Two-way MIMO DF Relaying for Non-Simultaneous Traffic in Cellular Systems

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Background

- Cooperative communication vastly improves performance of wireless systems.
- Half-duplex one-way relaying is an example.[1]
- Half-duplex constraint is imposed on the relay (easy to design)
  - Relay cannot concurrently transmit and receive on same resource.

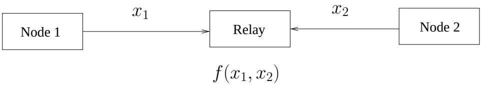
Figure: One-way relaying protocol.

- Four channel uses are required to exchange two data units.

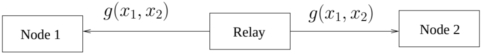
[1] L. Sanguinetti, A. DAmico, and Y. Rong, A tutorial on the optimization of amplify-and-forward MIMO relay systems, IEEE J. Sel. Areas Commun., vol. 30, pp. 13311346, Sep. 2012.

Half-duplex two-way relaying[2]

- Two source nodes simultaneously transmit to the relay during first phase.



- Relay broadcasts a function of the sum-signal during second phase.



- Both nodes can cancel back-propagating interference as both know self-data.

- Two channel uses are required to exchange two data units

[2] Y. Rong, Joint source and relay optimization for two-way linear non-regenerative MIMO relay communications, IEEE Trans. Signal Process., vol. 60, pp. 65336546, Dec. 2012.

Basic assumption in two-way relaying

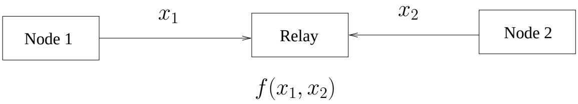


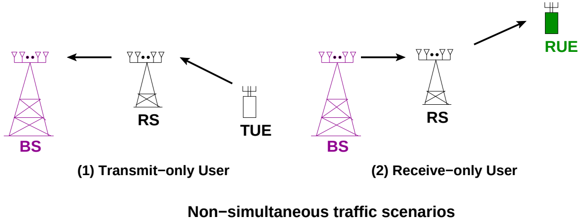
Figure: First phase of two-way relaying

Two nodes want to exchange data via a relay.

Two flows are aggregated to establish bi-directional data flow via a relay.

Data exchange in cellular systems

- Usually does not happen!

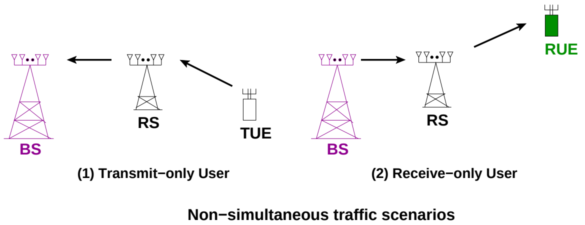


- Example 1: User TUE uploading a Youtube video.
- Example 2: User RUE watching a Netflix movie.
- Two flows cannot be aggregated to establish bi-directional data flow via relay.

Two way relaying cannot be used in these scenarios.

Option for BS to serve TUE and RUE

- Use one way relaying.

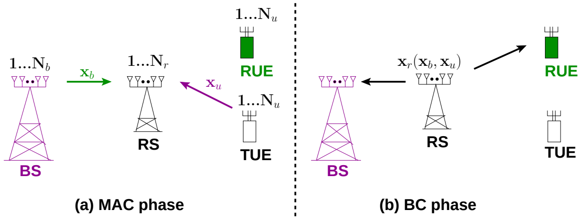


- One way relaying creates two non-interfering end-to-end links
  - TUE→RS→BS and BS→RS→RUE.

- BS will require 4 time slots – spectrally inefficient.

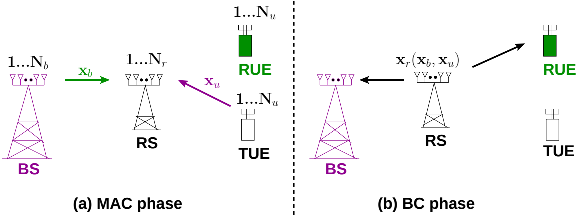
Proposed non-simultaneous two-way relaying (NS-TWR)

- Aggregates two flow to establish bi-directional data flow via relay.
- MAC phase: Both BS and TUE transmit to the relay.
- BC phase: Relay broadcasts to both BS and RUE.



- BS requires two channel uses to serve two users.

Proposed non-simultaneous two-way relaying (NS-TWR)



- Relay Rx signal: $\mathbf{y}_r = \mathbf{H}_u\mathbf{x}_u + \mathbf{H}_b\mathbf{x}_b + \mathbf{n}_r$.
- Relay Tx signal: $\mathbf{x}_r = \mathbf{W}\mathbf{y}_r$ (for an AF relay).
- RUE Rx signal: $\mathbf{y}_u = \mathbf{G}_u\mathbf{x}_r = \mathbf{G}_u(\underbrace{\mathbf{W}\mathbf{H}_u\mathbf{x}_u}_{\text{BI}} + \mathbf{W}\mathbf{H}_b\mathbf{x}_b + \mathbf{W}\mathbf{n}_r) + \mathbf{n}_u$.
- BS Rx signal: $\mathbf{y}_b = \mathbf{G}_b\mathbf{x}_r = \mathbf{G}_b(\mathbf{W}\mathbf{H}_u\mathbf{x}_u + \underbrace{\mathbf{W}\mathbf{H}_b\mathbf{x}_b}_{\text{BI}} + \mathbf{W}\mathbf{n}_r) + \mathbf{n}_b$.

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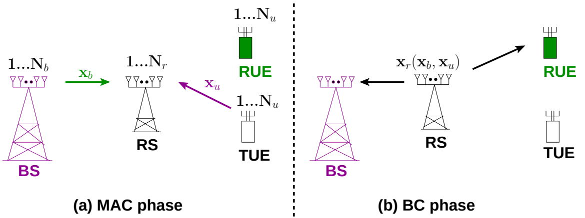

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Proposed non-simultaneous two-way relaying (NS-TWR)

- TUE→RS→BS link is BI-free while the BS→RS→RUE link experiences BI.
  - Unlike one-way relaying solution where both these links are non-interfering.

Aim: Cancel BI for BS→RS→RUE link.

- NS-TWR will create two non-interfering links as in one-way relaying (OWR).
- We will show that NS-TWR provides higher sum-rate than OWR.
- RUE can cancel BI by overhearing TUE's MAC-phase transmission.[3]
- In our work, we assume that RUE does not overhear TUE
  - Designed precoder $\mathbf{W}$ to cancel BI for AF relay.[4]

[3] F. Sun, T. M. Kim, A. J. Paulraj, E. de Carvalho, and P. Popovski,Cell-edge multi-user relaying with overhearing, IEEE Commun. Lett.,vol. 17, pp. 11601163, Jun. 2013.

[4] Rohit Budhiraja, Karthik KS and Bhaskar Ramamurthi "Linear Precoders for Non-Regenerative Asymmetric Two-way Relaying in Cellular Systems", accepted in Trans. Wireless Commun., 2014

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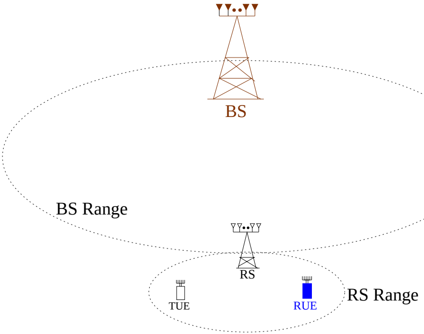
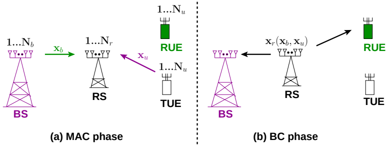
System model for NS-TWR in present work (1)

- We consider a decode and forward relay.
- No direct links between the BS and two users.
- Users observe this channel in coverage-extension/coverage-hole scenarios.



System model for decode and forward NS-TWR (2)



- All nodes have multiple antennas.
- Relay has complete CSIT and CSIR. The BS and RUE have CSIR alone.
- Sum-signal received by the relay: $\mathbf{y}_r = \mathbf{H}_u\mathbf{x}_u + \mathbf{H}_b\mathbf{x}_b + \mathbf{n}_r$.
- Assumption: RS successfully decodes the MAC phase data.
- RS re-encodes the RUE and BS signals as $\mathbf{s}_u$ and $\mathbf{s}_b$, respectively.

System model for decode and forward NS-TWR (3)

- Signal transmitted by the relay: $\mathbf{x}_r = \mathbf{W}_u\mathbf{s}_u + \mathbf{W}_b\mathbf{s}_b = \mathbf{W}\mathbf{s}$.
  - Covariance matrices of $\mathbf{s}_u$ and $\mathbf{s}_b$ are $\mathbf{\Lambda}_u$ and $\mathbf{\Lambda}_b$.

- RUE receive signal: $\mathbf{y}_u = \mathbf{G}_u\mathbf{W}_u\mathbf{s}_u + \underbrace{\mathbf{G}_u\mathbf{W}_b\mathbf{s}_b}_{\text{BI}} + \mathbf{n}_u$.

- BS receive signal: $\mathbf{y}_b = \underbrace{\mathbf{G}_b\mathbf{W}_u\mathbf{s}_u}_{\text{BI}} + \mathbf{G}_b\mathbf{W}_b\mathbf{s}_b + \mathbf{n}_b$.

Objectives

1) Design precoder $\mathbf{W}$ to cancel BI for RUE alone.

2) Design $\mathbf{\Lambda}_u$ and $\mathbf{\Lambda}_b$ to maximize sum-rate – algorithm uses two SDPs.

Proposed precoder design (1)

- $\mathbf{W}$ can be chosen as ZF/MMSE precoder. Cancels BI for both BS and RUE.
- ZF/MMSE precoders are sub-optimal as BS can itself cancel BI.

Proposed precoder design

- Cancels BI for RUE alone.
- Sum-rate performance is better than ZF/MMSE precoders.

- Stack the signals received by RUE and BS during the BC phase:

$$\begin{bmatrix} \mathbf{y}_u \\ \mathbf{y}_b \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{G}_u\mathbf{W}_u & \mathbf{G}_u\mathbf{W}_b \\ \mathbf{G}_b\mathbf{W}_u & \mathbf{G}_b\mathbf{W}_b \end{bmatrix}}_{\widetilde{\mathbf{G}}} \begin{bmatrix} \mathbf{s}_u \\ \mathbf{s}_b \end{bmatrix} + \begin{bmatrix} \mathbf{n}_u \\ \mathbf{n}_b \end{bmatrix}. \quad (1)$$

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Proposed precoder design (2)

Lemma

To cancel RUE's BI, design $\mathbf{W}$ *such that* $\widetilde{\mathbf{G}}$ *is a block lower-triangular matrix.*

With the block lower-triangular matrix, $\widetilde{\mathbf{G}}$, Eq. (1) will become:

$$\begin{bmatrix} \mathbf{y}_u \\ \mathbf{y}_b \end{bmatrix} = \begin{bmatrix} \mathbf{G}_u\mathbf{W}_u & \mathbf{0} \\ \mathbf{G}_b\mathbf{W}_u & \mathbf{G}_b\mathbf{W}_b \end{bmatrix} \begin{bmatrix} \mathbf{s}_u \\ \mathbf{s}_b \end{bmatrix} + \begin{bmatrix} \mathbf{n}_u \\ \mathbf{n}_b \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} \mathbf{y}_u \\ \mathbf{y}_b \end{bmatrix} = \begin{bmatrix} \mathbf{G}_u\mathbf{W}_u\mathbf{s}_u \\ \mathbf{G}_b\mathbf{W}_u\mathbf{s}_u + \mathbf{G}_b\mathbf{W}_b\mathbf{s}_b \end{bmatrix} + \begin{bmatrix} \mathbf{n}_u \\ \mathbf{n}_b \end{bmatrix} \tag{3}$$

- RUE receives its desired data $\mathbf{s}_u$ without experiencing BI.
- As desired, BI experienced by BS is not cancelled.

Proposed precoder design (3)

- For a block lower-triangular $\widetilde{\mathbf{G}} = \begin{bmatrix} \mathbf{G}_u\mathbf{W}_u & \mathbf{G}_u\mathbf{W}_b \\ \mathbf{G}_b\mathbf{W}_u & \mathbf{G}_b\mathbf{W}_b \end{bmatrix}$, $\mathbf{G}_u\mathbf{W}_b = \mathbf{0}$.

- The SVD of $\mathbf{G}_u$ is performed to determine its nullspace:

$$\mathbf{G}_u = \mathbf{U}_{\mathbf{G}_u}\mathbf{\Sigma}_{\mathbf{G}_u}[\mathbf{V}_{\mathbf{G}_u}^{(1)}\ \mathbf{V}_{\mathbf{G}_u}^{(0)}]^H, \quad (4)$$

- The columns of $\mathbf{V}_{\mathbf{G}_u}^{(0)}$ form an orthonormal basis set for the nullspace of $\mathbf{G}_u$.
  - We choose $\mathbf{V}_{\mathbf{G}_u}^{(0)}$ as the precoder matrix $\mathbf{W}_b$.

- To design $\mathbf{W}_u$, we note that RUE receive signal $\mathbf{y}_u = \mathbf{G}_u\mathbf{W}_u\mathbf{s}_u + \mathbf{n}_u$.
  - To decode RUE signal, $\mathbf{G}_u\mathbf{W}_u \neq \mathbf{0}$ ($\mathbf{W}_u$ should not lie in nullspace of $\mathbf{G}_u$).
  - Columns of $\mathbf{V}_{\mathbf{G}_u}^{(1)}$ form an orthonormal basis for the row space of $\mathbf{G}_u$.
  - We choose $\mathbf{W}_u = \mathbf{V}_{\mathbf{G}_u}^{(1)}$.

Proposed precoder design (3)

- For a block lower-triangular $\widetilde{\mathbf{G}} = \begin{bmatrix} \mathbf{G}_u\mathbf{W}_u & \mathbf{G}_u\mathbf{W}_b \\ \mathbf{G}_b\mathbf{W}_u & \mathbf{G}_b\mathbf{W}_b \end{bmatrix}$, $\mathbf{G}_u\mathbf{W}_b = \mathbf{0}$.

- The SVD of $\mathbf{G}_u$ is performed to determine its nullspace:

$$\mathbf{G}_u = \mathbf{U}_{\mathbf{G}_u}\mathbf{\Sigma}_{\mathbf{G}_u}[\mathbf{V}^{(1)}_{\mathbf{G}_u}\ \mathbf{V}^{(0)}_{\mathbf{G}_u}]^H, \tag{4}$$

- The columns of $\mathbf{V}^{(0)}_{\mathbf{G}_u}$ form an orthonormal basis set for the nullspace of $\mathbf{G}_u$.
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Sum-rate comparison of various precoders

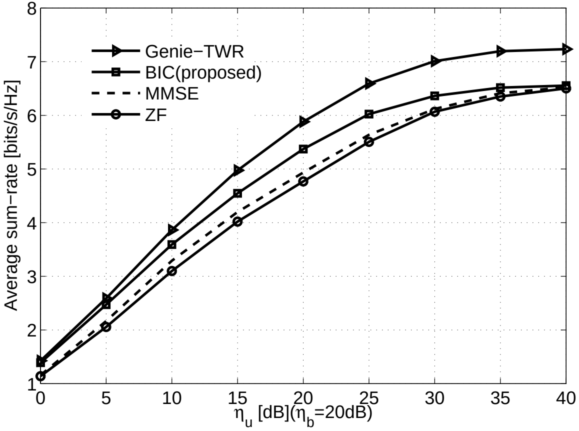
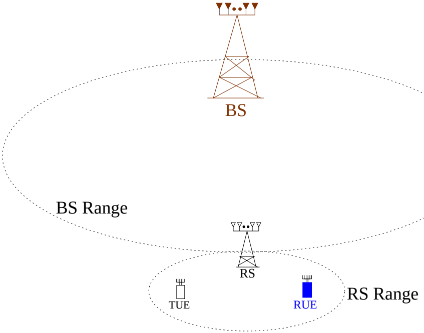


Figure: Sum-rate with 2 antennas at the RS and 1 antenna at the TUE, RUE and BS.

System-level comparison of various protocols

- Coverage extension scenario.
- Distance between BS and RS is 1 Km.
- RUE is located at the edge of RS range (500 m).



System parameters based on 802.16j methodology

System parameters	Value
System Bandwidth	10 MHz
Carrier Frequency	2 GHz
Noise Figure	5 dB
Thermal Noise	-174 dBm/Hz
BS / UE Transmit power	46 dBm / 24 dBm
BS / RS / UE height	30 m / 15 m / 1 m
BS-RS channel model	IEEE 802.16j, Type D
BS-MS / RS-UE channel model	IEEE 802.16j, Type B
RS Transmit power	37 dBm

Table: System parameters

System-level comparison of various protocols

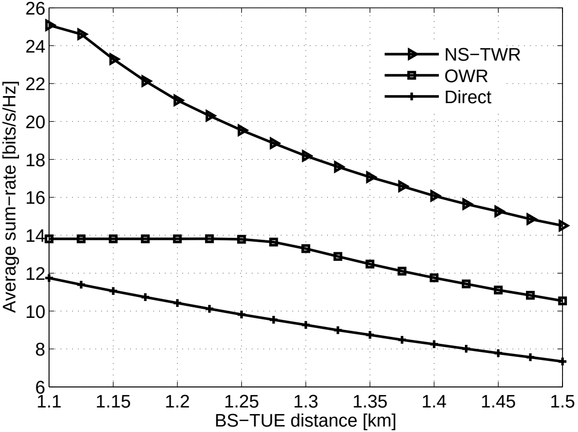


Figure: Average sum-rate comparison with 6 antennas at the RS, 3 antennas at the TUE, RUE and BS. Here BS-RUE distance = 1.5 km.

Conclusions

- Considered problem of non-simultaneous data-flow in two-way DF relaying.
- Designed a novel precoder to selectively cancel back-propagating interference.
- Maximized sum-rate using SDP-based algorithm.
- Proposed precoder outperforms conventional precoders.
- Sum-rate of proposed protocol is significantly better than OWR.

Extensions of the Work

- Designed precoder with global CSI at all the nodes.[5] [6]

- Extended the system model to include multiple such TUEs and RUEs.[7]

[5] Rohit Budhiraja and Bhaskar Ramamurthi "Diagonalized Two-way MIMO AF Relaying for Non-Simultaneous Traffic in Cellular Systems", presented in SPAWC 2014, Toronto.

[6] Rohit Budhiraja and Bhaskar Ramamurthi "Two-way Diagonalized MIMO AF Relaying for Non-Simultaneous Traffic in Cellular Systems", submitted to Trans. Wireless Commun. 2014.

[7] Rohit Budhiraja and Bhaskar Ramamurthi "Multiuser Two-Way Non-Regenerative MIMO Relaying With Non-Concurrent Traffic", accepted in Trans. Vehicular Tech., 2014