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

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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.

![One-way relaying protocol](image)

**Figure:** One-way relaying protocol.

Four channel uses are required to exchange two data units.

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Half-duplex two-way relaying\textsuperscript{2}

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

\[
f(x_1, x_2)\]

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

\[
g(x_1, x_2)\]

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

- Two channel uses are required to exchange two data units

Basic assumption in 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.

Figure: First phase of two-way relaying

\[
f(x_1, x_2)
\]
Data exchange in cellular systems

- Usually does not happen!

1. Transmit-only User
2. Receive-only User

Non-simultaneous traffic scenarios

- 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.

Non-simultaneous traffic scenarios

- 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: \( y_r = H_u x_u + H_b x_b + n_r \).
- Relay Tx signal: \( x_r = W y_r \) (for an AF relay).
- RUE Rx signal: \( y_u = G_u x_r = G_u (\underbrace{W H_u x_u + W H_b x_b + W n_r}_B) + n_u \).
- BS Rx signal: \( y_b = G_b x_r = G_b (\underbrace{W H_u x_u + W H_b x_b + W n_r}_B) + n_b \).
Proposed non-simultaneous two-way relaying (NS-TWR)

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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 \(W\) to cancel BI for AF relay.\(^4\)

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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.
• All nodes have multiple antennas.

• Relay has complete CSIT and CSIR. The BS and RUE have CSIR alone.

• Sum-signal received by the relay: $y_r = H_u x_u + H_b x_b + n_r$.

• Assumption: RS successfully decodes the MAC phase data.

• RS re-encodes the RUE and BS signals as $s_u$ and $s_b$, respectively.
System model for decode and forward NS-TWR (3)

- Signal transmitted by the relay: \( \mathbf{x}_r = \mathbf{W}_u \mathbf{s}_u + \mathbf{W}_b \mathbf{s}_b = \mathbf{W}s \).
  - 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)

- $W$ 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.

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

$$
\begin{bmatrix}
y_u \\
y_b
\end{bmatrix} = \begin{bmatrix}
G_u W_u & G_u W_b \\
G_b W_u & G_b W_b
\end{bmatrix} \begin{bmatrix}
s_u \\
s_b
\end{bmatrix} + \begin{bmatrix}
n_u \\
n_b
\end{bmatrix}.
$$

(1)
Proposed precoder design (1)

- $W$ 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:

$$
\begin{bmatrix}
  y_u \\
  y_b
\end{bmatrix} =
\underbrace{egin{bmatrix}
  G_u W_u & G_u W_b \\
  G_b W_u & G_b W_b
\end{bmatrix}}_{\tilde{G}}
\begin{bmatrix}
  s_u \\
  s_b
\end{bmatrix} +
\begin{bmatrix}
  n_u \\
  n_b
\end{bmatrix}.
$$ (1)
Proposed precoder design (2)

Lemma

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

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

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

Eq. (2)

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

Eq. (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 \( \tilde{G} = \begin{bmatrix} G_u W_u & G_u W_b \\ G_b W_u & G_b W_b \end{bmatrix} \), \( G_u W_b = 0 \).

- The SVD of \( G_u \) is performed to determine its nullspace:

\[
G_u = U_G \Sigma_G \begin{bmatrix} V_G^{(1)} & V_G^{(0)} \end{bmatrix}^H ,
\]

(4)

- The columns of \( V_G^{(0)} \) form an orthonormal basis set for the nullspace of \( G_u \).
  - We choose \( V_G^{(0)} \) as the precoder matrix \( W_b \).

- To design \( W_u \), we note that RUE receive signal \( y_u = G_u W_u s_u + n_u \).
  - To decode RUE signal, \( G_u W_u \neq 0 \) (\( W_u \) should not lie in nullspace of \( G_u \)).
  - Columns of \( V_G^{(1)} \) form an orthonormal basis for the row space of \( G_u \).
  - We choose \( W_u = V_G^{(1)} \).
Proposed precoder design (3)

- For a block lower-triangular \( \widetilde{G} = \begin{bmatrix} G_u W_u & G_u W_b \\ G_b W_u & G_b W_b \end{bmatrix} \), \( G_u W_b = 0 \).

- The SVD of \( G_u \) is performed to determine its nullspace:
  \[
  G_u = U_{G_u} \Sigma_{G_u} [V_{G_u}^{(1)} V_{G_u}^{(0)}]^H,
  \]  
  \hspace{1cm} (4)

- The columns of \( V_{G_u}^{(0)} \) form an orthonormal basis set for the nullspace of \( G_u \).
  - We choose \( V_{G_u}^{(0)} \) as the precoder matrix \( W_b \).

- To design \( W_u \), we note that RUE receive signal \( y_u = G_u W_u s_u + n_u \).
  - To decode RUE signal, \( G_u W_u \neq 0 \) (\( W_u \) should not lie in nullspace of \( G_u \)).
  - Columns of \( V_{G_u}^{(1)} \) form an orthonormal basis for the row space of \( G_u \).
  - We choose \( W_u = V_{G_u}^{(1)} \).
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

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

**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.\(^7\)

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\(^7\) Rohit Budhiraja and Bhaskar Ramamurthi “Multiuser Two-Way Non-Regenerative MIMO Relaying With Non-Concurrent Traffic”, accepted in Trans. Vehicular Tech., 2014