In-band Full-Duplex Radio Transceivers with Imperfect RF Components: Analysis and Enhanced Cancellation Algorithms

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9th International Conference on Cognitive Radio Oriented Wireless Networks, DUPLO Workshop

4.6.2014
Outline

• Introduction
• RF impairments in a typical full-duplex transceiver
• Overall feasibility with linear digital cancellation
• Enhanced digital cancellation algorithm
• Waveform simulations
• Conclusion
Introduction

- Simultaneous transmission and reception at the same center frequency is an appealing scheme
  - Increased data rate, MAC level benefits, etc.
• However, it has also its downsides
  – Increased complexity due to self-interference cancellation, RF impairments, etc.
RF impairments

• The self-interference (SI) signal is distorted in numerous ways within the transceiver chain
  – This affects the accuracy with which the SI signal can be regenerated for cancellation in the digital domain
  – Using only linear processing results in insufficient digital SI cancellation
Full-duplex transceiver model
IQ imbalance

- It has been observed that imbalance between I- and Q-branches is a serious concern in in-band full-duplex transceivers.
- Complex conjugate of the input signal is summed on top of it with certain attenuation:
  \[ x_{IQ}(t) = g_1(t) * x(t) + g_2(t) * x^*(t) \]
- Image rejection ratio (IRR) is the power difference between the direct and image component.
Nonlinear distortion

- Amplifiers distort the signal nonlinearly if the input power is too high
  - Due to the high power of the SI signal, even a mild distortion can be significant interference for the weak received signal of interest
- Power of $n$th order nonlinear distortion can be approximated with the well known equation:
  \[ P_{NL,nth} = P_{out} - (n - 1)(IIPn - P_{in}) \]
Quantization noise

- If the power of the SI signal at the input of the ADC is very high, also quantization noise can be a serious issue
  - Only little dynamic range is available for the received signal of interest
- The quantization noise floor can be expressed as $P_q = P_{AD} - SNR_{ADC}$. 
Transmitter-induced thermal noise

- Something that has not been studied before
- The active components in the TX chain and RF cancellation path produce additional thermal noise
  - Part of it is cancelled by RF cancellation
- With high levels of analog SI attenuation, TX-induced thermal noise is not an issue
Typical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>SNR requirement</td>
<td>10 dB</td>
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<tr>
<td>Bandwidth</td>
<td>12.5 MHz</td>
</tr>
<tr>
<td>Sensitivity level</td>
<td>-88.9 dBm</td>
</tr>
<tr>
<td>Received signal power</td>
<td>-83.9 dBm</td>
</tr>
<tr>
<td>Antenna separation</td>
<td>40 dB</td>
</tr>
<tr>
<td>RF cancellation</td>
<td>30 dB</td>
</tr>
<tr>
<td>ADC bits</td>
<td>12</td>
</tr>
<tr>
<td>IRR (RX &amp; TX)</td>
<td>30 dB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Gain (dB)</th>
<th>IIP2 (dBm)</th>
<th>IIP3 (dBm)</th>
<th>NF (dB)</th>
</tr>
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<tbody>
<tr>
<td>PA (TX)</td>
<td>27</td>
<td>-</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>VM</td>
<td>-10</td>
<td>-</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>LNA (RX)</td>
<td>25</td>
<td>43</td>
<td>-9</td>
<td>4.1</td>
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<tr>
<td>IQ Mixer (RX)</td>
<td>6</td>
<td>42</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>VGA (RX)</td>
<td>0-69</td>
<td>43</td>
<td>14</td>
<td>4</td>
</tr>
</tbody>
</table>
Overall feasibility with linear digital cancellation

- SI mirror image is dominating
- Also PA-induced nonlinearities are problematic
- TX-induced thermal noise is not an issue in this case
Joint cancellation algorithm

• The previous observations motivate the development of a digital cancellation algorithm capable of modeling both IQ imaging and nonlinear distortion
• The simplest way to do this is just to combine widely-linear and nonlinear cancellation algorithms
Joint cancellation algorithm (cont.)

- Assuming that there is only IQ imaging in the transceiver chain, the SI signal in the digital domain is of the form

\[ y_{ADC,IQ} = Xh_1 + X^*h_2 = [X \quad X^*] \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = X_{aug}h_{aug} \]

where \( X \) is a convolution data matrix constructed from the original transmit signal \( x(n) \), \( X^* \) is its element wise complex conjugate and \( \mathbf{h}_{aug} \) is the total channel response.
Joint cancellation algorithm (cont.)

• Assuming only a nonlinear PA, the observed SI signal is of the following form:

\[ y_{ADC,NL} = \Psi f_{eff} \]

where \( \Psi \) is a convolution data matrix constructed from basis functions \( \psi_p(x(n)) = |x(n)|^{p-1}x(n) \) and \( f_{eff} \) consists of the corresponding responses of the different basis functions.
Joint cancellation algorithm (cont.)

- A simple way to approximate the combined effect of IQ imbalance and nonlinear PA is to write the observed signal as

\[ y_{ADC} = X_{aug} h_{aug} + \tilde{\Psi} f_{eff} + z = [X_{aug} \quad \tilde{\Psi}] h_{tot} + z = \Psi_{aug} h_{tot} + z \]

where the accent \( \sim \) denotes the removal of the linear SI term and \( z \) is the additional noise.

- Thus, by excluding the cross terms arising from the cascade of the PA and IQ mixers, a simple SI signal model can be derived.
Joint cancellation algorithm (cont.)

- The total effective channel response can be estimated easily based on the signal model.
- For instance, an estimate for the response can be calculated with least squares as:
  \[
  \hat{h}_{tot} = \left( \Psi_{aug}^H \Psi_{aug} \right)^{-1} \Psi_{aug}^H y_{ADC}
  \]
- The channel estimate can then be used to cancel the SI signal:
  \[
  y_{canc} = y_{ADC} - \Psi_{aug} \hat{h}_{tot}
  \]
Waveform simulations

- Same transceiver model as before, with the same parameters
- OFDM signal
- All the nonidealities are modelled in the simulations, including RX nonlinearities and quantization noise
Waveform simulations (cont.)

- A significant performance gain is attained even with this type of a simple joint cancellation scheme.
- RX nonlinearities and the cross terms decrease the SINR with high transmit powers.

![Graph showing SINR vs. Transmit Power](Image)
Conclusion

• There are several sources of nonidealities, which make in-band full-duplex communications a challenging concept.

• Typically, IQ imbalance and PA-induced nonlinear distortion are the most harmful impairments.

• It was shown that even a simple joint cancellation scheme can help in preventing the SINR decrease caused by these nonidealities.
Thank you!

• Questions or comments?

Supporting references

