Equipping Millimeter-Wave Full-Duplex with Analog Self-Interference Cancellation

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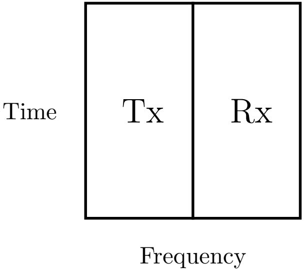
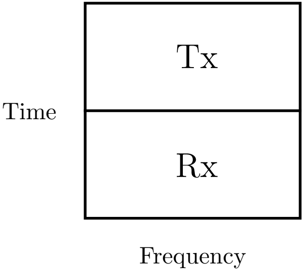
Introduction

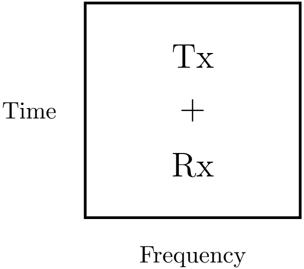
Conventional radios operate in a half-duplex fashion (e.g., FDD, TDD).





Introduction

We are interested in **full-duplex** operation, where transmission and reception take place on the same time-frequency resource.



Tx

+

Rx

Time

Frequency

This sort of operation introduces **self-interference** since transmission and reception are no longer orthogonal.

Introduction

In particular, we look at equipping millimeter-wave (mmWave) devices with full-duplex capability.

Wideband, high-rate communication at mmWave is enabled by three key technologies:

- dense antenna arrays for beamforming gains
- hybrid digital/analog beamforming architectures for efficiently utilizing these arrays
- “beamtraining” (or “beam alignment”) schemes to address initial access and channel estimation

Introduction

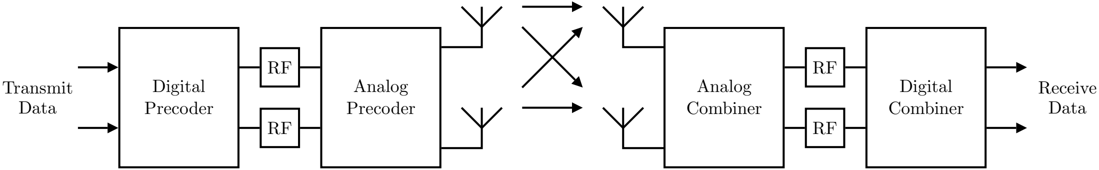


Figure 1: Hybrid digital/analog beamforming architecture used in mmWave systems.

Introduction

Why do we care about full-duplex at mmWave?

- capitalize on inherently high-rate communication
- lower latency
- interference management
- deployment solutions
- in-band coexistence
- . . .

mmWave is a very exciting domain for full-duplex!

Introduction

Full-duplex has been well-explored in sub-6 GHz systems.

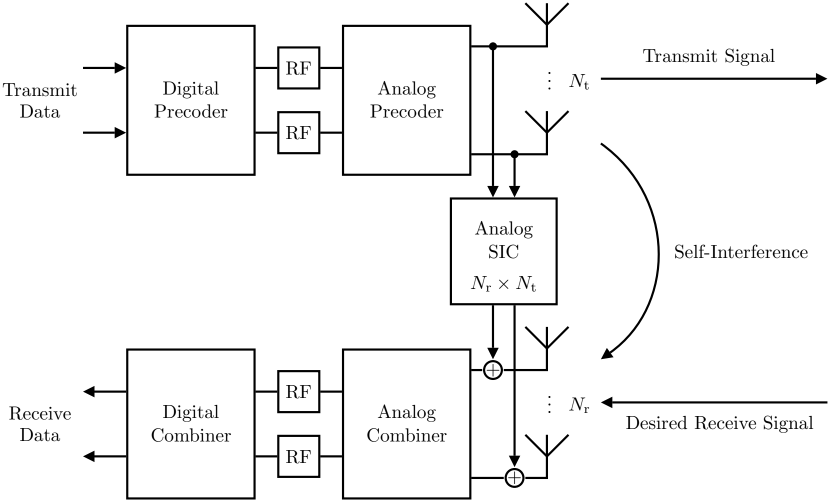
- analog self-interference cancellation (SIC)
- digital SIC

There are significant challenges in translating analog SIC solutions to mmWave systems.

- dense antenna arrays → large MIMO self-interference channel

This is an issue for mmWave full-duplex because the need remains to prevent ADC saturation!

Introduction



Introduction

Fortunately, the dense antenna arrays at mmWave offer the spatial domain as a promising means for self-interference mitigation.

- "beamforming cancellation"

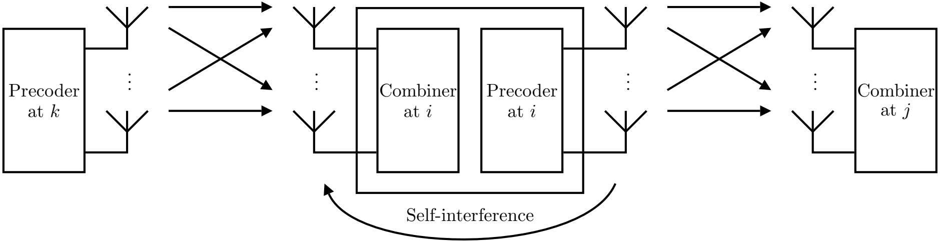
This is courtesy of the fact that, at mmWave,

$$\text{number of antennas} \gg \text{number of data streams}$$

This affords us the opportunity to address self-interference **spatially**.

System Model & Problem Statement

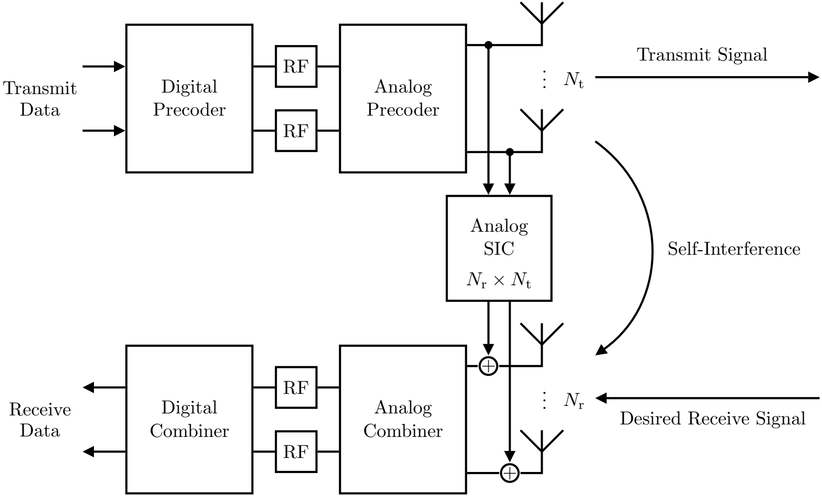
A full-duplex device i transmits to j while receiving from k.



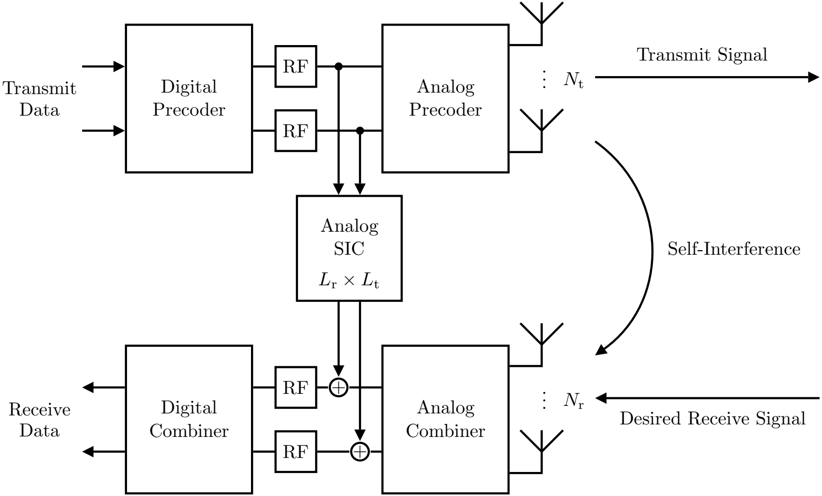
How to handle the self-interference? → beamforming cancellation

Can we also use analog SIC?

System Model & Problem Statement



System Model & Problem Statement



System Model & Problem Statement

The goal of this work is to take an initial look at how analog SIC can be used in conjunction with beamforming cancellation to enable mmWave full-duplex.

A few key assumptions:

- frequency-flat channels
- transceiver nonlinearity is ignored (e.g., handled by digital SIC)
- LNAs are not saturated (e.g., handled by beamforming cancellation, isolation)
- perfect channel state information
- analog SIC suffers from some degree of quantized control

Contribution

Three stages to our design:

- Stage 0: Beamtraining
- Stage 1: Analog SIC
- Stage 2: Beamforming cancellation

Contribution — Stage 0: Beamtraining

Beamtraining is the search through RF beamformers that "work well" between two devices.

- can be thought of as finding rays in the channel to transmit and receive on

There are a variety of beamtraining schemes. Our work does not rely on a particular one; we simply assume on takes place as follows.

Following beamtraining, the RF beamformers on all links are fixed.

$$\tilde{\mathbf{H}}_{ij} \triangleq \mathbf{W}_{\mathrm{RF}}^{(j)*} \mathbf{H}_{ij} \mathbf{F}_{\mathrm{RF}}^{(i)} \tag{1}$$

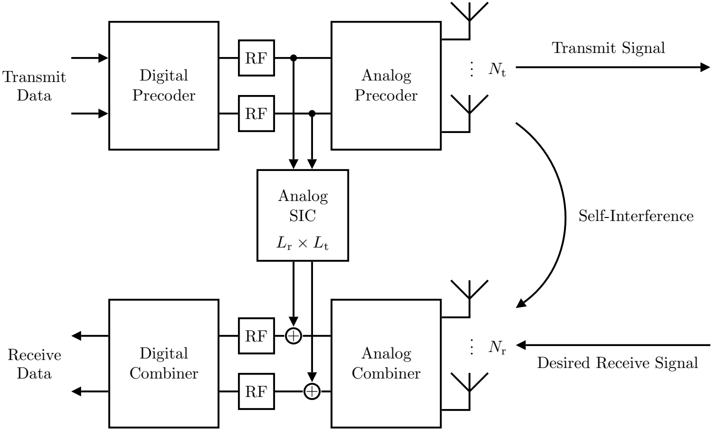
$$\tilde{\mathbf{H}}_{ki} \triangleq \mathbf{W}_{\mathrm{RF}}^{(i)*} \mathbf{H}_{ki} \mathbf{F}_{\mathrm{RF}}^{(k)} \tag{2}$$

$$\tilde{\mathbf{H}}_{ii} \triangleq \mathbf{W}_{\mathrm{RF}}^{(i)*} \mathbf{H}_{ii} \mathbf{F}_{\mathrm{RF}}^{(i)} \tag{3}$$

Much easier to estimate these channels!

Contribution — Stage 1: Analog SIC Configuration

Post-beamtraining, the effective self-interference channel is $\tilde{\mathbf{H}}_{ii}$.



The analog SIC seeks to recreate $\tilde{\mathbf{H}}_{ii}$.

Contribution — Stage 1: Analog SIC Configuration

Recall that we assume the analog SIC solution to have quantized entries (e.g., M-bit entries).

We decompose the $\tilde{\mathbf{H}}_{ii}$ into the portion analog SIC implements and the residual quantization error.

$$\tilde{\mathbf{H}}_{ii} = \underbrace{\hat{\tilde{\mathbf{H}}}_{ii}}_{\text{analog SIC}} + \underbrace{\Delta\tilde{\mathbf{H}}_{ii}}_{\text{quantization error}} \tag{4}$$

If analog SIC takes care of $\hat{\tilde{\mathbf{H}}}_{ii}$, beamforming cancellation will address $\Delta\tilde{\mathbf{H}}_{ii}$.

Contribution — Stage 2: Beamforming Cancellation

The goal of beamforming cancellation is to mitigate self-interference by avoiding the **residual** self-interference channel $\Delta\tilde{\mathbf{H}}_{ii}$.

First, let's set the baseband precoder at k and the baseband combiner at j.

$$\tilde{\mathbf{H}}_{ij} = \mathbf{U}_{ij}\ \mathbf{\Sigma}_{ij}\ \mathbf{V}_{ij}^{*} \tag{5}$$

$$\tilde{\mathbf{H}}_{ki} = \mathbf{U}_{ki}\ \mathbf{\Sigma}_{ki}\ \mathbf{V}_{ki}^{*} \tag{6}$$

$$\mathbf{W}_{\mathrm{BB}}^{(j)} = \left[\mathbf{U}_{ij}\right]_{:,0:N_{\mathrm{s}}^{(i)}-1} \tag{7}$$

$$\mathbf{F}_{\mathrm{BB}}^{(k)} = \left[\mathbf{V}_{ki}\right]_{:,0:N_{\mathrm{s}}^{(k)}-1} \tag{8}$$

Contribution — Stage 2: Beamforming Cancellation

Next, we set the baseband combiner at the full-duplex device i.

$$\mathbf{W}_{\mathrm{BB}}^{(i)} = \left[\mathbf{U}_{ki}\right]_{:,0:N_{\mathrm{s}}^{(k)}-1} \tag{9}$$

Contribution — Stage 2: Beamforming Cancellation

The only knob we have left to turn is the baseband precoder at i.

The baseband precoder of the full-duplex device i is designed in an MMSE fashion.

1. avoids contributing self-interference
2. transmits to j

Contribution — Stage 2: Beamforming Cancellation

Having set all other precoders and combiners and the analog SIC, we get the following effective channels.

$$\mathbf{H}_{\mathrm{des}} \triangleq \mathbf{W}_{\mathrm{BB}}^{(j)*} \mathbf{W}_{\mathrm{RF}}^{(j)*} \mathbf{H}_{ij} \mathbf{F}_{\mathrm{RF}}^{(i)} \tag{10}$$

$$\mathbf{H}_{\mathrm{int}} \triangleq \mathbf{W}_{\mathrm{BB}}^{(i)*} \underbrace{\left(\mathbf{W}_{\mathrm{RF}}^{(i)*} \mathbf{H}_{ii} \mathbf{F}_{\mathrm{RF}}^{(i)} - \hat{\tilde{\mathbf{H}}}_{ii} \right)}_{=\Delta \tilde{\mathbf{H}}_{ii}} \tag{11}$$

We can design the baseband precoder as

$$\mathbf{F}_{\mathrm{BB}}^{(i)} = \left[\left(\mathbf{H}_{\mathrm{des}}^{*} \mathbf{H}_{\mathrm{des}} + \frac{\mathrm{SNR}_{ii}}{\mathrm{SNR}_{ij}} \mathbf{H}_{\mathrm{int}}^{*} \mathbf{H}_{\mathrm{int}} + \frac{N_{\mathrm{s}}^{(i)}}{\mathrm{SNR}_{ij}} \mathbf{I} \right)^{-1} \mathbf{H}_{\mathrm{des}}^{*} \right]_{:,0:N_{\mathrm{s}}^{(i)}-1} \tag{12}$$

This concludes our design.

Simulation & Results

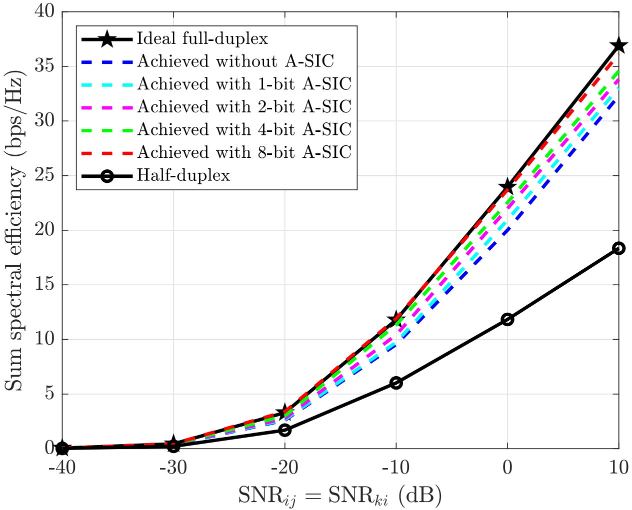


Figure 2: Sum spectral efficiency as a function of SNR for various scenarios. As the resolution of A-SIC improves, the sum spectral efficiency approaches that of ideal (interference-free) full-duplex.

Simulation & Results

Takeaway points:

- Analog SIC can have a place in mmWave full-duplex systems without being prohibitively large.
- The shortcomings of beamforming cancellation can be reduced with help from coarse analog SIC solutions.

Future work:

- Investigate how analog SIC and beamforming cancellation can share the load in frequency-selective settings.
- System-wide analysis and design of analog SIC, beamforming cancellation, and digital SIC.
- Characterization of the self-interference channel to see if correlations can further reduce the size of analog SIC.

Thank you. Feel free to email us with any questions or feedback.

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Bonus Slides

$$\mathbf{H} = \sqrt{\frac{N_{\mathrm{t}} N_{\mathrm{r}}}{N_{\mathrm{rays}} N_{\mathrm{cl}}}} \sum_{m=1}^{N_{\mathrm{cl}}} \sum_{n=1}^{N_{\mathrm{rays}}} \beta_{m,n} \mathbf{a}_{\mathrm{r}}(\theta_{m,n}) \mathbf{a}_{\mathrm{t}}^{*}(\phi_{m,n}) \tag{13}$$

Bonus Slides

$$\mathbf{H}_{\mathrm{SI}} = \sqrt{\frac{\kappa}{\kappa+1}}\mathbf{H}_{\mathrm{SI}}^{\mathrm{LOS}} + \sqrt{\frac{1}{\kappa+1}}\mathbf{H}_{\mathrm{SI}}^{\mathrm{NLOS}} \tag{14}$$

Bonus Slides

The entries of the line-of-sight (LOS) contribution are modeled as

$$\left[\mathbf{H}_{\mathrm{SI}}^{\mathrm{LOS}}\right]_{n,m} = \frac{\rho}{r_{m,n}} \exp\left(-\mathrm{j}2\pi \frac{r_{m,n}}{\lambda}\right) \tag{15}$$

where ρ is a normalization constant such that $\mathbb{E}\left[\|\mathbf{H}_{ii}\|_{\mathrm{F}}^{2}\right] = N_{\mathrm{t}} N_{\mathrm{r}}$ and $r_{m,n}$ is the distance from the mth element of the transmit array to the nth element of the receive array.

For the non-line-of-sight (NLOS) portion, we use the ray/cluster model (13).