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

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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

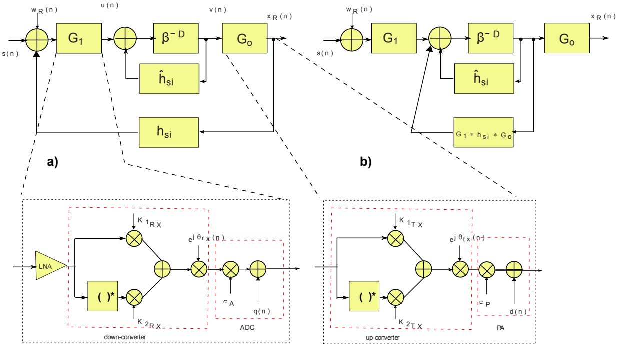
- Passive and active antenna cancellation are implemented.
- Analog RF cancellation is necessary to avoid the operation of the mixers and ADC in the saturation region.
- Digital cancellation removes the residual self-interference.
- ADC dynamic range and resolution are key aspects to define the required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



$\tilde{h}_{SI}(n) = h_{SI}(n)A_c A_{rf}$ 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.

RF impairments

- LNA and ADC

  The LNA gain is calculated as

$$G_L = \frac{P_{adc}}{\frac{P_{yR}}{A_c A_{rf}} + P_{soi} + PAPR}$$

  - 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.

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

  - α_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

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

  - K_{1_x} and K_{2_x} 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.

$$g[|x_{rf}(n)|] = \sum_{k=1}^{Kpa} c_k x_{rf}(n)|x_{rf}(n)|^{k-1}$$

  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

$$\begin{aligned}
z(n) &= (G_o(n)r(n) * \tilde{h}_{si}(n)) * G_1(n) \\
&= \alpha_a\alpha_p G_L k_{1_r} k_{1_t} e^{j\phi_r(n)} * \tilde{h}_{si}(n) e^{j\phi_t(n)} r(n) + \alpha_a\alpha_p G_L k_{2_t} k_{1_r} e^{j\phi_r(n)} * h_{si}(n) e^{j\phi_t(n)} r^*(n) \\
&+ \alpha_a\alpha_p G_L k_{1_t}^* k_{2_r} e^{-j\phi_r(n)} * \tilde{h}_{si}^*(n) e^{j\phi_t(n)} r^*(n) + \alpha_a\alpha_p G_L k_{2_t}^* k_{2_r}^* e^{-j\phi_r(n)} * \tilde{h}_{si}^*(n) e^{j\phi_t(n)} r(n) \\
&+ \alpha_a\alpha_p G_L (k_{1_r} d(n) + k_{2_r} d^*(n)) e^{j\phi_r(n)} + Q(n) \\
&= \textbf{Dominant term} + \textbf{Residual terms}
\end{aligned}$$

where $r(n)$ and $z(n)$ denote the input and output signal of the equivalent feedback channel.

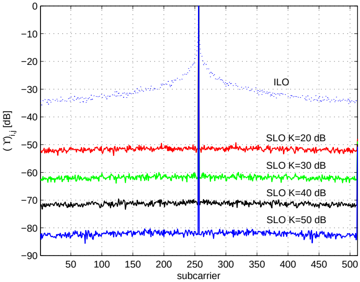
Analysis of self-interference mitigation

Study of the dominant term in frequency domain:

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

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

- For a flat self-interference channel, $(\Upsilon)_{i,j} = 0 \; \forall j \neq i$, and $(\Upsilon)_{i,j} = \tilde{H}_{si}(k) \; \forall j = i$.
- 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.



Analysis of self-interference mitigation

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:

$$\hat{H}_{si_{eq}}(k) = \alpha_p G_L k_{1_r} k_{1_t} \tilde{H}_{si}(k) + \epsilon_H(k)$$

where $\epsilon_H(k)$ is considered Gaussian with variance $\sigma_\epsilon^2(k)$.

Signal-to-interference-plus-noise ratio at relay output

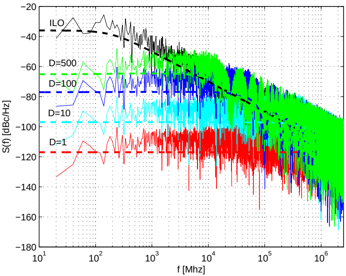
Based on the equivalent channel model and the channel estimate derived previously, we calculate the SINR at the relay output.

$$SINR_o = \frac{P_{soi}}{P_{ici} + P_{iq} + P_Q + P_{rsi} + P_{pa} + P_{feed} + P_n}$$

- 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

$$P_{ici} = |\alpha_a|^2|\alpha_p|^2|\beta|^2|G_L|^2|k_{1_r}|^2|k_{1_t}|^2\sigma_\lambda^2$$

- P_{iq} is the interference due to IQ imbalance

$$P_{iq} = |\alpha_a|^2|\alpha_p|^2|\beta|^2|G_L|^2(|k_{1_t}|^2|k_{2_r}|^2 + |k_{2_t}|^2|k_{1_r}|^2)E_s$$

- P_Q is associated with the ADC quantization noise

$$P_Q = |\beta|^2(|k_{1_t}|^2 + |k_{2_t}|^2)\sigma_Q^2$$

- P_{rsi} is the residual self-interference due to the noisy channel estimation

$$P_{rsi} = |\beta|^2(|k_{1_t}|^2 + |k_{2_t}|^2)\sigma_\epsilon^2 P_{y_R}$$

- P_{feed} is the residual self-interference due to RF impairments

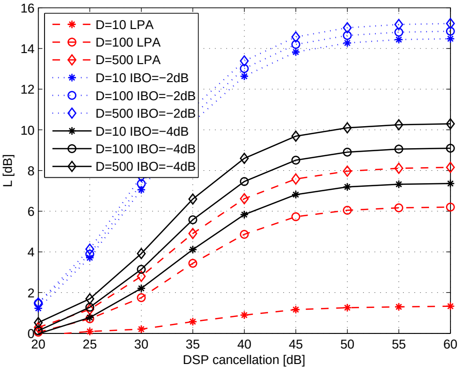
$$\begin{aligned} P_{feed} &= |\alpha_a|^2|\beta|^2|G_L|^2[(|k_{1_r}|^2 + |k_{2_r}|^2)(|k_{1_t}|^2 + |k_{2_t}|^2)\sigma_d^2 + |\alpha_p|^2(|k_{1_t}|^2|k_{2_t}|^2|k_{1_r}|^2 + |k_{1_t}|^2|k_{2_t}|^2|k_{2_r}|^2 \\ &+ (|k_{2_t}|^2|k_{2_t}|^2|k_{1_r}|^2 + |k_{2_t}|^2|k_{1_t}|^2|k_{2_r}|^2))P_{y_R}]\sigma_{\tilde{H}}^2 \end{aligned}$$

- P_n is the thermal noise at the relay output

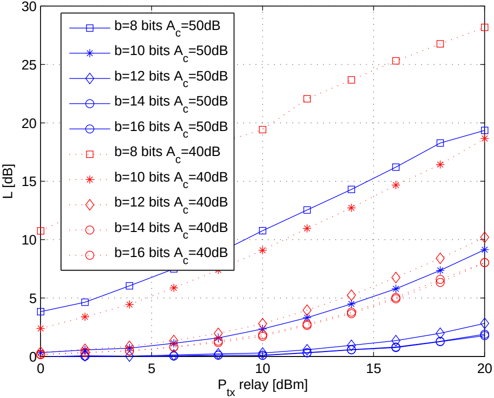
$$P_n = |\alpha_a|^2|\beta|^2|G_L|^2|\alpha_p|^2(|k_{1_t}|^2 + |k_{2_r}|^2)(|k_{1_r}|^2 + k_{2_r}|^2)\sigma_w^2$$

Numerical results: Nonlinear distortion and phase noise

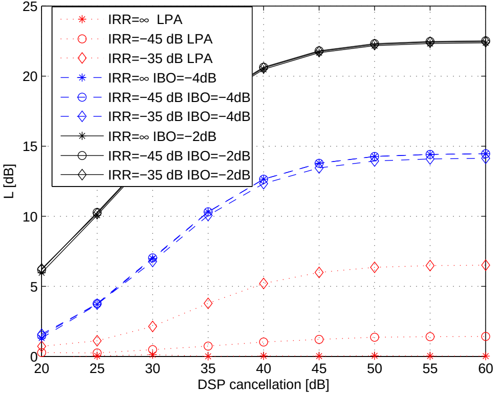
The considered figure of merit is $L = SINR_{id} - SINR_{rf}$. This value is useful to evaluate the performance of the relay in terms of the SI cancellation method and the robustness against the RF imperfections.



Numerical results: Tx power and ADC resolution



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!