RF Front-End Implementation Challenges of In-band Full-Duplex Relay Transceivers

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19th May 2016
Motivation

- Full-duplex (FD) technology has emerged to reach high data rates by incrementing the spectral efficiency.
- Ideal FD systems duplicate the efficiency by allowing to transmit and receive simultaneously in the same frequency band.
- Strong self-interference due to its own transmitted signal need to be mitigated.
Motivation

- Passive and active antenna cancellation are implemented.
- Analog RF cancellation is necessary to avoid the operation of the mixers and ADC in the saturation region.
- Digital cancellation removes the residual self-interference.
- ADC dynamic range and resolution are key aspects to define the required amount of cancellation.
Objectives

- Transceiver hardware imperfections limit the self-interference suppression capability and affect the system performance.
- We derive an expression for the SNR at the relay output considering the effects of several RF imperfections:
  - Power amplifiers with nonlinear response
  - Phase noise and IQ imbalances from down/up-converters
  - ADC quantization noise
- The amplify-forward relay scenario is studied.
System model

Full-duplex relay model with RF imperfections and equivalent model

\[ \hat{h}_{SI}(n) = h_{SI}(n) A_c A_{rf} \] denotes the residual SI channel after antenna and RF cancellation, \( A_c \) is the attenuation provided by antenna separation/cancellation, and \( A_{rf} \) is RF cancellation.
LNA and ADC
The LNA gain is calculated as

$$ G_L = \frac{P_{adc}}{\frac{P_yR}{A_cA_{rf}}} + P_{soi} + \text{PAPR} $$

- $P_{soi}$ is power of the signal of interest.
- PAPR is the peak-to-average-power ratio of the OFDM signal.

A linearized model of the ADC effects is employed.

$$ x_Q(n) = \alpha_A x(n) + Q(n) $$

- $\alpha_A$ is a constant scaling factor.
- $Q(n)$ is a distortion noise term due to the quantization error.

Mixers: IQ imbalance and phase noise
The output of the IQ modulator can be written as

$$ x_{rf} (n) = (K_{1x} x(n) + K_{2x} x^*(n)) e^{j\phi_x(n)} = x_{iq}(n) e^{j\phi_x(n)} $$

- $K_{1x}$ and $K_{2x}$ depend on the amplitude and phase mismatches in the transmitter ($x = t$) or receiver ($x = r$)
- $\phi_x(n)$ random phase shift.
RF impairments...

- **Mixers**: Phase noise in frequency domain
  At \( k \)-th subcarrier,
  \[
  X_{rf}(k) = \sum_{l=0}^{N-1} X_{iq}(m)\Lambda(m - k) = \Lambda(0)X_{iq}(k) + \gamma(k)
  \]
  - \( \Lambda(k) = \frac{1}{N} \sum_{m=0}^{N-1} \exp\left(j\phi(m)\right)\exp\left(j\frac{2\pi}{N}km\right) \)
  - \( \gamma(k) \) denotes the ICI term due to phase noise.

- **Power amplifier**: A memoryless polynomial model is considered. Based on the 1-dB compression point and 3-rd and 5-th order intersection points, a polynomial model can be adjusted to model the amplifier response.
  \[
  g[|x_{rf}(n)|] = \sum_{k=1}^{K_{pa}} c_k x_{rf}(n)|x_{rf}(n)|^{k-1}
  \]
  where \( K_{pa} \) is the polynomial order. A linearized model is also employed to characterize the PA response, i.e., \( \alpha p x(n) + d(n) \).
Analysis of self-interference mitigation

Derivation of equivalent feedback loop

The feedback signal

\[ z(n) = (G_0(n)r(n) \ast \tilde{h}_s(n)) \ast G_1(n) \]

\[ = \alpha_a \alpha_p G_L k_1 r(n) e^{j\phi_r(n)} \ast \tilde{h}_s(n) e^{j\phi_t(n)} r(n) + \alpha_a \alpha_p G_L k_2 r(n) e^{j\phi_r(n)} \ast \tilde{h}_s(n) e^{j\phi_t(n)} r^*(n) \]

\[ + \alpha_a \alpha_p G_L k_1^* r^*(n) \ast \tilde{h}_s^*(n) e^{j\phi_t(n)} r(n) + \alpha_a \alpha_p G_L k_2^* r^*(n) \ast \tilde{h}_s^*(n) e^{j\phi_t(n)} r(n) \]

\[ + \alpha_a \alpha_p G_L (k_1 d(n) + k_2 d^*(n)) e^{j\phi_r(n)} + Q(n) \]

\[ = \text{Dominant term} + \text{Residual terms} \]

where \( r(n) \) and \( z(n) \) denote the input and output signal of the equivalent feedback channel.
Analysis of self-interference mitigation

Study of the dominant term in frequency domain:

\[
(\gamma)_{i,j} = \sum_{k=0}^{N-1} \Lambda |N - j + k|_N \tilde{H}_{si}(k) \Lambda^* |N - i + k|_N
\]

where \(|N - j + k|_N\) stands for \((N - j + k) \mod N\).

- For a flat self-interference channel, \((\gamma)_{i,j} = 0 \forall j \neq i\), and \((\gamma)_{i,j} = \tilde{H}_{si}(k) \forall j = i\).
- In the case of frequency-selective channels, we verify that the ICI terms are almost negligible for moderate phase noise and considering Ricean channels with large \(K\) factor.
Estimation of self-interference channel

Considering that the channel is estimated using a set of pilots symbols defined in order to minimize the effect of RF impairments, the estimate is a noisy version of the dominant term:

\[ \hat{H}_{s_{\text{seq}}}(k) = \alpha_p G_L k_1 r_1 t \hat{H}_{s_i}(k) + \epsilon_H(k) \]

where \( \epsilon_H(k) \) is considered Gaussian with variance \( \sigma^2_{\epsilon}(k) \).
Signal-to-interference-plus-noise ratio at relay output

Based on the equivalent channel model and the channel estimate derived previously, we calculate the SINR at the relay output.

\[
SINR_0 = \frac{P_{soi}}{P_{ici} + P_{iq} + P_Q + P_{rsi} + P_{pa} + P_{feed} + P_n}
\]

- Signal of interest (soi) is given by

\[
\alpha_a\alpha_p\beta G_L k_1 r k_1 t e^{j\phi_r(n)} e^{-j\phi_r(n-D)} s(n - D)
\]

Considering a single local oscillator and a short processing delay, the ICI due to phase noise can be considered negligible.
Signal-to-interference-plus-noise ratio at relay output

- $P_{pa} = \sigma_d^2$ is the power of PA nonlinear distortion.
- $P_{ici}$ is the ICI due to LO phase noise
  $$P_{ici} = |\alpha_a|^2 |\alpha_p|^2 |\beta|^2 G_L^2 |k_{1r}|^2 |k_{1t}|^2 \sigma_d^2$$
- $P_{iq}$ is the interference due to IQ imbalance
  $$P_{iq} = |\alpha_a|^2 |\alpha_p|^2 |\beta|^2 G_L^2 (|k_{1t}|^2 |k_{2r}|^2 + |k_{2t}|^2 |k_{1r}|^2) E_s$$
- $P_Q$ is associated with the ADC quantization noise
  $$P_Q = |\beta|^2 (|k_{1t}|^2 + |k_{2t}|^2) \sigma_Q^2$$
- $P_{rsi}$ is the residual self-interference due to the noisy channel estimation
  $$P_{rsi} = |\beta|^2 (|k_{1t}|^2 + |k_{2t}|^2) \sigma_{pr}^2 P_{yR}$$
- $P_{feed}$ is the residual self-interference due to RF impairments
  $$P_{feed} = |\alpha_a|^2 |\beta|^2 G_L^2 (|k_{1r}|^2 + |k_{2r}|^2) \sigma_d^2 + |\alpha_p|^2 (|k_{1t}|^2 |k_{2t}|^2 |k_{1r}|^2 + |k_{1t}|^2 |k_{2t}|^2 |k_{2r}|^2)$$
  $$+ \frac{(|k_{2t}|^2 |k_{2t}|^2 |k_{1r}|^2 + |k_{2t}|^2 |k_{1t}|^2 |k_{2r}|^2)}{P_{yR} \sigma_{fl}^2}$$
- $P_n$ is the thermal noise at the relay output
  $$P_n = |\alpha_a|^2 |\beta|^2 G_L^2 |\alpha_p|^2 (|k_{1t}|^2 + |k_{2r}|^2) (|k_{1r}|^2 + k_{2r}|^2) \sigma_w^2$$
Numerical results: Nonlinear distortion and phase noise

The considered figure of merit is $L = SINR_{id} - SINR_{rf}$. This value is useful to evaluate the performance of the relay in terms of the SI cancellation method and the robustness against the RF imperfections.
Numerical results: Tx power and ADC resolution

The graph illustrates the relationship between the transmit power of the relay ($P_{tx\ relay}$) and the loss ($L$) for different ADC resolutions and attenuation ($A_c$) values. The x-axis represents the transmit power in dBm, while the y-axis represents the loss in dB. The graph shows multiple curves for different ADC resolutions (8, 10, 12, 14, 16 bits) and attenuation levels (50 dB for b=8 bits, 40 dB for b=10, 12, 14, 16 bits). The curves indicate a positive correlation between transmit power and loss, with higher loss values at higher transmit powers for each resolution and attenuation combination.
Numerical results: IQ imbalances
Conclusion

- We derive expressions to quantify the performance of a full-duplex relay considering RF front-end impairments.
- The resolution of the ADC limits considerably the system performance.
- PA nonlinear distortion need to be reduced. The linearization of the power amplifier needs to be further studied.
- A single local oscillator alleviates the phase noise problem for short processing delays.
Thank you!