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Optimal Eigenbeamforming for Suppressing Self-Interference in Full-Duplex MIMO Relays

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Introduction

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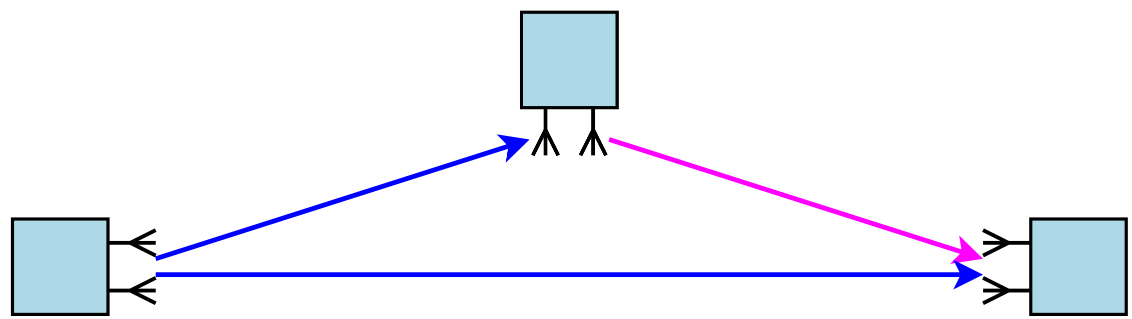
Half-Duplex Relaying: The Prevalent Concept

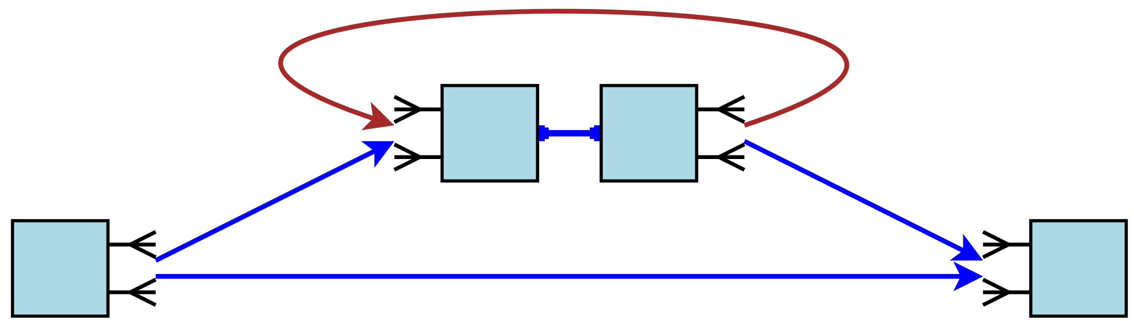
- Two-hop MIMO relay links have been a hot research topic recently



- Most of the literature assumes half-duplex relaying mode
  - ▷ Different time slots or frequency bands for relay Rx and Tx
    - – Disadvantage: $\sim 50\%$ loss in *system* spectral efficiency
  - ▷ Inevitable choice for relays with single antenna array: Weaker desired signal would be drowned by strong self-interference

Full-Duplex Relaying: Better Spectral Efficiency!

- MIMO relay with separated receive and transmit antenna arrays



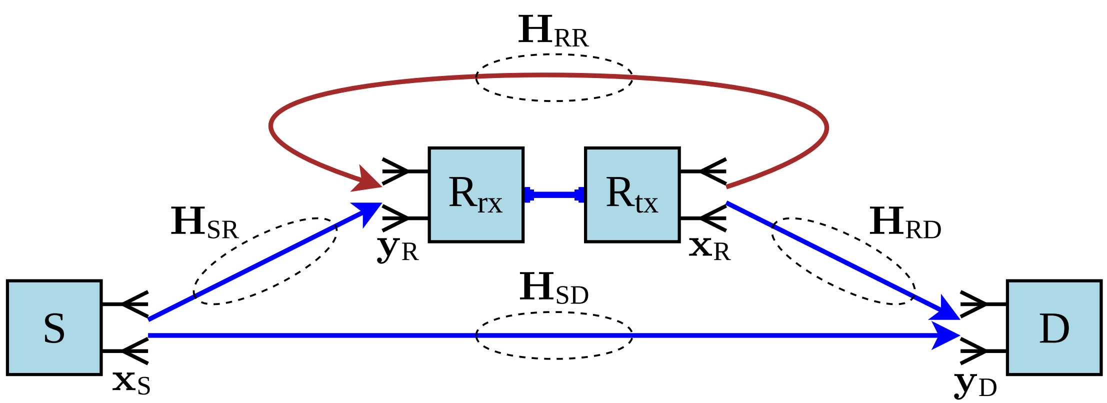
- It may be viable to choose the full-duplex mode, and avoid the loss of spectral efficiency which is inherent for the half-duplex mode
- Technical challenge: To keep residual self-interference minimal
  - ▷ *Natural isolation* facilitates the usage of signal processing techniques to provide *additional isolation*

In Our Paper

- Most earlier papers on full-duplex relays pay little attention to the existence of self-interference
  - ▷ We model explicitly the inevitable self-interference signal and study how to suppress it
- The SVD of the self-interference channel is previously exploited only in a suboptimal manner
  - ▷ We apply optimal eigenbeam selection and minimize the power of the self-interference
- Some earlier studies only simulate the performance of full-duplex MIMO relay links with self-interference
  - ▷ We evaluate the performance of the system using real-world channel measurement data

System Model and Experimental Setups

Signal Model



- Two-hop transmission through a full-duplex MIMO relay
  - Simultaneously, the source and the relay transmit

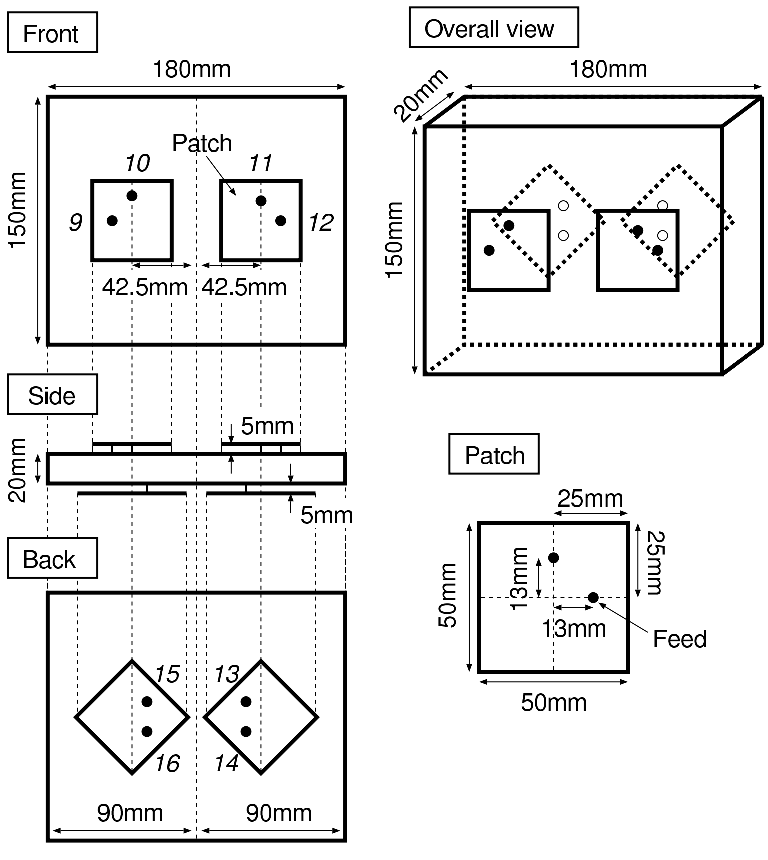
$$\mathbf{x}_{\mathrm{S}} \in \mathbb{C}^{N_{\mathrm{S}} \times 1} \quad \text{and} \quad \mathbf{x}_{\mathrm{R}} \in \mathbb{C}^{N_{\mathrm{tx}} \times 1}$$

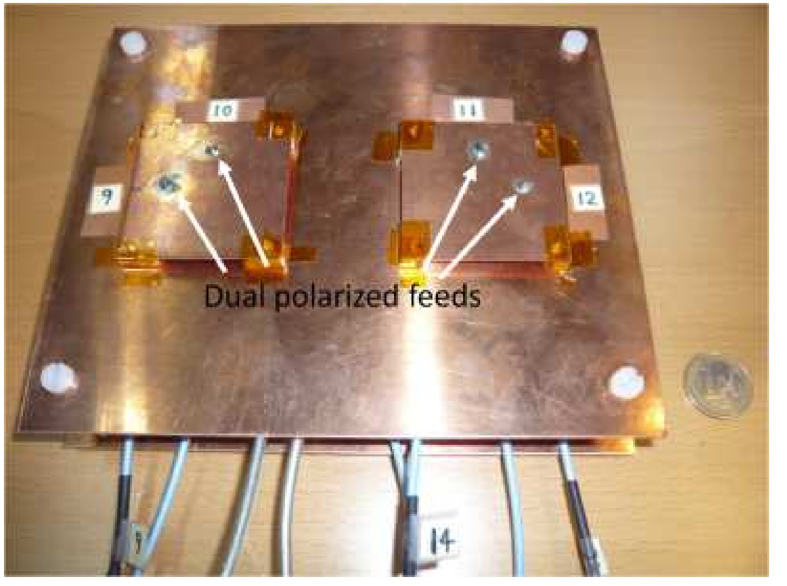
  - and the relay and the destination receive

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

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

Experimental Antenna Arrays for Full-Duplex MIMO Relay*

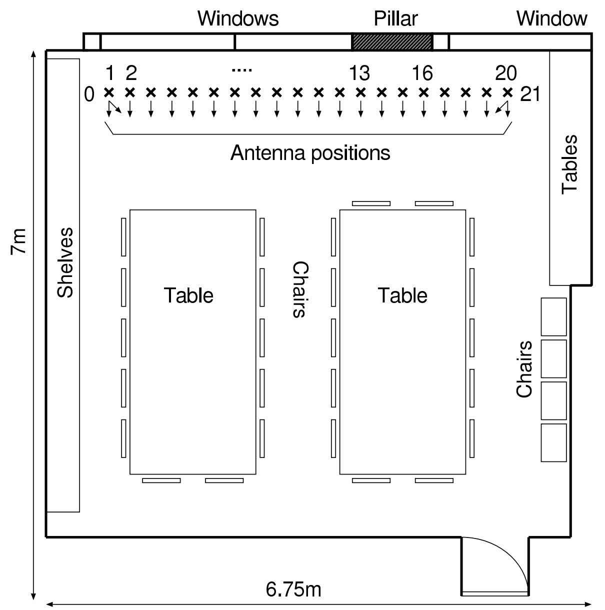


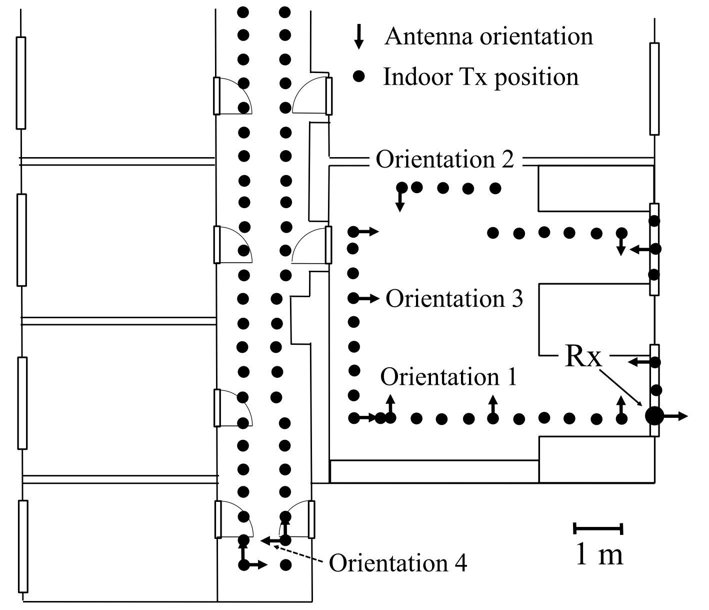


- Design goals:
  1. Compact size but high isolation
  2. 2.6GHz $\pm$ 100MHz operation band
  3. Multiple Rx and Tx antenna elements
- $N_{\mathrm{rx}} = N_{\mathrm{tx}} = 4$ in all numerical results!

*Further details are provided in [EuCAP'10]:
K. Haneda et al., "Measurement of loop-back interference channels for outdoor-to-indoor full-duplex radio relays," April 2010.

Channel Measurement Campaign for Outdoor-to-Indoor Relaying Scenarios*





Compact array configuration

- Arrays attached side-by-side (2cm)
- Small box like a Wi-Fi router
- Several positions next to windows

Separate array configuration

- Four Tx antenna orientations
- LOS: Tx in the same room as Rx
- NLOS: Tx in the adjacent corridor

* Further details are provided in [EuCAP'10]:
K. Haneda et al., "Measurement of loop-back interference channels for outdoor-to-indoor full-duplex radio relays," April 2010.

Experimental Results on Natural Isolation

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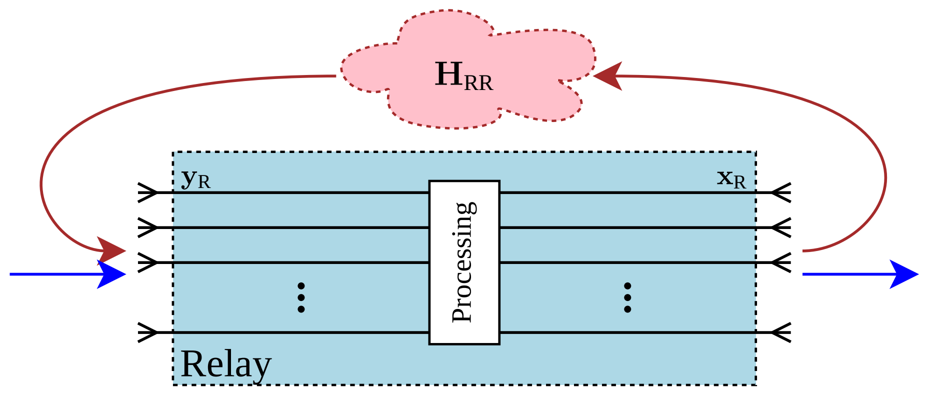
Natural Isolation



- The power of the undesired self-interference term is

$$P_{\mathrm{I}} = \mathcal{E}\{\|\mathbf{H}_{\mathrm{RR}}\mathbf{x}_{\mathrm{R}}\|_2^2\} = \mathrm{tr}\{\mathbf{H}_{\mathrm{RR}}\mathbf{R}_{\mathbf{x}_{\mathrm{R}}}\mathbf{H}_{\mathrm{RR}}^H\} \text{ where } \mathbf{R}_{\mathbf{x}_{\mathrm{R}}} = \mathcal{E}\{\mathbf{x}_{\mathrm{R}}\mathbf{x}_{\mathrm{R}}^H\}$$

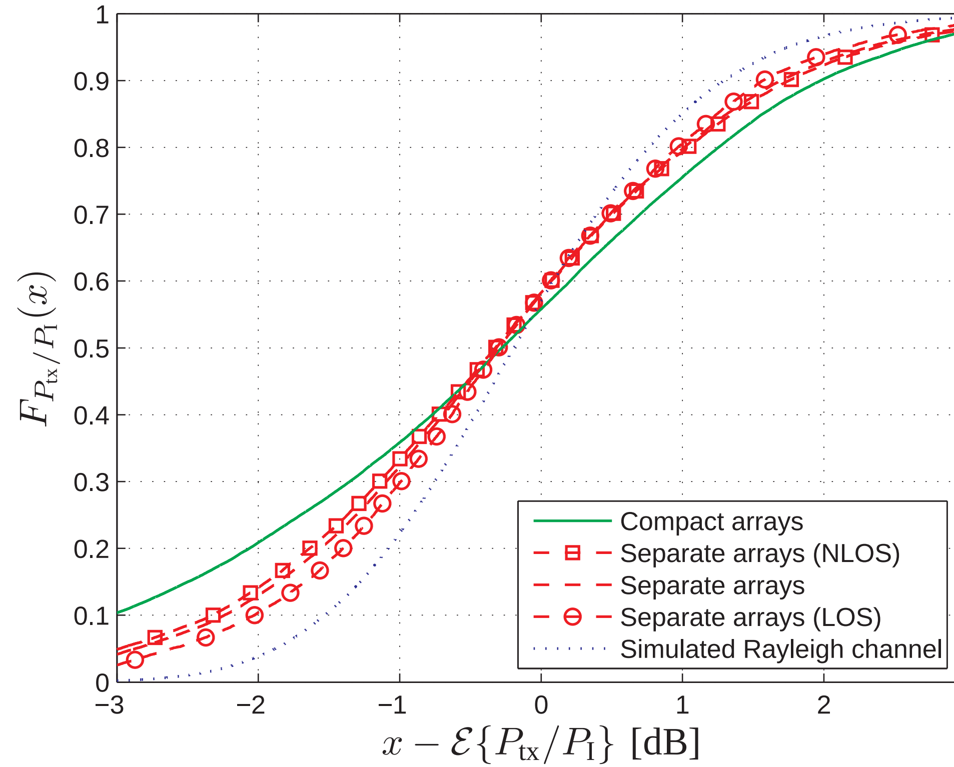
- Next slides: Analysis of experimental natural isolation given by

$$P_{\mathrm{tx}}/P_{\mathrm{I}} = 1/\|\mathbf{H}_{\mathrm{RR}}\|_F^2 \text{ when } \mathbf{R}_{\mathbf{x}_{\mathrm{R}}} = P_{\mathrm{tx}}\mathbf{I}$$

  - Distribution of natural isolation: $F_{P_{\mathrm{tx}}/P_{\mathrm{I}}}(\cdot)$
  - Average natural isolation: $\mathcal{E}\{P_{\mathrm{tx}}/P_{\mathrm{I}}\}$

Variation of Natural Isolation (1)

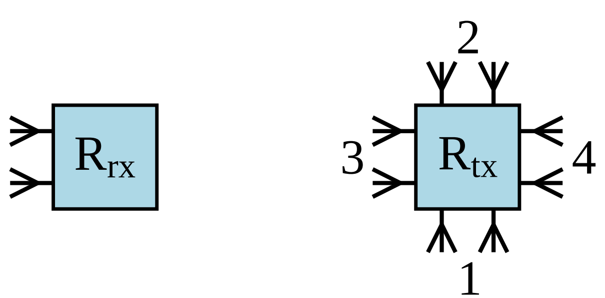
- Empirical cumulative distribution function of natural isolation
- Channel samples from measurements over different frequency bins and antenna locations
- Comparison of the configurations

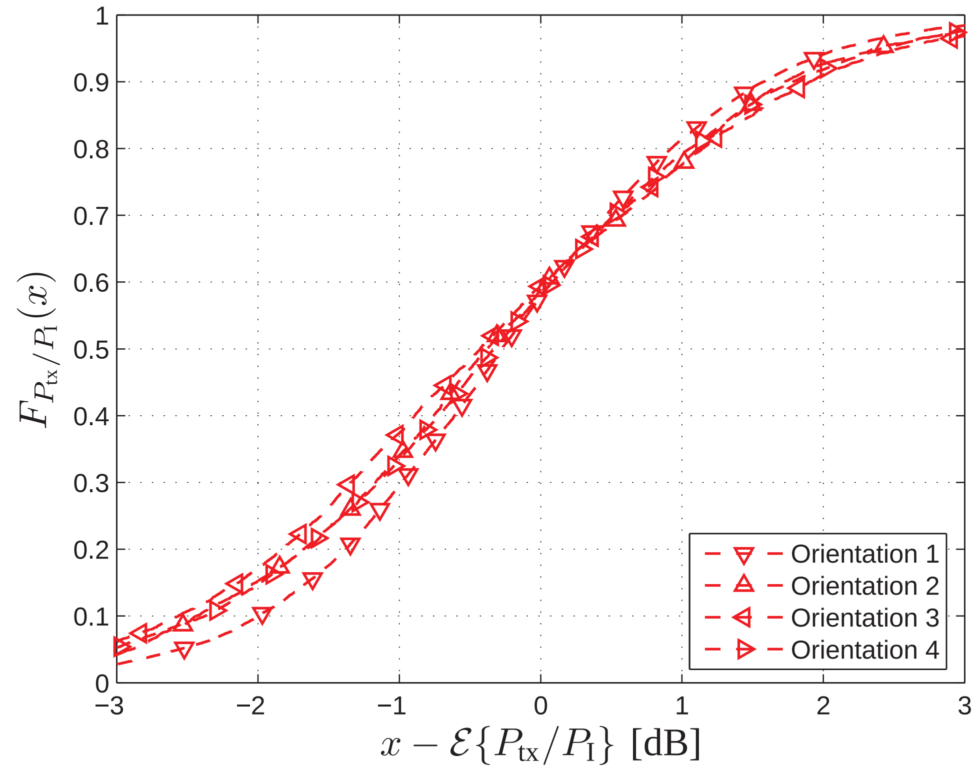


- Variance around the average isolation:
  Compact arrays $>$ Separate arrays $>$ Rayleigh channel
- LOS channels vary less than NLOS channels (this is intuitive)

Variation of Natural Isolation (2)

- Empirical cumulative distribution function of natural isolation
- Channel samples from measurements over different frequency bins and antenna positions
- Comparison of the orientations

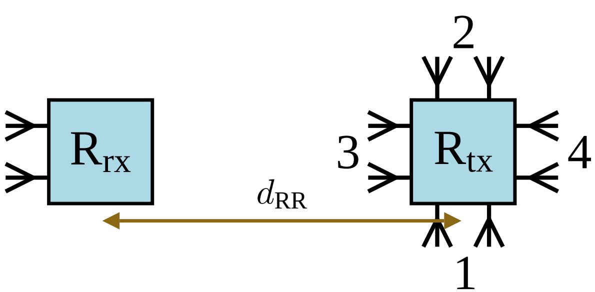


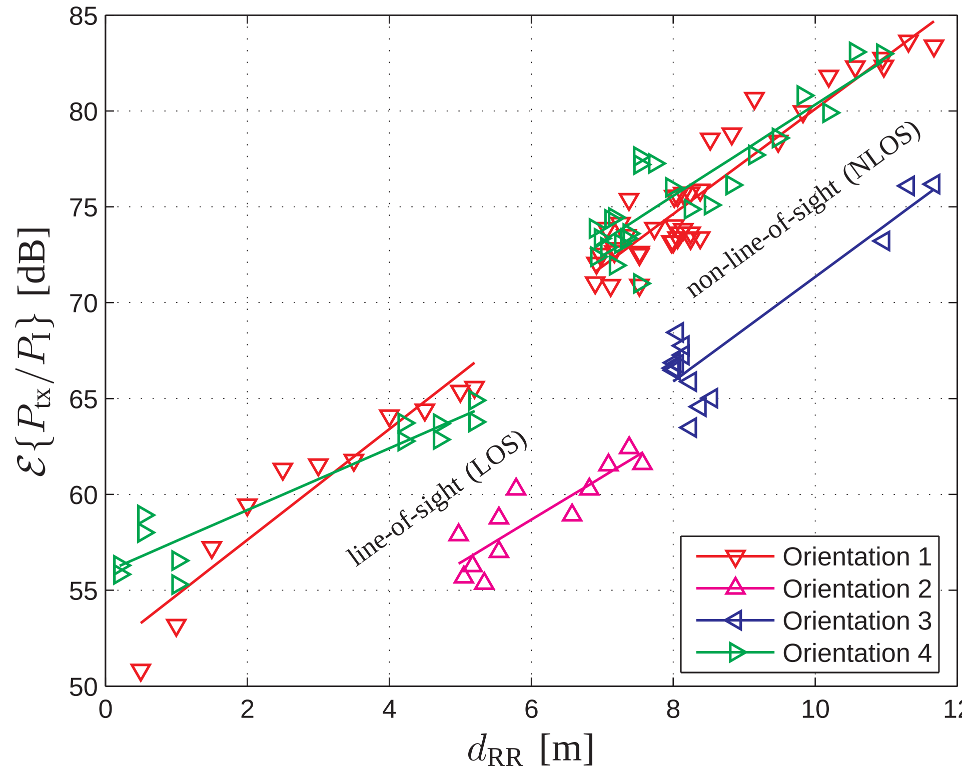


- Tx array orientation affects significantly the *natural isolation*, while we will see that the *additional isolation* due to eigenbeamforming is quite the same with all orientations

Average Natural Isolation

- For compact array configuration, $\mathcal{E}\{P_{\rm tx}/P_{\rm I}\} = 36.2$dB
- For separate array configuration, $\mathcal{E}\{P_{\rm tx}/P_{\rm I}\}$ is directly proportional to antenna separation (2–3dB/m)

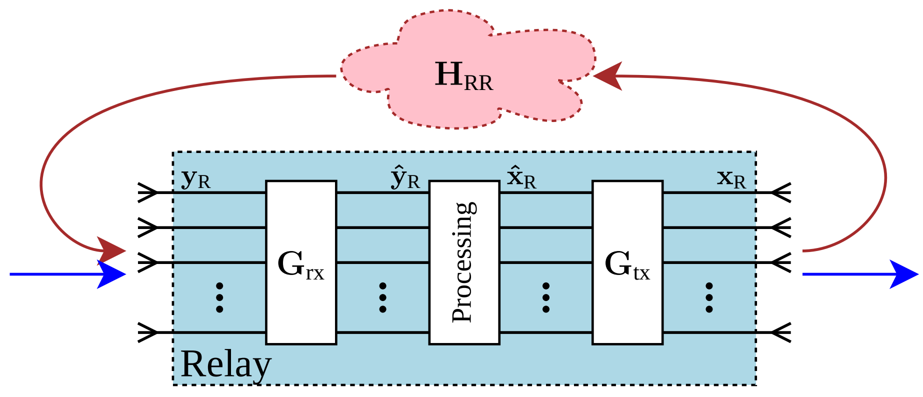




- 20dB isolation from window glass for separate array configuration
- Mere natural isolation may not be sufficient which motivates us to obtain additional isolation with signal processing

Additional Isolation from Eigenbeamforming

Spatial Suppression



- Received and transmitted signals with spatial filters:

$$\hat{\mathbf{y}}_{\mathrm{R}} = \mathbf{G}_{\mathrm{rx}}\mathbf{y}_{\mathrm{R}} \quad \text{and} \quad \mathbf{x}_{\mathrm{R}} = \mathbf{G}_{\mathrm{tx}}\hat{\mathbf{x}}_{\mathrm{R}}$$

  - ▹ With successful mitigation, any MIMO relaying protocol could be used for generating $\hat{\mathbf{x}}_{\mathrm{R}} \in \mathbb{C}^{\hat{N}_{\mathrm{tx}}\times 1}$ based on $\hat{\mathbf{y}}_{\mathrm{R}} \in \mathbb{C}^{\hat{N}_{\mathrm{rx}}\times 1}$

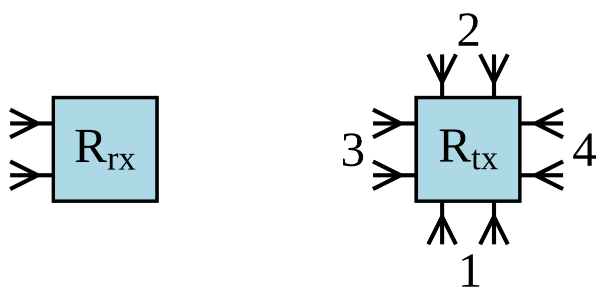
- Filter design such that $\mathbf{G}_{\mathrm{rx}}\mathbf{H}_{\mathrm{RR}}\mathbf{G}_{\mathrm{tx}} \approx \mathbf{0}$ in

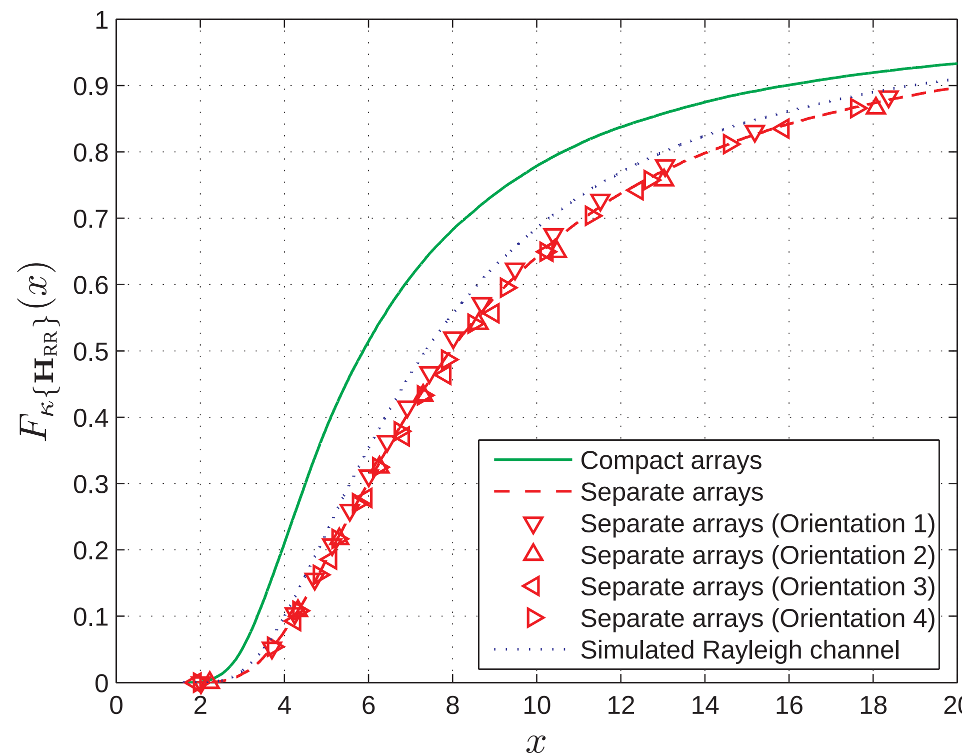
$$\hat{\mathbf{y}}_{\mathrm{R}} = \mathbf{G}_{\mathrm{rx}}(\mathbf{H}_{\mathrm{SR}}\mathbf{x}_{\mathrm{S}} + \mathbf{n}_{\mathrm{R}}) + \mathbf{G}_{\mathrm{rx}}\mathbf{H}_{\mathrm{RR}}\mathbf{G}_{\mathrm{tx}}\hat{\mathbf{x}}_{\mathrm{R}}$$

Motivation for Eigenbeamforming

- Channel condition number

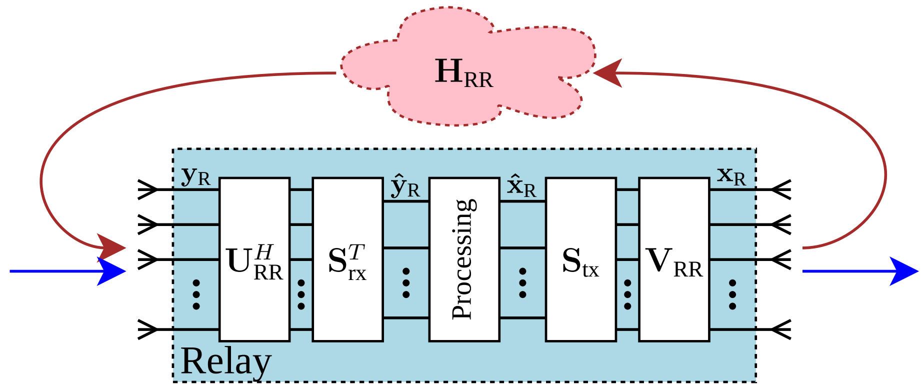
$$\kappa\{\mathbf{H}_{\text{RR}}\} = \|\mathbf{H}_{\text{RR}}\|_2 \cdot \|\mathbf{H}_{\text{RR}}^{-1}\|_2$$
$$= \frac{\sigma_{\text{RR}}[1]}{\sigma_{\text{RR}}[\min\{N_{\text{rx}}, N_{\text{tx}}\}]}$$





- For measured channels, $\text{rk}\{\mathbf{H}_{\text{RR}}\} = \min\{N_{\text{rx}}, N_{\text{tx}}\}$ (full rank) but still $\kappa\{\mathbf{H}_{\text{RR}}\} > 1$ (non-uniform eigenmodes)
  - ▷ Idea: The relay could point interfering transmit and receive beams to the minimum eigenmodes!

Eigenbeamforming



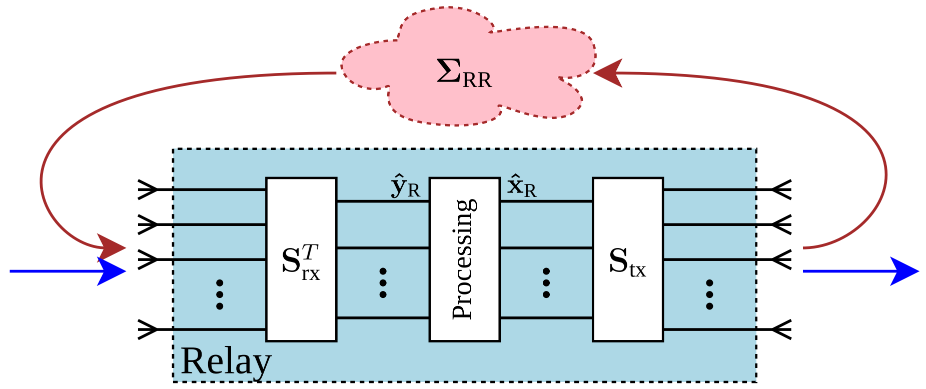
- Let us choose the receive and transmit filters as

$$\mathbf{G}_{\mathrm{rx}} = \mathbf{S}_{\mathrm{rx}}^{T}\mathbf{U}_{\mathrm{RR}}^{H} \quad \text{and} \quad \mathbf{G}_{\mathrm{tx}} = \mathbf{V}_{\mathrm{RR}}\mathbf{S}_{\mathrm{tx}}$$

  - SVD of the self-interference channel: $\mathbf{H}_{\mathrm{RR}} = \mathbf{U}_{\mathrm{RR}}\mathbf{\Sigma}_{\mathrm{RR}}\mathbf{V}_{\mathrm{RR}}^{H}$
  - Generic row and column subset selection matrices: $\mathbf{S}_{\mathrm{rx}}^{T} \in \{0,1\}^{\hat{N}_{\mathrm{rx}}\times N_{\mathrm{rx}}}$, $\mathbf{S}_{\mathrm{tx}} \in \{0,1\}^{N_{\mathrm{tx}}\times \hat{N}_{\mathrm{tx}}}$

- Eigenbeamforming yields a sparse residual interference channel: $\mathbf{G}_{\mathrm{rx}}\mathbf{H}_{\mathrm{RR}}\mathbf{G}_{\mathrm{tx}} = \mathbf{S}_{\mathrm{rx}}^{T}(\mathbf{U}_{\mathrm{RR}}^{H}\mathbf{U}_{\mathrm{RR}})\mathbf{\Sigma}_{\mathrm{RR}}(\mathbf{V}_{\mathrm{RR}}^{H}\mathbf{V}_{\mathrm{RR}})\mathbf{S}_{\mathrm{tx}} = \mathbf{S}_{\mathrm{rx}}^{T}\mathbf{\Sigma}_{\mathrm{RR}}\mathbf{S}_{\mathrm{tx}}$

Optimal Beam Selection

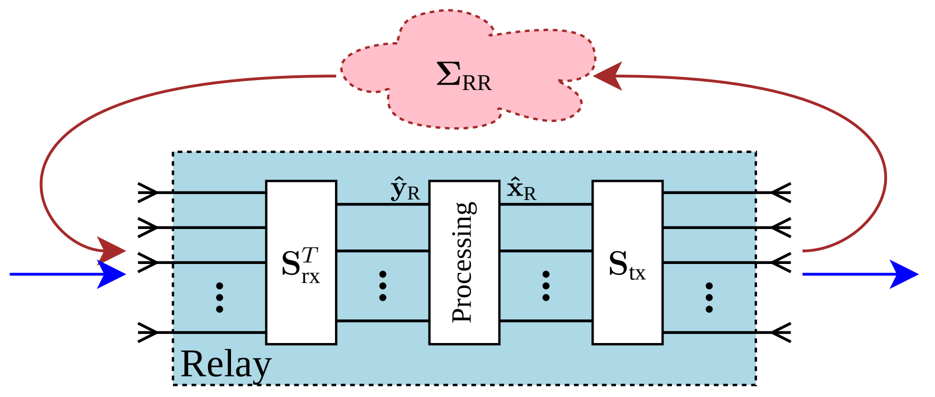


- Minimize $\|\mathbf{S}_{\mathrm{rx}}^T \mathbf{\Sigma}_{\mathrm{RR}} \mathbf{S}_{\mathrm{tx}}\|_F^2$ to suppress self-interference efficiently and $\|\mathbf{\Sigma}_{\mathrm{RR}} \mathbf{S}_{\mathrm{tx}}\|_F^2$ to reduce the risk of Rx front-end saturation
  $\Rightarrow$ Example solution

$$\mathbf{S}_{\mathrm{rx}}^T = \begin{bmatrix} \mathbf{I}_{N_{\mathrm{tx}}-\hat{N}_{\mathrm{tx}}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}_{\hat{N}_{\mathrm{rx}}+\hat{N}_{\mathrm{tx}}-N_{\mathrm{tx}}} \end{bmatrix} \quad \text{and} \quad \mathbf{S}_{\mathrm{tx}} = \begin{bmatrix} \mathbf{0} \\ \mathbf{I}_{\hat{N}_{\mathrm{tx}}} \end{bmatrix}$$

- Residual interference power: $P_{\mathrm{I}} = P_{\mathrm{tx}} \sum_{n=N_{\mathrm{rx}}+N_{\mathrm{tx}}-(\hat{N}_{\mathrm{rx}}+\hat{N}_{\mathrm{tx}})+1}^{\min\{N_{\mathrm{rx}},N_{\mathrm{tx}}\}} \sigma_{\mathrm{RR}}^2[n]$
  - ▷ Sum of $\hat{N}_{\mathrm{rx}} + \hat{N}_{\mathrm{tx}} - \max\{N_{\mathrm{rx}}, N_{\mathrm{tx}}\}$ smallest singular values

Special Case: Null-Space Projection



- Transmission and reception in orthogonal subspaces
- Optimal beam selection yields $\mathbf{S}_{\mathrm{rx}}^T \mathbf{\Sigma}_{\mathrm{RR}} \mathbf{S}_{\mathrm{tx}} = \mathbf{0}$, i.e., $P_{\mathrm{I}} = 0$, if

$$\hat{N}_{\mathrm{rx}} + \hat{N}_{\mathrm{tx}} \leq N_{\mathrm{rx}} + N_{\mathrm{tx}} - \mathrm{rk}\{\mathbf{H}_{\mathrm{RR}}\}$$

  - ▷ But measurements indicate that $\mathrm{rk}\{\mathbf{H}_{\mathrm{RR}}\} = \min\{N_{\mathrm{rx}}, N_{\mathrm{tx}}\}$

- In practice, the condition becomes

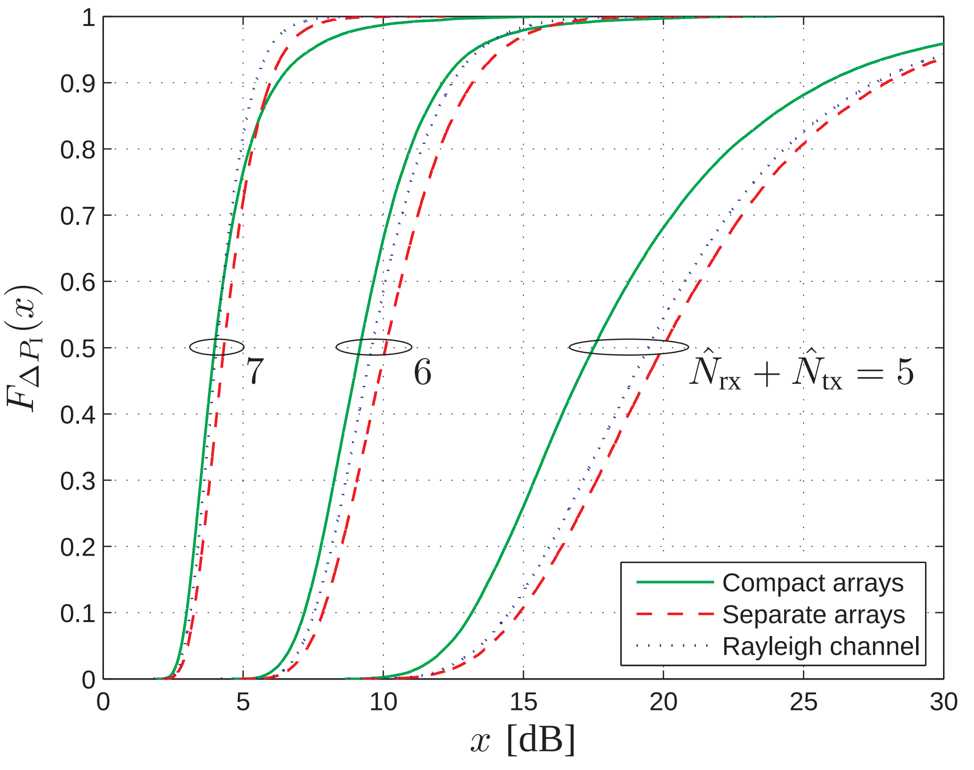
$$\hat{N}_{\mathrm{rx}} + \hat{N}_{\mathrm{tx}} \leq \max\{N_{\mathrm{rx}}, N_{\mathrm{tx}}\}$$

Variation of Additional Isolation (1)

- Isolation improvement

$$\Delta P_{\mathrm{I}} = \frac{\|\mathbf{H}_{\mathrm{RR}}\|_F^2}{\|\mathbf{S}_{\mathrm{rx}}^T \mathbf{\Sigma}_{\mathrm{RR}} \mathbf{S}_{\mathrm{tx}}\|_F^2}$$

- Comparison of the configurations



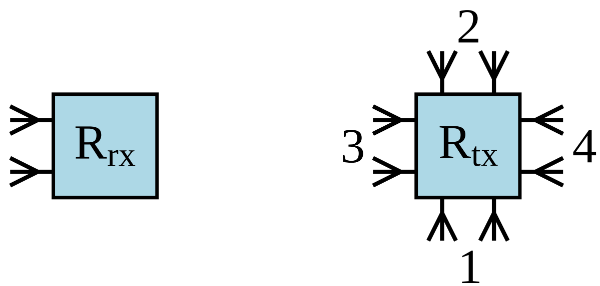
- The separate array configuration seems to benefit more from eigenbeamforming than the compact array configuration
- Rayleigh model is in between the two measured configurations

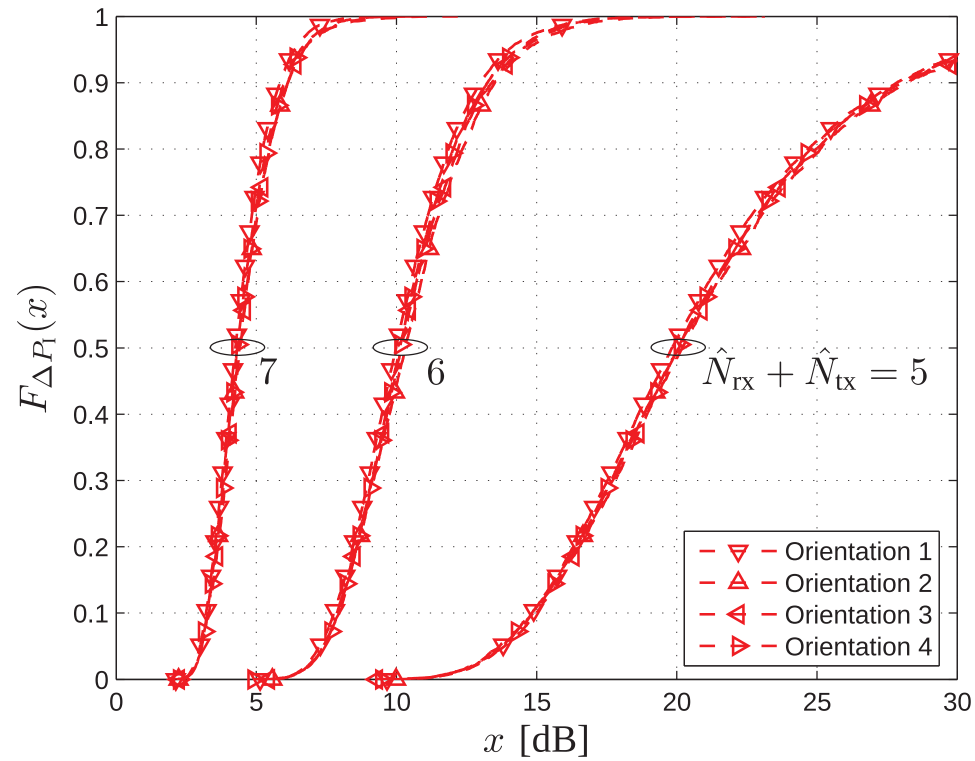
Variation of Additional Isolation (2)

- Isolation improvement

$$\Delta P_{\mathrm{I}} = \frac{\|\mathbf{H}_{\mathrm{RR}}\|_F^2}{\|\mathbf{S}_{\mathrm{rx}}^T \mathbf{\Sigma}_{\mathrm{RR}} \mathbf{S}_{\mathrm{tx}}\|_F^2}$$

- Comparison of the orientations





- Tx array orientation affects little the additional isolation
- The difference between LOS and NLOS channels is even smaller than the differences between the orientations (not shown here)

Conclusion

Total Isolation

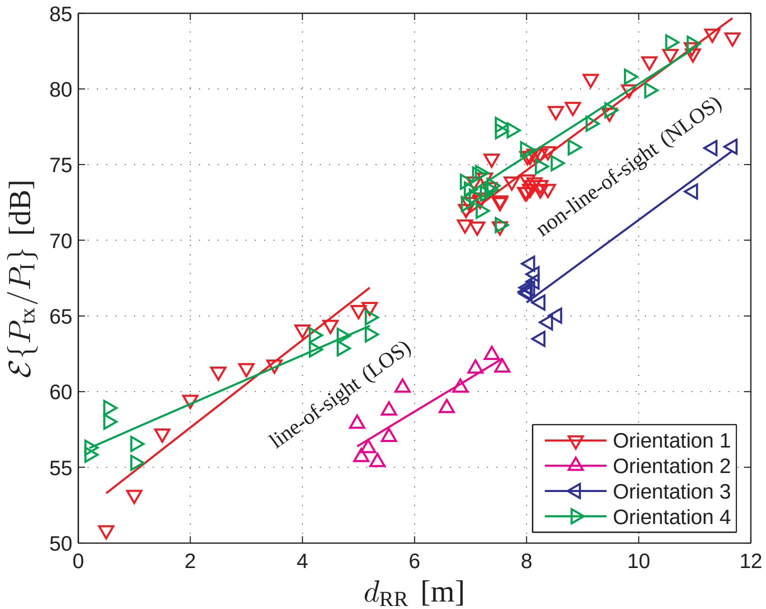
Natural isolation

$\mathcal{E}\{P_{\text{tx}}/P_{\text{I}}\}$

+

Additional isolation

$\mathcal{E}\{\Delta P_{\text{I}}\}$



$\hat{N}_{\text{rx}} + \hat{N}_{\text{tx}}$	Compact arrays	Separate arrays	Rayleigh channel
2	∞	∞	∞
3	∞	∞	∞
4	∞	∞	∞
5	24.8dB	26.5dB	26.3dB
6	10.2dB	10.9dB	10.4dB
7	4.8dB	4.6dB	4.3dB
8	0dB	0dB	0dB

- 2–4 streams: null-space projection
- 5–7 streams: eigenbeamforming
- 8 streams: no additional isolation

- In practice, total isolation is also limited by imperfections in the side information needed for suppression (see [ACSSC'09, ACSSC'10])

Conclusion

- Full-duplex relaying could offer significantly improved spectral efficiency w.r.t. conventional half-duplex relaying
- Main technical problem: self-interference in the relay
  - ▷ Separated Rx and Tx antenna arrays for natural isolation
  - ▷ Signal processing for additional isolation
    - In this paper: optimal eigenbeamforming
- We investigated how much isolation could be achieved in practice
  - ▷ Design and manufacturing of prototype antenna arrays
  - ▷ Channel measurement campaign for outdoor-to-indoor relaying scenarios at 2.6GHz band
  - ▷ Analysis of achievable total (= natural + additional) isolation

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