Spatial Loop Interference Suppression in Full-Duplex MIMO Relays

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Introduction

- Full-duplex relay a.k.a. on-channel repeater a.k.a. gap filler

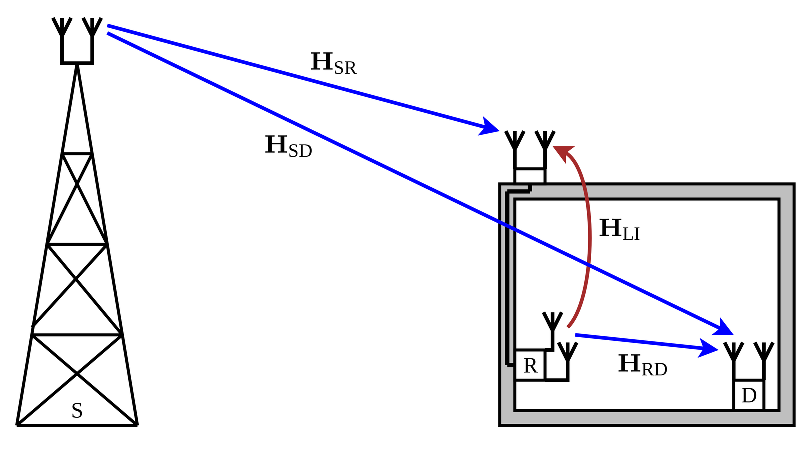


Fig. 1. Two-hop full-duplex multi-antenna relay link in a typical outdoor-to-indoor transmission scenario. The MIMO channels are represented by $\mathbf{H}_{\text{SR}}$, $\mathbf{H}_{\text{RD}}$, $\mathbf{H}_{\text{LI}}$, and $\mathbf{H}_{\text{SD}}$.

  - Patching coverage holes cost-efficiently
  - Boosting cell edge coverage by reducing path losses
  - MIMO relay is needed if the end-to-end transmission exploits multiantenna techniques
  - Separated receive and transmit antenna arrays in the relay

- The main technical challenge is the *loop interference*, i.e., crosstalk between transmission and reception of the relay

System model

- Signal model with processing delay τ

$$\begin{aligned}\mathbf{r}[i] &= \mathbf{H}_{\text{SR}}\mathbf{x}[i] + \mathbf{H}_{\text{LI}}\mathbf{t}[i] + \mathbf{n}_{\text{R}}[i]\\ \mathbf{t}[i] &= f(\mathbf{r}[i-\tau], \mathbf{r}[i-(\tau+1)], \mathbf{r}[i-(\tau+2)], \ldots)\\ \mathbf{y}[i] &= \mathbf{H}_{\text{RD}}\mathbf{t}[i] + \mathbf{H}_{\text{SD}}\mathbf{x}[i] + \mathbf{n}_{\text{D}}[i]\end{aligned}$$

  - Source and relay have $N_{\text{S,tx}}$ and $N_{\text{R,tx}}$ transmit antennas, respectively
  - Relay and destination have $N_{\text{R,rx}}$ and $N_{\text{D,rx}}$ receive antennas, respectively
  - *Example protocol I*: Decode-and-forward with rate adaptation, $\mathbf{t}[i] = \mathbf{x}[i-\tau]$
    - End-to-end signal model becomes

$$\begin{aligned}\mathbf{r}[i] &= \mathbf{H}_{\text{SR}}\mathbf{x}[i] + \mathbf{H}_{\text{LI}}\mathbf{x}[i-\tau] + \mathbf{n}_{\text{R}}[i]\\ \mathbf{y}[i] &= \mathbf{H}_{\text{RD}}\mathbf{x}[i-\tau] + \mathbf{H}_{\text{SD}}\mathbf{x}[i] + \mathbf{n}_{\text{D}}[i]\end{aligned}$$

    - Achievable rate is reduced at the first hop due to loop interference
  - *Example protocol II*: Amplify-and-forward, $\mathbf{t}[i] = \mathbf{B}\mathbf{r}[i-\tau]$
    - End-to-end signal model becomes

$$\begin{aligned}\mathbf{r}[i] &= \sum_{j=0}^{\infty}(\mathbf{H}_{\text{LI}}\mathbf{B})^{j}\left(\mathbf{H}_{\text{SR}}\mathbf{x}[i-j\tau] + \mathbf{n}_{\text{R}}[i-j\tau]\right)\\ \mathbf{y}[i] &= \mathbf{H}_{\text{SD}}\mathbf{x}[i] + \mathbf{H}_{\text{RD}}\mathbf{B}\sum_{j=1}^{\infty}(\mathbf{H}_{\text{LI}}\mathbf{B})^{j-1}\left(\mathbf{H}_{\text{SR}}\mathbf{x}[i-j\tau] + \mathbf{n}_{\text{R}}[i-j\tau]\right) + \mathbf{n}_{\text{D}}[i]\end{aligned}$$

    - Noise amplification and interfering echo signals

- Estimate $\tilde{\mathbf{H}}_{\text{LI}}$ of the actual loop interference channel $\mathbf{H}_{\text{LI}}$
  - Needed in order to mitigate the loop interference

$$\mathbf{H}_{\text{LI}} = \tilde{\mathbf{H}}_{\text{LI}} + \Delta\tilde{\mathbf{H}}_{\text{LI}}$$

  - Standard pilot-based or adaptive filtering techniques available in literature

- Special case: no processing delay ($\tau = 0$)
  - Earlier literature covers only this case
  - *Example protocol I*: Signal model reduces to

$$\begin{aligned}\mathbf{r}[i] &= (\mathbf{H}_{\text{SR}} + \mathbf{H}_{\text{LI}})\mathbf{x}[i] + \mathbf{n}_{\text{R}}[i]\\ \mathbf{y}[i] &= (\mathbf{H}_{\text{RD}} + \mathbf{H}_{\text{SD}})\mathbf{x}[i] + \mathbf{n}_{\text{D}}[i]\end{aligned}$$

    - Looping signal just amplifies the desired signal
  - *Example protocol II*: Signal model reduces to

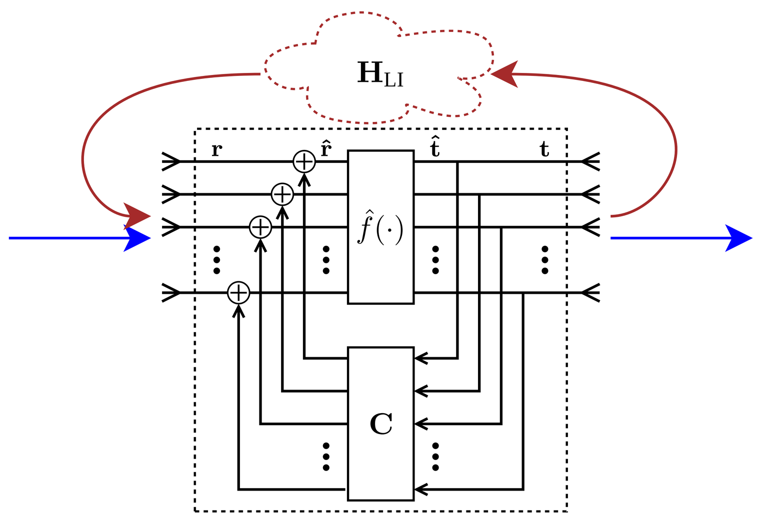
$$\begin{aligned}\mathbf{r}[i] &= (\mathbf{I} - \mathbf{H}_{\text{LI}}\mathbf{B})^{-1}(\mathbf{H}_{\text{SR}}\mathbf{x}[i] + \mathbf{n}_{\text{R}}[i])\\ \mathbf{y}[i] &= \left(\mathbf{H}_{\text{SD}} + \mathbf{H}_{\text{RD}}\hat{\mathbf{B}}\mathbf{H}_{\text{SR}}\right)\mathbf{x}[i] + \mathbf{H}_{\text{RD}}\hat{\mathbf{B}}\mathbf{n}_{\text{R}}[i] + \mathbf{n}_{\text{D}}[i]\end{aligned}$$

    - The system is actually equivalent to an interference-free relay link with effective amplification $\hat{\mathbf{B}} = \mathbf{B}(\mathbf{I} - \mathbf{H}_{\text{LI}}\mathbf{B})^{-1}$, i.e., $\mathbf{B} = \hat{\mathbf{B}}(\mathbf{I} + \mathbf{H}_{\text{LI}}\hat{\mathbf{B}})^{-1}$

→ If $\tau = 0$, the loop interference is not harmful at all!
  - No need for mitigation techniques
  - But system without processing delay cannot be implemented in practice!?
  - New in our paper: we will consider the more relevant case $\tau \geq 1$

Mitigation of loop interference

- MIMO extension of conventional SISO cancellation:



  - Subtract an estimate of the interfering signal, i.e., $\mathbf{C} = -\tilde{\mathbf{H}}_{\text{LI}}$

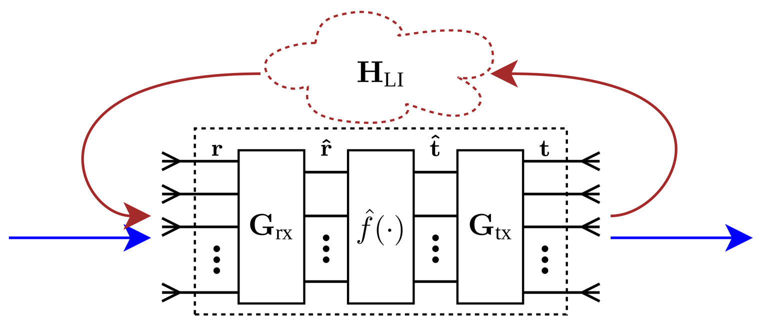
$$\begin{aligned}\mathbf{t}[i] &= \hat{\mathbf{t}}[i]\\ \hat{\mathbf{r}}[i] &= \mathbf{r}[i] + \mathbf{C}\mathbf{t}[i]\\ &= \mathbf{H}_{\text{SR}}\mathbf{x}[i] + \hat{\mathbf{H}}_{\text{LI}}\hat{\mathbf{t}}[i] + \mathbf{n}_{\text{R}}[i]\end{aligned}$$

  - Residual loop interference:

$$\hat{\mathbf{H}}_{\text{LI}} = \mathbf{H}_{\text{LI}} + \mathbf{C} = \Delta\tilde{\mathbf{H}}_{\text{LI}}$$

  - No benefit from low rank of $\mathbf{H}_{\text{LI}}$

- Spatial loop interference suppression:



  - Receive and transmit filters:

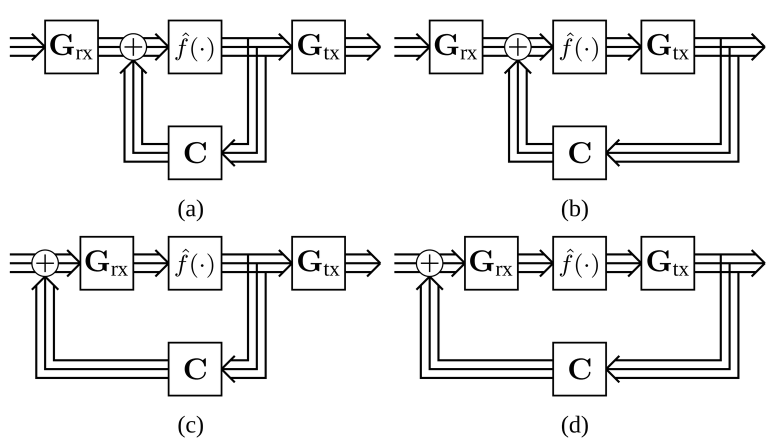
$$\begin{aligned}\mathbf{t}[i] &= \mathbf{G}_{\text{tx}}\hat{\mathbf{t}}[i]\\ \hat{\mathbf{r}}[i] &= \mathbf{G}_{\text{rx}}\mathbf{r}[i]\\ &= \mathbf{G}_{\text{rx}}\mathbf{H}_{\text{SR}}\mathbf{x}[i] + \hat{\mathbf{H}}_{\text{LI}}\hat{\mathbf{t}}[i] + \mathbf{G}_{\text{rx}}\mathbf{n}_{\text{R}}[i]\end{aligned}$$

  - Residual loop interference:

$$\hat{\mathbf{H}}_{\text{LI}} = \mathbf{G}_{\text{rx}}\tilde{\mathbf{H}}_{\text{LI}}\mathbf{G}_{\text{tx}} + \mathbf{G}_{\text{rx}}\Delta\tilde{\mathbf{H}}_{\text{LI}}\mathbf{G}_{\text{tx}}$$

  - Zero forcing (ZF) of loop interference by guaranteeing $\mathbf{G}_{\text{rx}}\tilde{\mathbf{H}}_{\text{LI}}\mathbf{G}_{\text{tx}} = \mathbf{0}$
    - Singular value decomposition: $\mathbf{G}_{\text{rx}}[\mathbf{U}_{(1)}|\mathbf{U}_{(0)}]\mathbf{\Sigma}[\mathbf{V}_{(1)}|\mathbf{V}_{(0)}]^{H}\mathbf{G}_{\text{tx}} = \mathbf{0}$
    - *Receive side:* select $\mathbf{G}_{\text{rx}}$ as $\mathbf{U}_{(0)}^{H}$, $\mathbf{I} - \tilde{\mathbf{H}}_{\text{LI}}\tilde{\mathbf{H}}_{\text{LI}}^{+}$ or $\mathbf{I} - \tilde{\mathbf{H}}_{\text{LI}}\mathbf{G}_{\text{tx}}\left(\tilde{\mathbf{H}}_{\text{LI}}\mathbf{G}_{\text{tx}}\right)^{+}$
    - *Transmit side:* select $\mathbf{G}_{\text{tx}}$ as $\mathbf{V}_{(0)}$, $\mathbf{I} - \tilde{\mathbf{H}}_{\text{LI}}^{+}\tilde{\mathbf{H}}_{\text{LI}}$ or $\mathbf{I} - \left(\mathbf{G}_{\text{rx}}\tilde{\mathbf{H}}_{\text{LI}}\right)^{+}\mathbf{G}_{\text{rx}}\tilde{\mathbf{H}}_{\text{LI}}$
    - *Joint design:* select basis vectors of $\mathbf{G}_{\text{rx}}$ and $\mathbf{G}_{\text{tx}}$ from $\mathbf{U}^{H}$ and $\mathbf{V}$ such that they correspond to different or zero singular values
  - MMSE filtering by minimizing $\operatorname{tr}\left\{\mathcal{E}\left\{(\mathbf{H}_{\text{SR}}\mathbf{x} - \hat{\mathbf{r}})(\mathbf{H}_{\text{SR}}\mathbf{x} - \hat{\mathbf{r}})^{H}\right\}\right\}$
    - *Receive side:* $\mathbf{G}_{\text{rx}} = \mathbf{H}_{\text{SR}}\mathbf{R}_{\mathbf{x}}\mathbf{H}_{\text{SR}}^{H}\left(\mathbf{H}_{\text{SR}}\mathbf{R}_{\mathbf{x}}\mathbf{H}_{\text{SR}}^{H} + \tilde{\mathbf{H}}_{\text{LI}}\mathbf{R}_{\mathbf{t}}\tilde{\mathbf{H}}_{\text{LI}}^{H} + \mathbf{R}_{\mathbf{n}_{\text{R}}}\right)^{-1}$
    - Reduces to the ZF scheme at the transmit side

- Variations for combining cancellation and spatial suppression:

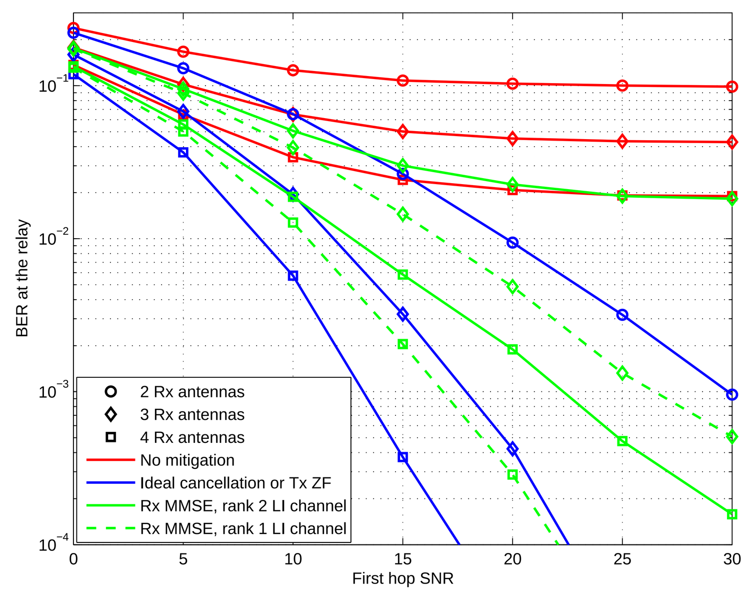


  - Order affects the residual loop interference channel:

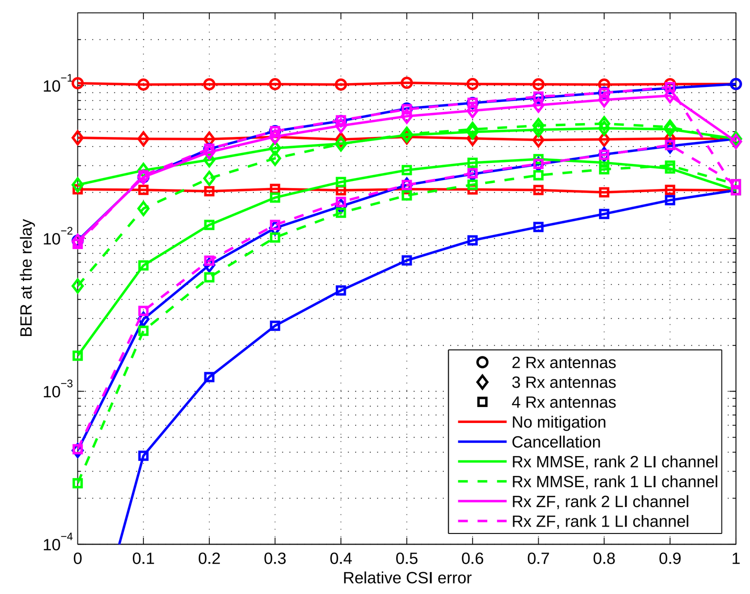
$$\hat{\mathbf{H}}_{\text{LI}} = \begin{cases}\mathbf{G}_{\text{rx}}\mathbf{H}_{\text{LI}}\mathbf{G}_{\text{tx}} + \mathbf{C}, & \text{variation (a)}\\ (\mathbf{G}_{\text{rx}}\mathbf{H}_{\text{LI}} + \mathbf{C})\mathbf{G}_{\text{tx}}, & \text{variation (b)}\\ \mathbf{G}_{\text{rx}}(\mathbf{H}_{\text{LI}}\mathbf{G}_{\text{tx}} + \mathbf{C}), & \text{variation (c)}\\ \mathbf{G}_{\text{rx}}(\mathbf{H}_{\text{LI}} + \mathbf{C})\mathbf{G}_{\text{tx}}, & \text{variation (d)}\end{cases}$$

Simulation results

- 2x2 end-to-end link with two spatial QPSK streams, decode-and-forward relay, Rayleigh channels



  - Performance with and without mitigation of loop interference (SIR=10dB)



  - The effect of channel estimation error (first hop SNR=20dB)

Asilomar 2009

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