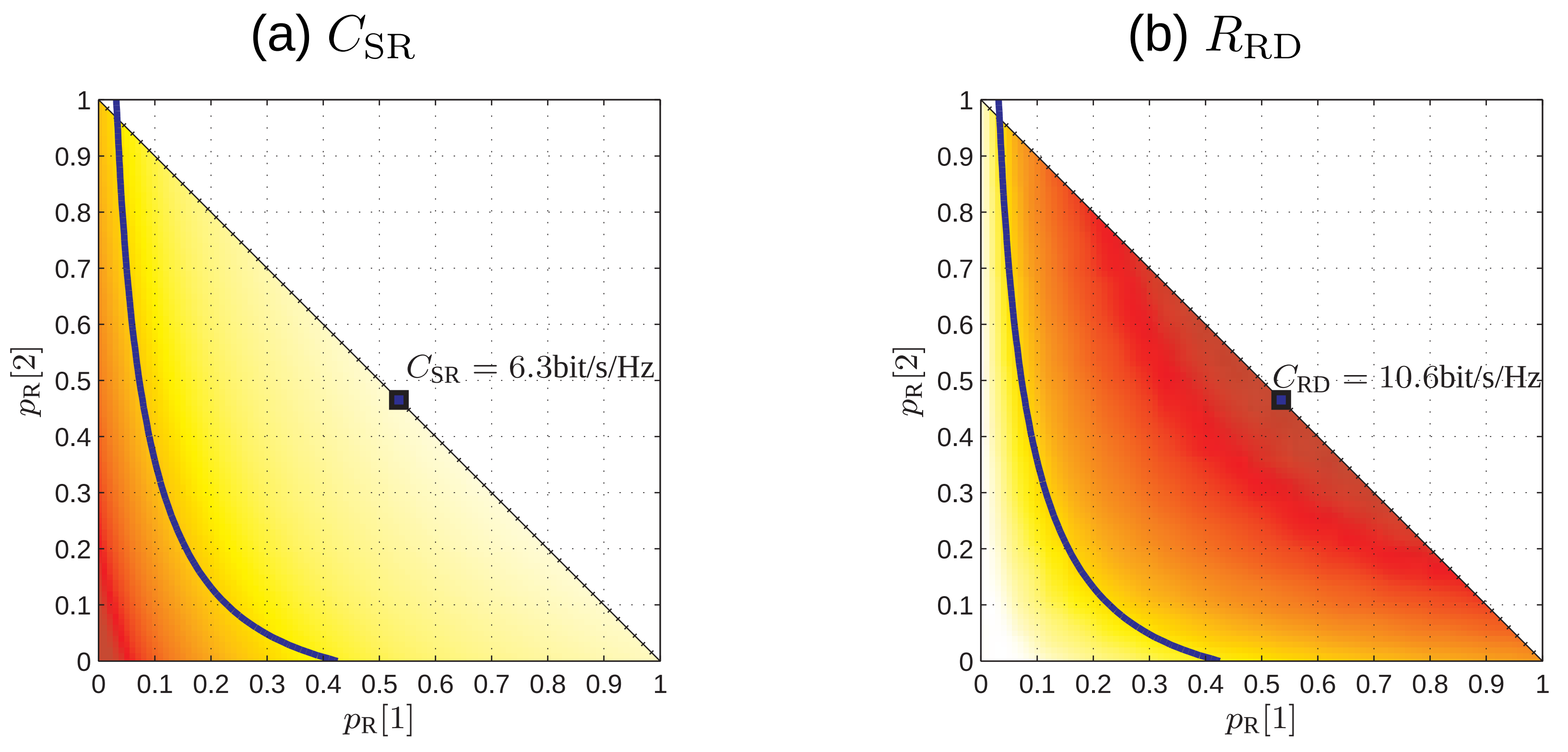


(b) R_{SR} when $p_{\mathrm{R}}[1] = p_{\mathrm{R}}[2] = \frac{1}{2}$



- The rate of the first hop drops significantly when the relay transmits
- The source should use maximum transmit power: $\sum_{n=1}^{N_{\mathrm{S}}} p_{\mathrm{S}}[n] = 1$

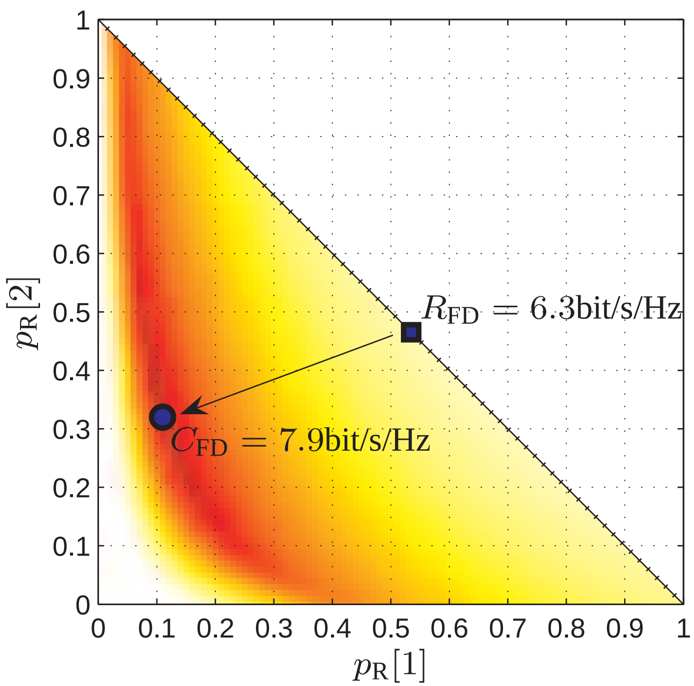
First Hop with Self-Interference vs. Second Hop



- Increasing relay transmit power benefits the second hop but harms the first hop. Equilibrium is optimal: $C_{\mathrm{SR}} = R_{\mathrm{RD}}$

Benefit of Transmit Power Optimization

(a) Full-duplex relay: R_{FD}



(b) Half-duplex relay

- Equal time shares:

$$R_{\mathrm{HD}} = 4.8\mathrm{bit/s/Hz}$$

- Optimal time shares:

$$C_{\mathrm{HD}} = 5.0\mathrm{bit/s/Hz}$$

- Full transmit power is used:

$$p_{\mathrm{R}}[1] + p_{\mathrm{R}}[2] = 1$$

- Transmit power adaptation increases the transmission rate by 25% while decreasing the total relay transmit power by 56%

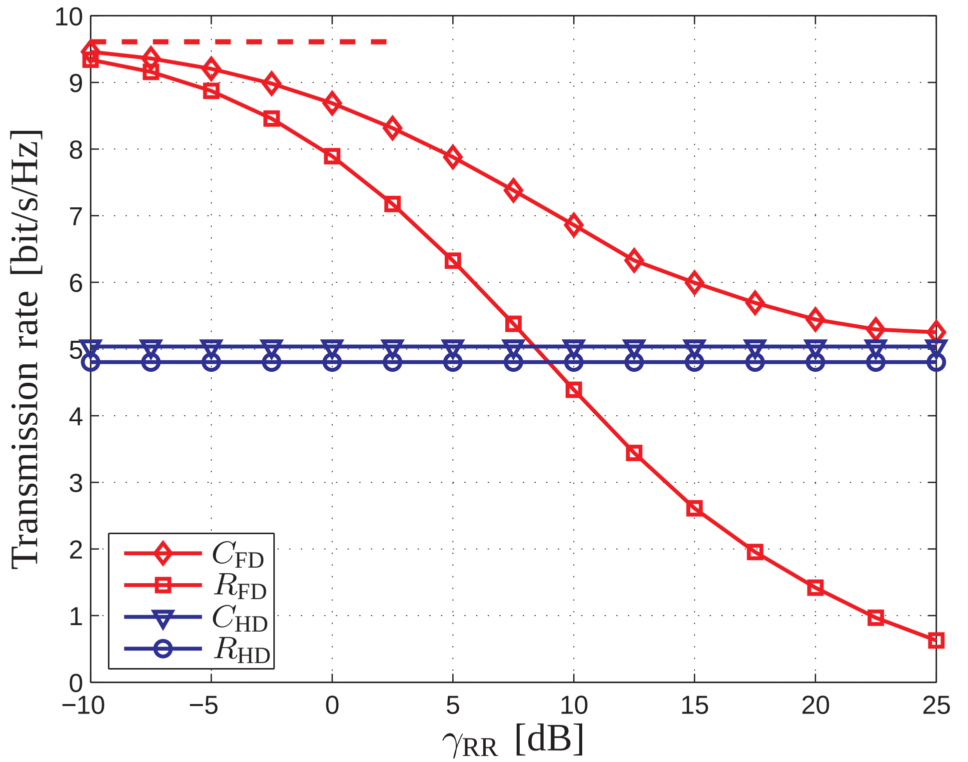
Transmission Rates vs. Self-Interference Level

- On the right: Varying γ_{RR} when

$$\gamma_{\mathrm{SR}} = 15\mathrm{dB}$$
$$\gamma_{\mathrm{RD}} = 20\mathrm{dB}$$

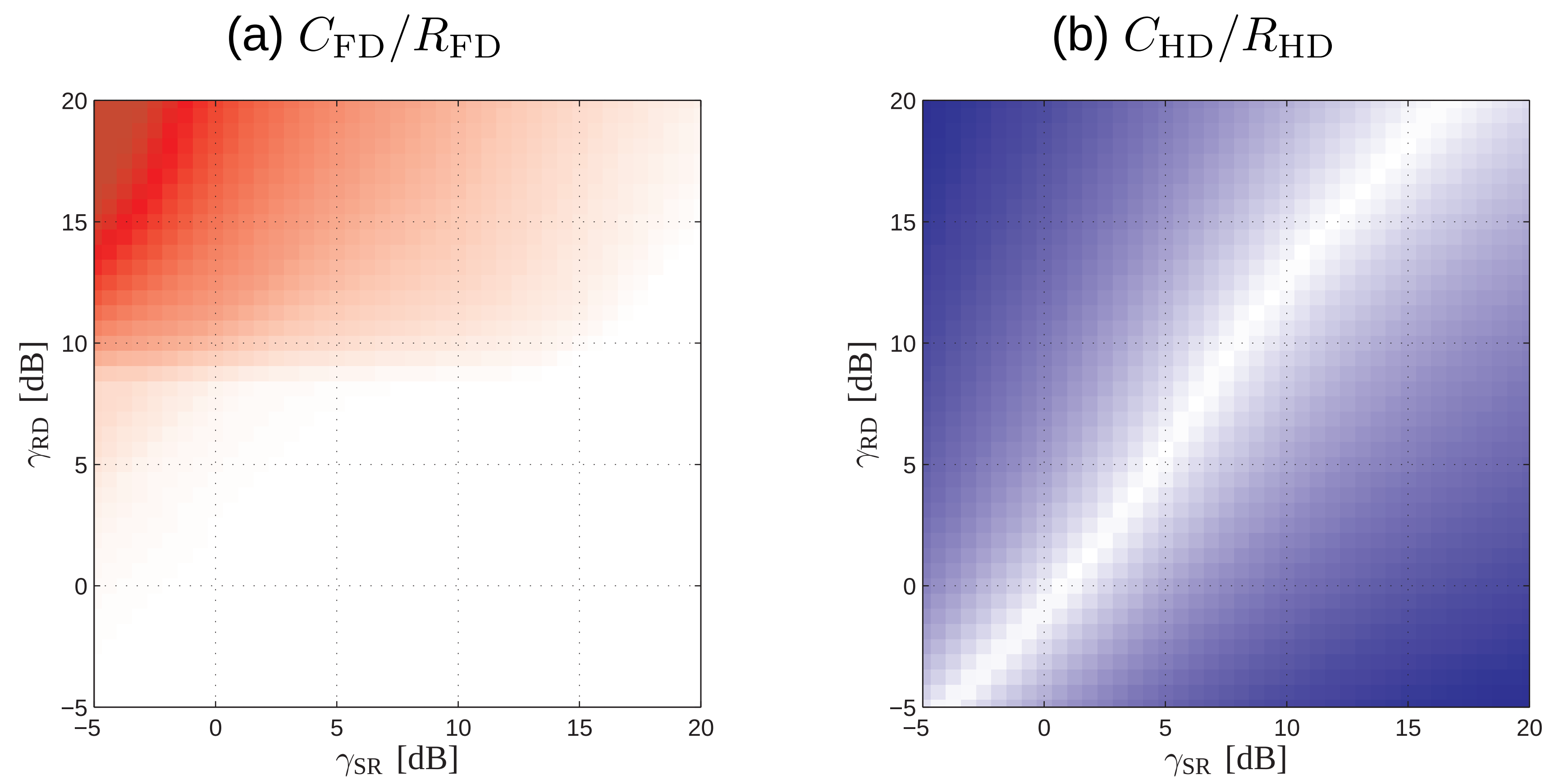
- Next slides: Varying γ_{SR} and γ_{RD} when

$$\gamma_{\mathrm{RR}} = 10\mathrm{dB}$$



- Spatial-division duplexing (SDD) vs. time-division duplexing (TDD)
  - ▷ If transmit power adaptation is used, full-duplex relay can achieve non-zero rate with any level of self-interference

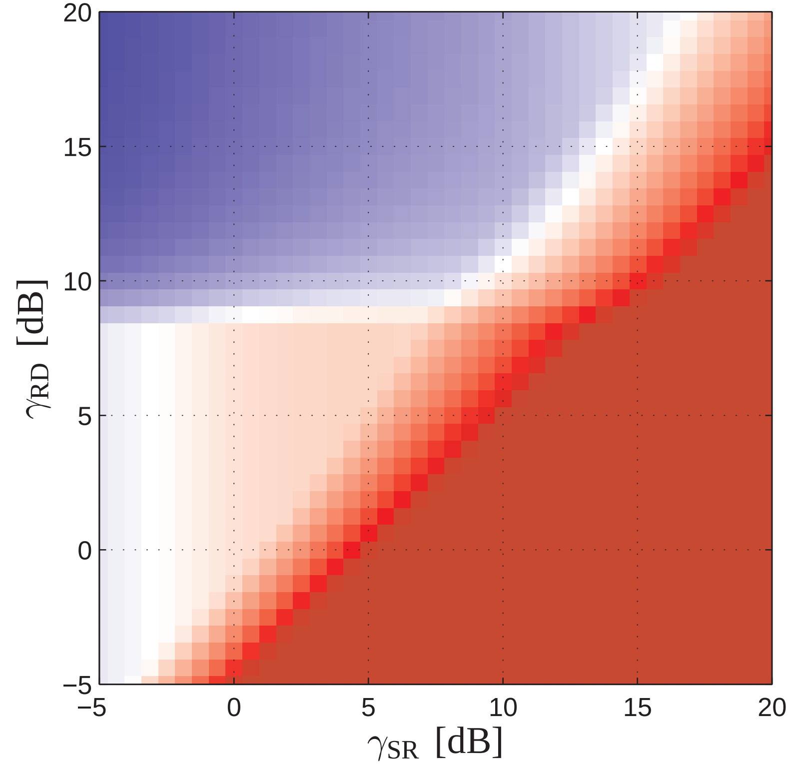
Power Optimization vs. Time Optimization



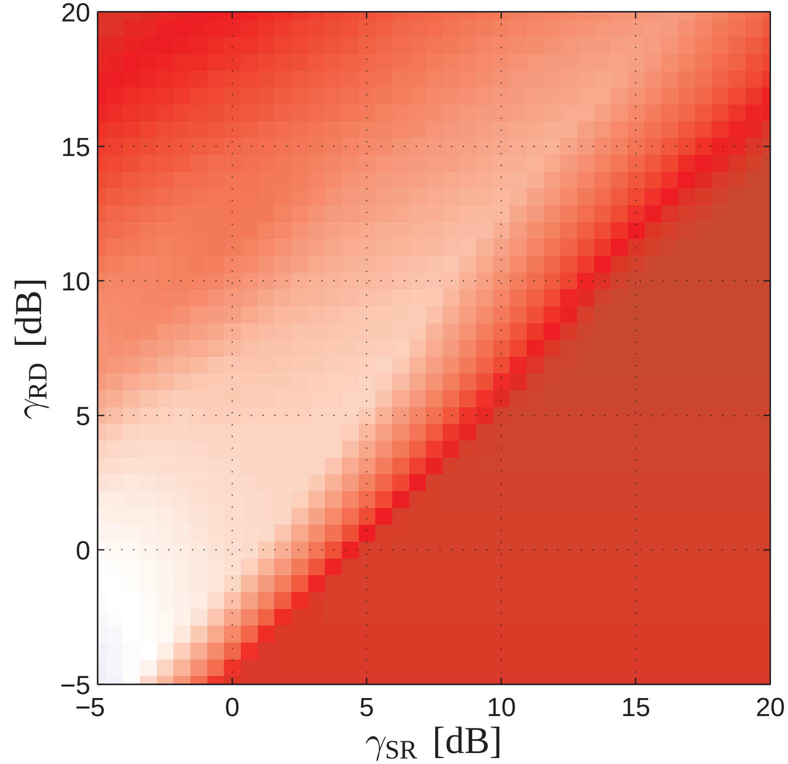
- FD: Up to *five* times larger rate using optimal transmit powers
- HD: Up to *two* times larger rate using optimal time shares

Full-Duplex Relaying vs. Half-Duplex Relaying (1)

(a) $R_{\text{FD}}/R_{\text{HD}}$



(b) $C_{\text{FD}}/R_{\text{HD}}$

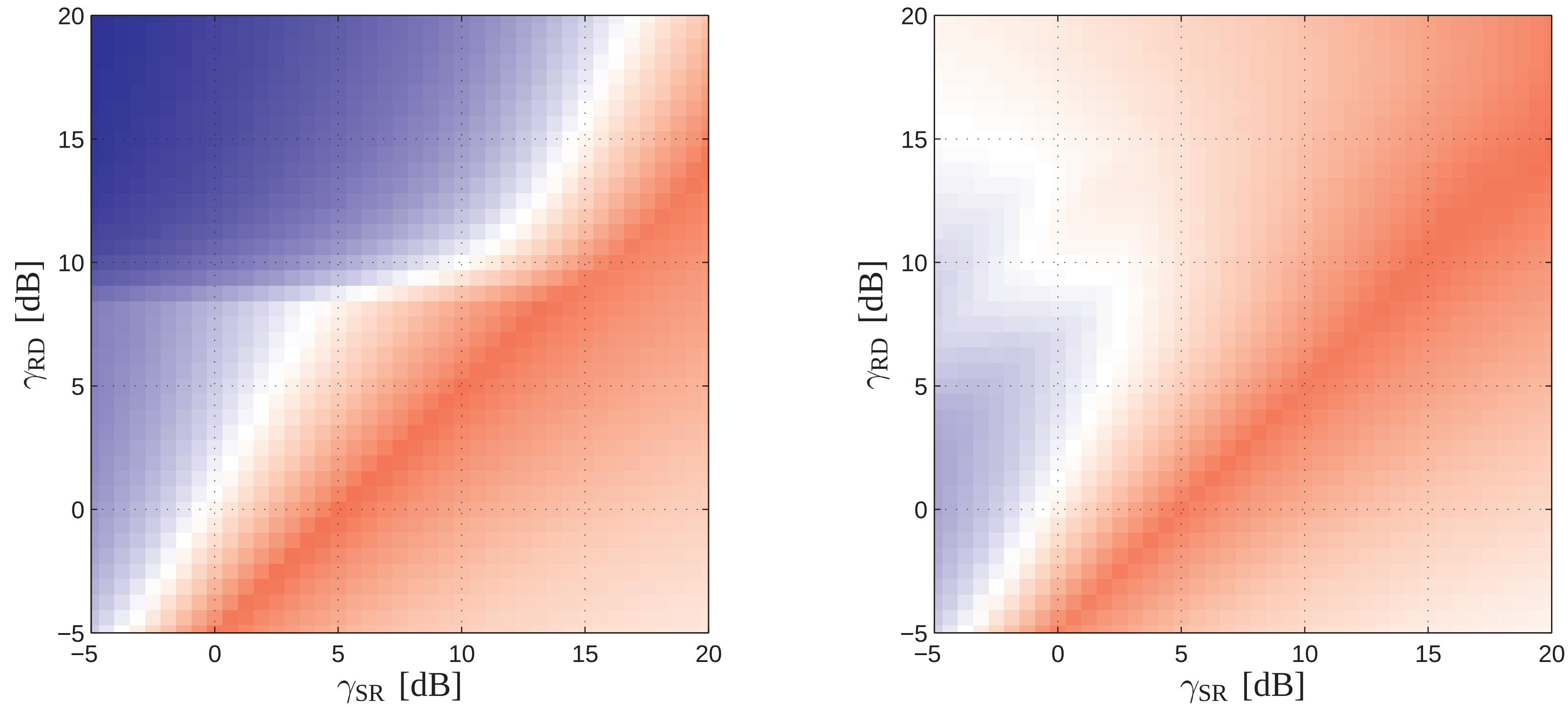


- Prefer FD when $\gamma_{\text{SR}} \gg \gamma_{\text{RD}}$
- Prefer HD when $\gamma_{\text{SR}} \ll \gamma_{\text{RD}}$

- FD is better or equal to HD within the whole SNR range

Full-Duplex Relaying vs. Half-Duplex Relaying (2)

(a) $R_{\text{FD}}/C_{\text{HD}}$ (b) $C_{\text{FD}}/C_{\text{HD}}$



- FD: Up to 60% higher rate
- HD: Up to 440% higher rate

- Up to 60% (FD) or 40% (HD) higher rate with mode selection

Conclusion

Conclusion

- Full-duplex MIMO relaying can offer significantly improved spectral efficiency w.r.t. half-duplex MIMO relaying
- Main technical problem: self-interference in the relay
  - ▷ Separated Rx and Tx antenna arrays for natural isolation
  - ▷ Mitigation schemes for additional isolation
- Optimal transmit power allocation for alleviating the effect of potential residual interference
  - ▷ Spatial-division duplexing instead of time-division half-duplex
  - ▷ Interference is directed to the least harmful dimensions
  - ▷ Simultaneous power savings and rate improvement
- Full-duplex vs. half-duplex relaying in an example case
  - ▷ Fair comparison: Half-duplex time slots can be optimized

References (SISO)

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