Advanced Self-Interference Cancellation and Multiantenna Techniques for Full-Duplex Radios

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Outline

Part 1: Development of a Compact Relay Terminal Achieving High Isolation between Transmit and Receive Antennas
• Previous work
• Research methods
• Coupling mechanisms
• Shielding
• Summary

Part 2: Cancellation of RX-induced nonlinear distortion
• Introduction and motivation
• MIMO full-duplex transceiver model
• Simplified example
• Cancellation of RX nonlinearities
• Simulations
• Conclusions
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Previous Work: Compact MIMO Relay Terminal at 2.6 GHz

- Tx element 1
- Tx element 2
- Rx element 1
- Rx element 2

Ground plane = metal box

Depth of the box + antenna = 20 mm
→ The same size as a WLAN AP

Use of slanted polarization → Increase isolation

Increased isolation

Tx and Rx are on the different side of the box

Haneda et al., EuCAP2010.
Prototype

Reflection coefficients

Isolation (front-back)

Measurements in an anechoic chamber

Mean isolation = 48 dB
Research Methods

• How to improve the isolation further?

1. Identify dominant coupling mechanism between antennas on either side of the ground plane.

2. Choose a method to improve isolation by, for example,
   a) Increasing separation between Tx and Rx antennas
   b) Increase antenna size
   c) Use different polarizations
   d) Reduce electromagnetic coupling
   e) Reduce surface currents
Reference Model of the Relay Terminal

50 mm

5 mm

18 mm

180 mm

50 mm

13 mm

150 mm

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Coupling Mechanisms

Galvanic coupling

Capacitive coupling

Inductive coupling
Determination of Coupling Mechanisms

- No direct contact \( \rightarrow \) No galvanic coupling

Magnetic field is more dominant, hence stronger inductive coupling!

Wave impedance \( \eta = \frac{|E|}{|H|} < \frac{|E_0|}{|H_0|} = 120\pi \ \Omega \)
Shielding

Loops that create cancelling magnetic fields

Electromagnetic induction

Part 1: Development of a Compact Relay Terminal
Achieving High Isolation between Transmit and Receive Antennas
Shielding

- Magnetic field reduced

Magnetic field in reference model

Magnetic field with loops

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• The worst isolation increased by 6 dB

Reference model: 49 dB

With metal loops: 55 dB
Summary

• Mission
  – Design of highly isolated transmit and receive antennas under size and volume constraint

• Finding
  – Inductive coupling due to magnetic field is the dominant mechanism affecting isolation

• Solution
  – Installing metal loops to produce counter-flowing magnetic fields

• Result
  – 6 dB improvement of the worst isolation relative to the reference case

• Future works
  – Antenna fabrication, testing other methods of coupling reduction
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Introduction and motivation

- In a full-duplex transceiver, the power of the SI signal is usually very high at the receiver chain input.
- Without highly linear components in the RX chain, the signal is nonlinearly distorted.
MIMO full-duplex transceiver model

Part 2: Cancellation of RX-induced nonlinear distortion
MIMO full-duplex transceiver model

<table>
<thead>
<tr>
<th>Component</th>
<th>Gain (dB)</th>
<th>IIP2 (dBm)</th>
<th>IIP3 (dBm)</th>
<th>NF (dB)</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNA (Rx)</td>
<td>25</td>
<td>43</td>
<td>-15</td>
<td>4.1</td>
<td>SNR requirement</td>
<td>10 dB</td>
</tr>
<tr>
<td>IQ Mixer (Rx)</td>
<td>6</td>
<td>42</td>
<td>15</td>
<td>4</td>
<td>Bandwidth</td>
<td>12.5 MHz</td>
</tr>
<tr>
<td>VGA (Rx)</td>
<td>0-69</td>
<td>43</td>
<td>10</td>
<td>4</td>
<td>Sensitivity level</td>
<td>-88.9 dBm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Received signal power</td>
<td>-83.9 dBm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Antenna separation</td>
<td>40 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RF cancellation</td>
<td>20 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ADC bits</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PAPR</td>
<td>10 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PA gain</td>
<td>20 dB</td>
</tr>
</tbody>
</table>

- RX components correspond to typical low-/medium-cost devices
- All the RX chains are assumed to be identical
- A linear transmit chain is assumed
Simplified example

- The RX–induced nonlinear distortion seems to be a significant factor with higher transmit powers.

- This motivates the development and utilization of SI regeneration methods capable of modeling also nonlinear distortion.
Cancellation of RX nonlinearities

- The signal model at the digital baseband is of the form \( y_i(n) = a_{i,1} x_i(n) + a_{i,2} |x_i(n)|^2 + a_{i,3} |x_i(n)|^2 x_i(n) + a_{i,4} (x_i^*(n))^3 \), where \( x_i(n) \) is the signal at the input of the \( i \)th receiver chain.

- The coefficients can be solved with linear least-squares as \( a_i = (X_{i,aug}^H X_{i,aug})^{-1} X_{i,aug} y_i \), where

  \[
  X_{i,aug} = \begin{bmatrix} x_i & |x_i|^2 & |x_i|^2 x_i & (x_i^*)^3 \end{bmatrix}, \quad \text{and} \quad \quad a_i = \begin{bmatrix} a_{i,1} & a_{i,2} & a_{i,3} & a_{i,4} \end{bmatrix}^T
  \]
Cancellation of RX nonlinearities

• The signal $x_i$ can be determined by estimating the SI coupling channel first with a low transmit power
  – Then, the receiver chain is linear and the known transmitted signal is only distorted by the coupling channel
  – This two-stage estimation procedure allows the cancellation of the RX-induced nonlinearities
Simulations

• The performance of the proposed nonlinear SI cancellation algorithm is evaluated with waveform simulations
  – Here, the previously presented 2x2 MIMO full-duplex transceiver model is used
  – The parameters of the OFDM signal are presented in the table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constellation</td>
<td>16-QAM</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>64</td>
</tr>
<tr>
<td>Number of data subcarriers</td>
<td>48</td>
</tr>
<tr>
<td>Guard interval</td>
<td>25 % of symbol duration</td>
</tr>
<tr>
<td>Sample length</td>
<td>15.625 ns</td>
</tr>
<tr>
<td>Symbol length</td>
<td>4 μs</td>
</tr>
<tr>
<td>Oversampling factor</td>
<td>4</td>
</tr>
</tbody>
</table>
Simulations

- Here, the SINR is shown for one receiver chain.
- The SINR is significantly increased when using the proposed nonlinear SI cancellation algorithm instead of only linear estimation.
Conclusions

• It was observed that with high transmit powers, the strong SI signal induces nonlinear distortion in the receiver chain.
• The proposed nonlinear SI cancellation algorithm allows the usage of higher transmit powers than can be achieved with linear processing.
Thank you!

• Questions?
• Comments?