Performance Analysis of Full-Duplex AF Relaying with Transceiver Hardware Impairments

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Motivation

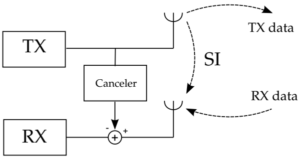
- Full duplex (FD) technology is one of the most important advances in communication systems of recent times.
- The main problem of FD transceivers is the self-interference (SI) generated by the simultaneous transmission and reception.
- Hardware imperfections prevents the use of FD mode in massive applications.
- It is necessary to model and compensate for hardware impairments.
- Amplify and forward relays benefit from the FD operation.

Proposal

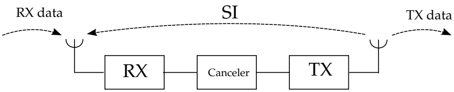
We propose a widely-linear SI canceler that also compensates for I/Q imbalance in an AF FD relay.

What is the difference between a canceler for transceiver or a relay?

- In a FD transceiver the cancellation follows an *identification* structure.
- In an AF FD relay the canceler adopts an *inverse filtering* structure.

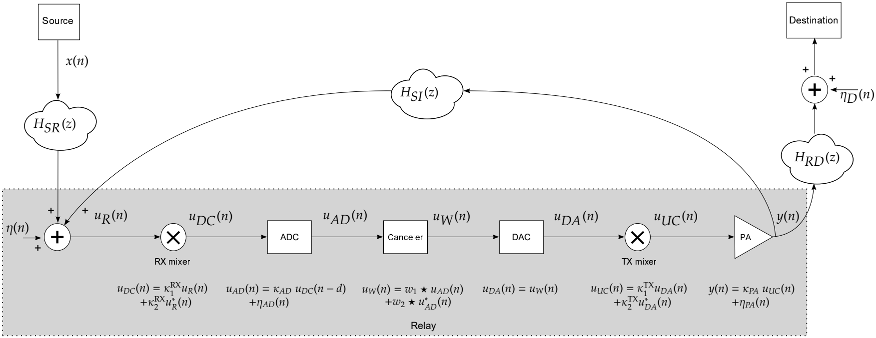


(a) FD transceiver



(b) FD relay

Two-hop relay link model with hardware impairments



Model of hardware imperfections

- Nonlinear power amplifier (PA).

$$y(n) = \frac{|u_{UC}|/\nu}{[1 + (|u_{UC}|/\nu A_s)^{2p}]^{1/2p}} \, e^{j\angle u_{UC}} \simeq \kappa_{PA} \, u_{UC}(n) + \eta_{PA}(n)$$

SSPA model where ν^2 is the IBO.
As PA input is Gaussian, the output follows a linear model (Bussgang theorem).
κ_{PA} is a complex scaling factor and $\eta_{PA}(n)$ is Gaussian (PA close to saturation).

- Up- and down-conversion mixers can be modeled as

$$u_{DC}(n) = \kappa_1^{\mathrm{RX}} u_R(n) + \kappa_2^{\mathrm{RX}} u_R^*(n) \qquad u_{UC}(n) = \kappa_1^{\mathrm{TX}} u_{DA}(n) + \kappa_2^{\mathrm{TX}} u_{DA}^*(n)$$

where

$$\kappa_1^{\mathrm{RX}} = (1 + \alpha^{\mathrm{RX}} e^{-j\theta^{\mathrm{RX}}})/2 \qquad \kappa_1^{\mathrm{TX}} = (1 + \alpha^{\mathrm{TX}} e^{-j\theta^{\mathrm{TX}}})/2$$
$$\kappa_2^{\mathrm{RX}} = (1 - \alpha^{\mathrm{RX}} e^{j\theta^{\mathrm{RX}}})/2 \qquad \kappa_2^{\mathrm{TX}} = (1 - \alpha^{\mathrm{TX}} e^{j\theta^{\mathrm{TX}}})/2$$

with α^{RX}, θ^{RX}, α^{TX} and θ^{TX} are respectively the amplitude and phase mismatch of RX and TX mixers.

Hardware imperfections and widely-linear canceler

- The ADC effects can be modeled by

$$u_{AD}(n) = \kappa_{AD}\, u_{DC}(n-d) + \eta_{AD}(n)$$

where κ_{AD} is a scaling factor, d is processing delay, and the variance of $\eta_{AD}(n)$ results

$$\sigma_{AD}^2 = \mathrm{E}\{|u_{DC}|^2\}\, 10^{-(6.02b+4.76-\mathcal{P}(u_{DC}))/10}$$

b is the number of bits and $\mathcal{P}(\cdot)$ is the peak-to-average power ratio in dB.

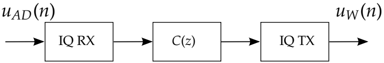
- The DAC is regarded ideal.
- The widely-linear canceler output becomes

$$u_W(n) = w_1(n) \star u_{AD}(n) + w_2(n) \star u_{AD}^*(n)$$

we have to design $w_1(n)$ and $w_2(n)$ to compensate for the SI and the I/Q imbalance.

Derivation of the widely-linear canceler

The widely-linear canceler has three cancellation stages:



where “IQ RX” is a post-canceler, $C(z)$ aims to cancel the SI, and “IQ TX” is a pre-canceler.

“IQ RX” and “IQ TX” are widely-linear cancellation filters with coefficients defined as

$$g_1^{\mathrm{RX}} = \frac{(\kappa_1^{\mathrm{RX}})^*}{|\kappa_1^{\mathrm{RX}}|^2 - |\kappa_2^{\mathrm{RX}}|^2} \qquad g_1^{\mathrm{TX}} = \frac{(\kappa_1^{\mathrm{TX}})^*}{|\kappa_1^{\mathrm{TX}}|^2 - |\kappa_2^{\mathrm{TX}}|^2}$$

$$g_2^{\mathrm{RX}} = \frac{-\kappa_2^{\mathrm{RX}}}{|\kappa_1^{\mathrm{RX}}|^2 - |\kappa_2^{\mathrm{RX}}|^2} \qquad g_2^{\mathrm{TX}} = \frac{-\kappa_2^{\mathrm{TX}}}{|\kappa_1^{\mathrm{TX}}|^2 - |\kappa_2^{\mathrm{TX}}|^2}$$

Widely-linear canceler and relay I/O relation

The combination of the three stages results

$$w_1(n) = \frac{(\kappa_1^{\mathrm{RX}})^*(\kappa_1^{\mathrm{TX}})^* c(n) + \kappa_2^{\mathrm{TX}}(\kappa_1^{\mathrm{RX}})^* c^*(n)}{(|\kappa_1^{\mathrm{RX}}|^2 - |\kappa_2^{\mathrm{RX}}|^2)(|\kappa_1^{\mathrm{TX}}|^2 - |\kappa_2^{\mathrm{TX}}|^2)} \qquad w_2(n) = \frac{-\kappa_2^{\mathrm{RX}}(\kappa_1^{\mathrm{TX}})^* c(n) - \kappa_1^{\mathrm{RX}}\kappa_2^{\mathrm{TX}} c^*(n)}{(|\kappa_1^{\mathrm{RX}}|^2 - |\kappa_2^{\mathrm{RX}}|^2)(|\kappa_1^{\mathrm{TX}}|^2 - |\kappa_2^{\mathrm{TX}}|^2)}$$

To obtain $c(n)$, we replace $w_1(n)$ and $w_2(n)$ in the complete system and obtain the I/O relation with I/Q compensation

$$\begin{aligned} y(n) = {} & \kappa_{PA}\kappa_{AD}[x \star h_{SR}(n-d) + y \star h_{SI}(n-d)] \star c(n) \\ & + \kappa_{PA}\Gamma_1\eta_{AD}(n) \star c^*(n) + \kappa_{PA}\Gamma_2\eta_{AD}^*(n) \star c(n) \\ & + \kappa_{PA}\eta(n-d) \star c(n) + \eta_{PA}(n) \end{aligned}$$

where

$$\Gamma_1 = \frac{[(\kappa_1^{\mathrm{RX}})^*\kappa_1^{\mathrm{TX}}\kappa_2^{\mathrm{TX}} - (\kappa_2^{\mathrm{RX}})^*\kappa_1^{\mathrm{TX}}\kappa_2^{\mathrm{TX}}]}{(|\kappa_1^{\mathrm{RX}}|^2 - |\kappa_2^{\mathrm{RX}}|^2)(|\kappa_1^{\mathrm{TX}}|^2 - |\kappa_2^{\mathrm{TX}}|^2)} \qquad \Gamma_2 = \frac{[|\kappa_2^{\mathrm{TX}}|^2\kappa_1^{\mathrm{RX}} - |\kappa_1^{\mathrm{TX}}|^2\kappa_2^{\mathrm{RX}}]}{(|\kappa_1^{\mathrm{RX}}|^2 - |\kappa_2^{\mathrm{RX}}|^2)(|\kappa_1^{\mathrm{TX}}|^2 - |\kappa_2^{\mathrm{TX}}|^2)}$$

Design of SI canceler $C(z)$

The relay output should be equal to (Z- transform, disregarding noise terms):

$$Y(z) = \frac{\kappa_{PA}\kappa_{AD}H_{SR}(z)C(z)X(z)z^{-d}}{1 - \kappa_{PA}\kappa_{AD}H_{SI}(z)C(z)z^{-d}} = \kappa_{PA}X(z)z^{-d}$$

$C(z)$ does not compensate for the delay or the IBO.

Then, the zero-forcing solution results

$$C(z) = \frac{1}{\kappa_{AD}[H_{SR}(z) + \kappa_{PA}H_{SI}(z)z^{-d}]}$$

The filter should be stable to enable a practical implementation.

BER trade-off

- A low IBO increases the transmission power and leads to a higher SNR at the destination but it produces a larger SI that reduce the SINR at the relay input.
- The IBO also controls the nonlinear behavior of the PA.
- To find the optimal IBO value we solve the following optimization problem:

$$\nu_{op}^2 = \arg\min_{\nu^2} \{\text{BER}_d\}$$

IBO optimization solution

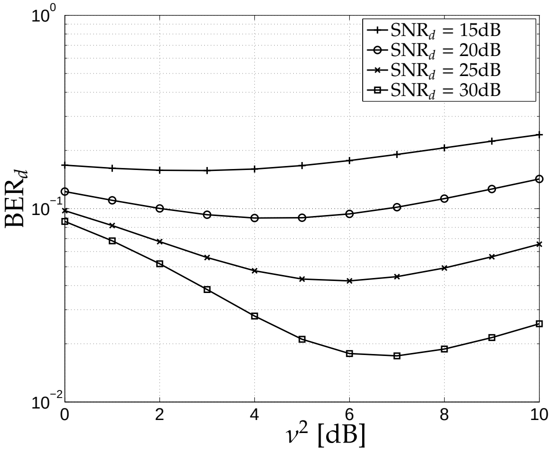


Figure: SSPA with $A_s = 1$, $p = 2$ and $\mathrm{SNR}_d = 15, 20, 25,$ and 30dB. $\mathrm{SNR}_r = 20$dB, $\nu_{op}^2 = 2.5, 4.2, 5.4,$ and 6.4dB.

BER_d performance

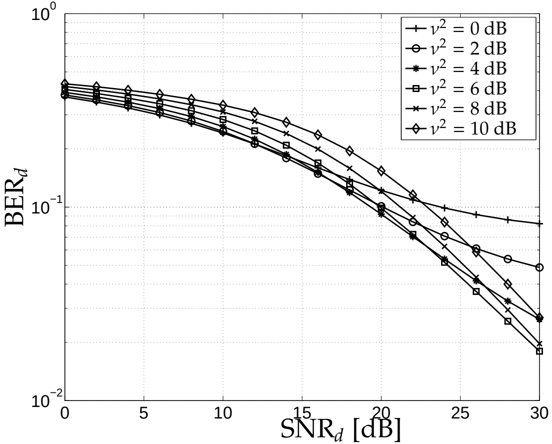


Figure: BER_d for $\nu^2 = 0, 2, 4, 6, 8$, and 10dB, considering an SSPA model with $A_s = 1$ and $p = 2$.

I/Q canceler performance

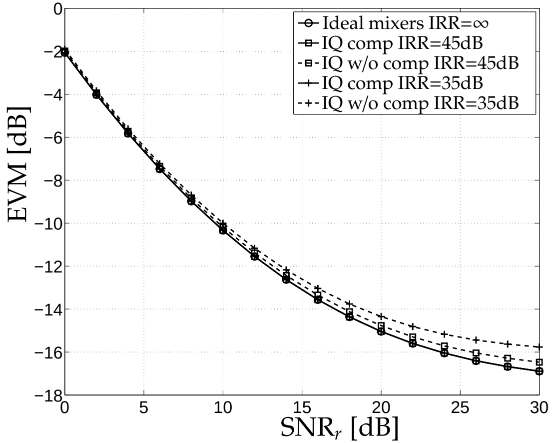


Figure: EVM at the relay output for $\nu_{op}^2 = 4.4$dB. I/Q imbalance and SI canceler (solid) and SI canceler (dashed).

Conclusion

- We propose a widely-linear I/Q imbalance and SI cancellation for an amplify-and-forward full-duplex relay.
- We evaluate the two-hop link's BER performance considering hardware impairments.
- We show that the IBO of the relay PA brings on a trade-off between the SNR at the destination and the SINR at the relay input.
- We find numerically the optimum IBO that minimizes the BER of the complete system.

Thank you!

Any questions?

Simulation parameters

- We use an OFDM signal with $N = 1024$ subcarriers, a cyclic prefix of $N_{cp} = 64$, and 16-QAM symbols.
- Amplitude and phase mixer distortions are: $\alpha^{\mathrm{RX}} = \alpha^{\mathrm{TX}} = 1.02$, $\theta^{\mathrm{RX}} = \theta^{\mathrm{TX}} = 1.5°$, corresponding to an IRR of 35dB.
- We consider an ADC of 12 bits, $\kappa_{AD} = 1$, $\mathcal{P}(u_{DC}) = 13$dB, and a delay of $d = 5$.
- We assume that $A_s = 1$ and $p = 2$ for the PA.
- The SR and SI links are respectively static Ricean channels with $L_{SR} = 3$ and $L_{SI} = 3$. The RD link is a time-varying Rayleigh channel with $L_{RD} = 5$.