Precoding Decision for Full-Duplex X-Relay Channel with Decode-and-Forward

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Introduction

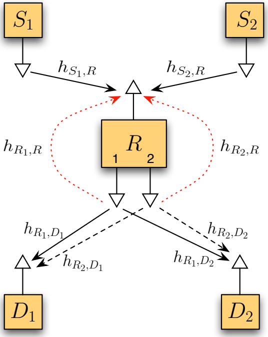
- Full-duplex (FD) relaying resolves the problem of bandwidth loss associated with half-duplex (HD)
- FD suffers from the interference caused from the relay output to the relay input
- Most of work done on FD relaying deals with the mitigation of the Loop Interference (LI)
- Interference Cancellation (IC) techniques do not completely remove LI $\rightarrow$ residual LI components remain
- To further mitigate the effects of LI, signal processing techniques, such as precoding design, have been investigated

Motivation

- X-relay channel: a basic network structure extensively studied when the relay is HD
- We study the precoding problem for an X-relay configuration with a FD relay
- Limited spatial degrees at the relay node and partial instantaneous channel state information (CSI)
- Relay node *cannot* perform real-time switchings of the precoding matrix (forced by strict hardware/complexity constraints)
- Design constraints $\rightarrow$ static precoding decision with only statistical knowledge of the channel conditions

System Model

- simple X-relay configuration: 2 sources, 2 destinations, and a relay
- a direct link from the sources to the destinations is not available
- relay node operates in a FD mode and employs a DF strategy
- sources access channel simultaneously and transmit with r_0 BPCU
- multi-packet reception channel (probabilistic receptions of simultaneously transmitted packets)



- LI is generated at R input and a MUI is generated at D_1 and D_2

Precoding

- interferences affect the decoding performance of the system
- goal is to design a precoding matrix $\boldsymbol{T} \in \mathbb{C}^{2\times 2}$

$$\boldsymbol{T} = \begin{pmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{pmatrix}$$

  that eliminate either the LI or the MUI

- Loop Interference Cancellation (LIC):

$$\begin{pmatrix} h_{R_1,R} & h_{R_2,R} \end{pmatrix} \begin{pmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{pmatrix} = \begin{pmatrix} 0 & 0 \end{pmatrix} \Rightarrow \boldsymbol{T} = \begin{pmatrix} \alpha_1 & \alpha_1 \\ \alpha_2 & \alpha_2 \end{pmatrix}$$

  where α_i, $i = \{1,2\}$ are constants

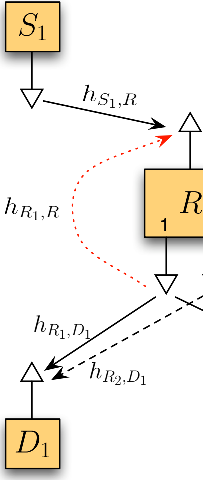
- Multi-User Interference Cancellation (MUIC):

$$\underbrace{\begin{pmatrix} h_{R_1,D_1} & h_{R_2,D_1} \\ h_{R_1,D_2} & h_{R_2,D_2} \end{pmatrix}}_{\boldsymbol{H}} \begin{pmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{pmatrix} = \begin{pmatrix} \beta_1 & 0 \\ 0 & \beta_2 \end{pmatrix} \Rightarrow \boldsymbol{T} = \underbrace{\boldsymbol{H}^H(\boldsymbol{H}\boldsymbol{H}^H)^{-1}}_{\text{zero-forcing precoder}}$$

  where β_i, $i = \{1,2\}$ are constants

Markov chain representation

Definition of events



$A_1 \triangleq \{\text{R decodes } x_1[n], x_2[n] \text{ with LI}\}$

$A_2 \triangleq \{\text{R decodes } x_1[n], x_2[n] \text{ without LI}\}$

$B_1 \triangleq \{D_1 \text{ decodes } x_1[n] \text{ with MUI}\}$

$B_2 \triangleq \{D_1 \text{ decodes } x_1[n] \text{ without MUI}\}$

$V_1 \triangleq \{\text{precoding matrix } \boldsymbol{T} \text{ suppresses LI}\}$

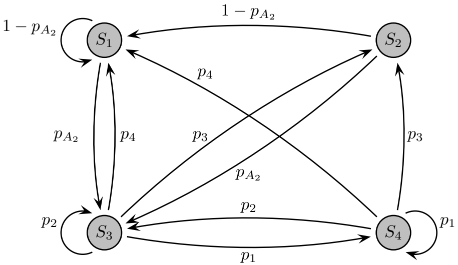
$V_2 \triangleq \{\text{precoding matrix } \boldsymbol{T} \text{ suppresses MUI}\}$

$Y \triangleq \{\text{R decodes } x_1[n-1], x_2[n-1]\}$

$B \triangleq \{D_1 \text{ decodes } x_1[n-1]\}$

Markov chain representation
Definition of events

$S_1 = \{00\}$ neither the relay nor the destinations have decoded a signal
$S_2 = \{01\}$ the relay didn't decode the received signal but the destinations did
$S_3 = \{10\}$ the relay only decodes a signal
$S_4 = \{11\}$ both the relay and the destinations decode the received signals



$$\mathbf{M} = \begin{pmatrix} 1-p_{A_2} & 1-p_{A_2} & p_4 & p_4 \\ 0 & 0 & p_3 & p_3 \\ p_{A_2} & p_{A_2} & p_2 & p_2 \\ 0 & 0 & p_1 & p_1 \end{pmatrix}$$

$\mathbb{P}(Y \cap B | Y) \triangleq p_1$, $\mathbb{P}(Y \cap \overline{B} | Y) \triangleq p_2$, $\mathbb{P}(\overline{Y} \cap B | Y) \triangleq p_3$ and $\mathbb{P}(\overline{Y} \cap \overline{B} | Y) \triangleq p_4$

Proposition

The Markov chain $\mathbf{M}$ is Stochastic, Indecomposable and Aperiodic (SIA).

- Probabilities p_1, p_2, p_3 and p_4

$$\begin{aligned}
p_1 &= (1-v)p_{A_2}p_{B_1} + vp_{A_1}p_{B_2} \\
p_2 &= (1-v)p_{A_2}(1-p_{B_1}) + vp_{A_1}(1-p_{B_2}) \\
p_3 &= (1-v)(1-p_{A_2})p_{B_1} + v(1-p_{A_1})p_{B_2} \\
p_4 &= 1-(p_1+p_2+p_3)
\end{aligned}$$

  where v is the probability that the precoding matrix $\boldsymbol{T}$ suppresses MUI

- The event of outage is given by

$$E = \left(\overline{Y}\bigcap\overline{A}_2\right)\bigcup Y\bigcap\left[\left[V_1\bigcap\left(\overline{A}_2\bigcup\left(A_2\bigcap\overline{B}_1\right)\right)\right]\bigcup\left[V_2\bigcap\left(\overline{A}_1\bigcup\left(A_1\bigcap\overline{B}_2\right)\right)\right]\right]$$

- The outage probability is given by

$$\boxed{\mathbb{P}(E) = 1 - p_{A_2} + p_{A_2}\frac{p_{A_2}(1-p_{B_1}) + v(p_{A_2}p_{B_1} - p_{A_1}p_{B_2})}{1 + v\left(p_{A_2} - p_{A_1}\right)}}$$

Precoding decision

The decision is the result of the following minimization problem

$$\min_{v\in[0,1]} \mathbb{P}(E) \equiv \min_{v\in[0,1]} \frac{p_{A_2}(1-p_{B_1}) + v(p_{A_2}p_{B_1} - p_{A_1}p_{B_2})}{1 + v\,(p_{A_2} - p_{A_1})}$$

Main Theorem

Given the probabilities p_{A_1}, p_{A_2}, p_{B_1} and p_{B_2}, the outage probability of the system $\mathbb{P}(E)$ is minimized if for

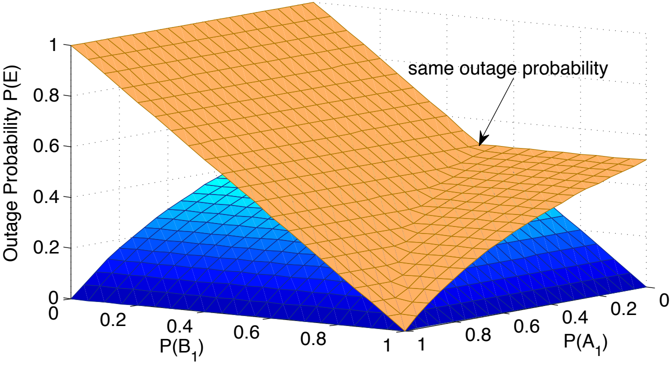
1. $p_{A_2}p_{B_1} - p_{A_1}p_{B_2} > p_{A_2}(1-p_{B_1})(p_{A_2} - p_{A_1})$
   the precoding matrix suppresses the loop interference
2. $p_{A_2}p_{B_1} - p_{A_1}p_{B_2} < p_{A_2}(1-p_{B_1})(p_{A_2} - p_{A_1})$
   the precoding matrix suppresses the multi-user interference

When $p_{A_2}p_{B_1} - p_{A_1}p_{B_2} = p_{A_2}(1-p_{B_1})(p_{A_2} - p_{A_1})$ any choice of precoding matrix yields the same results.

Remark:
The theorem provides *easily verifiable conditions* that do not require complex calculations and full knowledge of the channel states

Illustrative example

- $p_{A_2} = p_{B_2} = 1$
- $p(A_1)$ and $p(B_1)$ vary



- when $p_{A_2}p_{B_1} - p_{A_1}p_{B_2} = p_{A_2}(1 - p_{B_1})(p_{A_2} - p_{A_1})$ choice of precoding does not matter

Concluding remarks and future directions

Conclusions:

- simple X-relay configuration was studied:
  - shared relay operates in FD mode
  - not able to handle both the LI and the MUI due to critical energy/complexity/bandwidth constraints
- system formulated as a Markov chain:
  - outage probability was derived in close form
  - precoding decision as an *optimization parameter*
- precoding decision is made based only on statistical knowledge of the channel conditions

Future work:

1. study the achievable rates of this setup, which is essentially limited by the bottleneck link
2. investigate the case in which the relay can dynamically choose to cancel either the LI or the MUI

Thank You!

Questions?

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