Measurement-Based Characterization of Residual Self-Interference on a Full-Duplex MIMO Testbed

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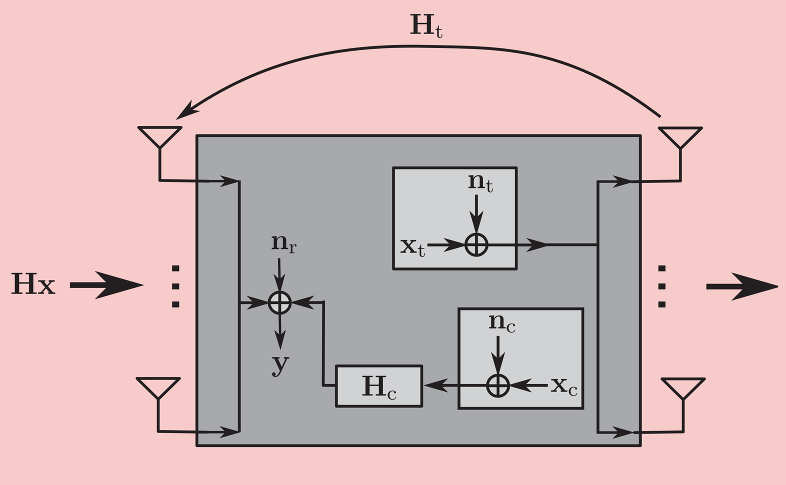
Motivation & Contribution

- In full-duplex (FD) systems, imperfect self-interference cancelation leads to **residual self-interference**
- Residual self-interference and thermal noise constitute the **effective noise** → which is the **optimal receiver**?
- **Contribution:** We measure the effective noise on a 2 × 2 FD-MIMO testbed to assess whether the usual assumptions hold
  - Is the effective noise **complex normal** distributed? Is the effective noise a **memoryless** process? Is the effective noise **spatially colored**?

FD-MIMO and Self-Interference Cancelation

Notation	
$\mathbf{x}$	remote signal
$\mathbf{H}$	remote signal channel
$\mathbf{x}_t$	self-interference signal
$\mathbf{H}_t$	self-interference channel
$\mathbf{x}_c$	cancelation signal
$\mathbf{H}_c$	cancelation channel
$\mathbf{n}_r$	receiver thermal noise



Complex baseband relation for FD-MIMO is: $\mathbf{y} = \mathbf{Hx} + \mathbf{H}_t\mathbf{x}_t + \mathbf{n}_r$

Active RF cancelation → construct $\mathbf{x}_c$ so that : $\mathbf{H}_c\mathbf{x}_c = -\mathbf{H}_t\mathbf{x}_t$

Ideally: $\mathbf{y} = \mathbf{Hx} + \mathbf{H}_t\mathbf{x}_t + \mathbf{H}_c\mathbf{x}_c + \mathbf{n}_r = \mathbf{Hx} + \mathbf{n}_r$

Transmitter Impairments

Transmitters have **impairments**, which we model as **additive noise**:

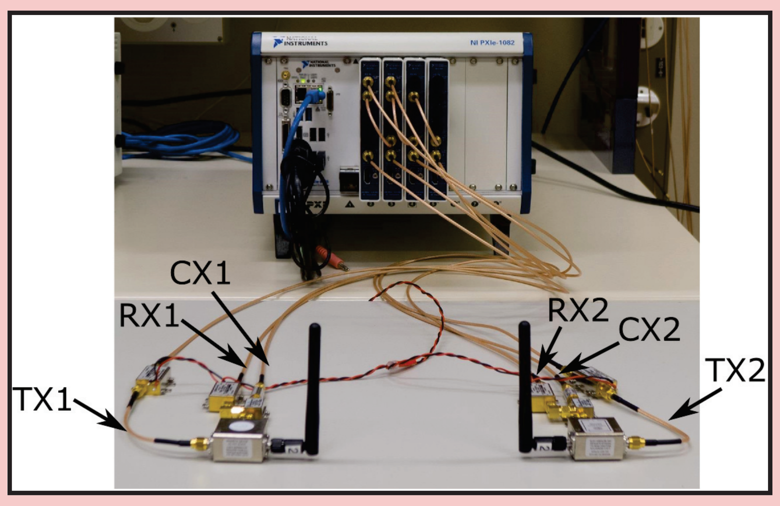
$$\tilde{\mathbf{x}}_t = \mathbf{x}_t + \mathbf{n}_t, \qquad \tilde{\mathbf{x}}_c = \mathbf{x}_c + \mathbf{n}_c$$

So, cancelation is **not perfect**: $\mathbf{y} = \mathbf{Hx} + \underbrace{\mathbf{H}_t\mathbf{n}_t + \mathbf{H}_c\mathbf{n}_c}_{\text{residual SI}} + \mathbf{n}_r$

We define the **effective noise** as: $\mathbf{n}_{\text{eff}} \triangleq \mathbf{H}_t\mathbf{n}_t + \mathbf{H}_c\mathbf{n}_c + \mathbf{n}_r$

FD-MIMO Testbed & Measurement Setup

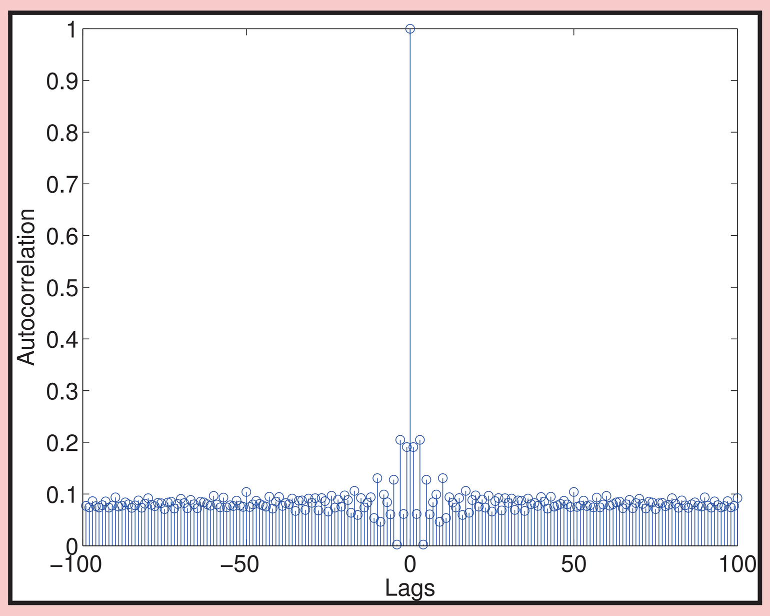
- NI PXIe-1082
  - 4× NI 5791R RF transceivers
  - **Circulator** antenna front-end
- 1× Desktop PC
  - LabVIEW and MATLAB



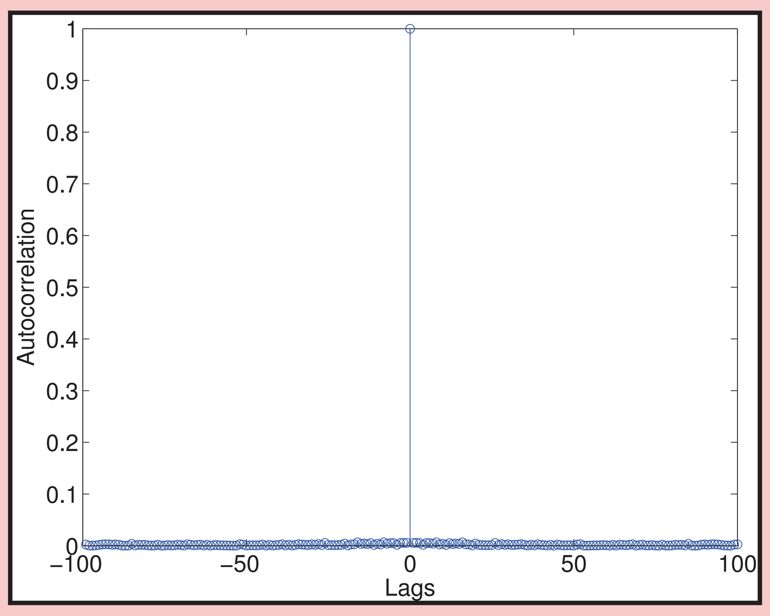
Measurement Parameters

- **2.45 GHz** carrier, **0 dBm** transmit power, **15 cm** antenna spacing
- **10 MHz** bandwidth, **256** OFDM carriers, **QPSK** modulation
- $\mathbf{N_f} = \mathbf{100}$ OFDM frames consisting of **40** OFDM symbols
- Remote signal $\mathbf{x}$ is absent (RX at max. sensitivity)
- **Channel estimation** is performed with a "very long" *aperiodic* sequence
- Residual noise recorded in $2 \times N$ matrix $\mathbf{N}$
- Statistical metrics used for effective noise characterization:
  1. Autocorrelation per receiver (**memory**)
  2. Histograms (**distribution**)
  3. Pseudo-variance and correlation between real and imag. part (**circularity**)
  4. Spatial covariance matrix (**spatial correlation**)

Autocorrelation (Receiver 1)



Time domain

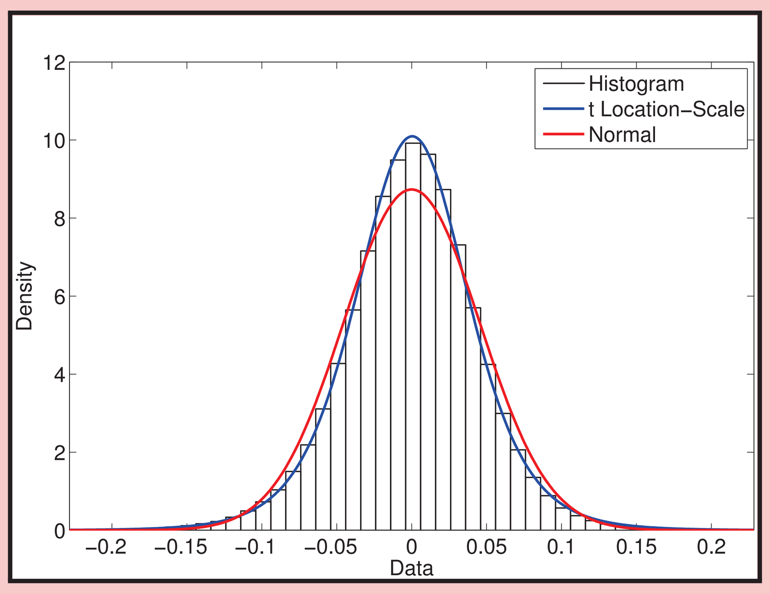


Frequency domain

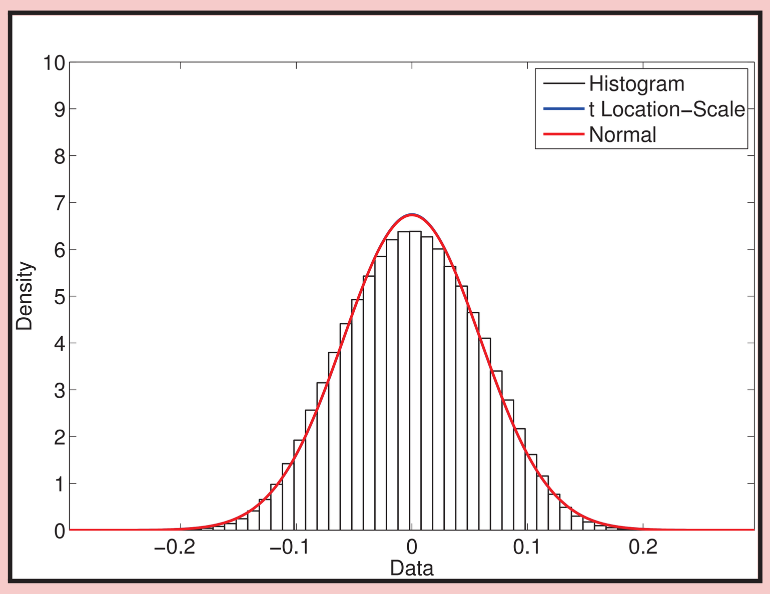
- **Time domain:** $\mathbf{n}_{\text{eff}}$ has **non-negligible memory**
- **Frequency domain:** $\mathbf{n}_{\text{eff}}$ is practically **memoryless**

Histograms (Receiver 1)

Real part of $\mathbf{n}_{\text{eff}}$



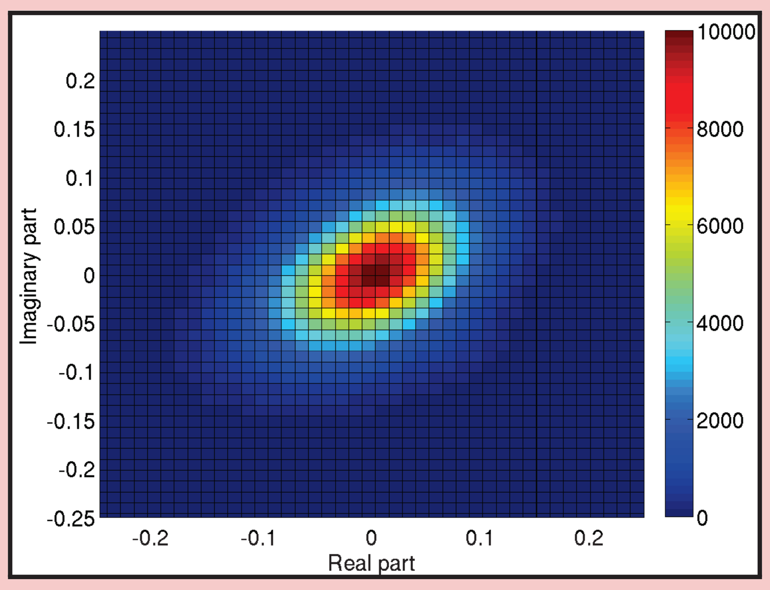
Time domain



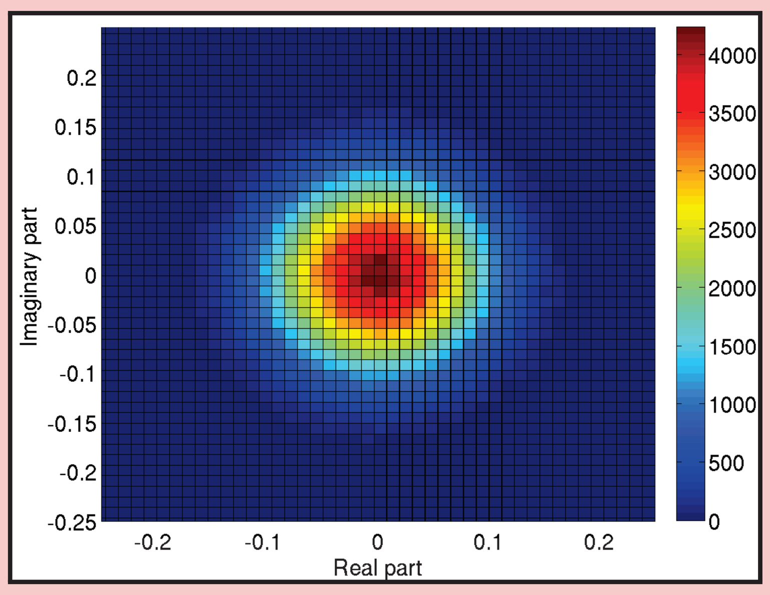
Frequency domain

- **Time domain: Not Gaussian** (Student's t-distribution is good fit)
- **Frequency domain: Gaussian** (central limit theorem)

Complex $\mathbf{n}_{\text{eff}}$



Time domain



Frequency domain

- **Time domain:** $\Re(\mathbf{n}_{\text{eff},1})$ and $\Im(\mathbf{n}_{\text{eff},1})$ are **strongly correlated**
- **Freq. domain:** $\Re(\mathbf{n}_{\text{eff},1})$ and $\Im(\mathbf{n}_{\text{eff},1})$ are **practically uncorrelated**

Pseudo-variance and Spatial Covariance

- For each chain i, the pseudo-variance is defined as: $\tau_i^2 \triangleq \mathbb{E}\left[\mathbf{n}_{\text{eff},i}^2\right]$
- A **smaller pseudo-variance** indicates a **more circular** random variable
- **Time domain:** $|\hat{\tau}_1^2| \approx 10^{-3}$
- **Frequency domain:** $|\hat{\tau}_1^2| \approx 10^{-5}$ → **more circular**

Spatial Covariance Matrices

- **Time domain:** $\hat{\mathbf{K}}_{\text{time}} = \begin{bmatrix} 0.0067 & -0.0013 - 0.0031i \\ -0.0013 + 0.0031i & 0.0053 \end{bmatrix}$
- **Freq. domain:** $\hat{\mathbf{K}}_{\text{freq}} = \begin{bmatrix} 0.0070 & -0.0013 - 0.0039i \\ -0.0013 + 0.0039i & 0.0057 \end{bmatrix}$
- **Spatial correlation remains** in the frequency domain

Summary of Effective Noise Properties

- **Time domain:**
  - ✗ Not memoryless
  - ✗ Not Gaussian
  - ✗ Not circular symmetric
  - ✗ Spatially correlated
- **Frequency domain:**
  - ✓ Memoryless
  - ✓ Gaussian
  - ✓ Circular symmetric
  - ✗ Spatially correlated

Effect of Residual Noise on ZF and ML MIMO Receivers

- Simulated **OFDM** ZF and ML receivers with noise samples from our testbed
- Receivers **suffer heavily** under spatially correlated noise
- **Noise whitening** can recover some of the loss