Frequency-Selective Beamforming Cancellation Design for Millimeter-Wave Full-Duplex

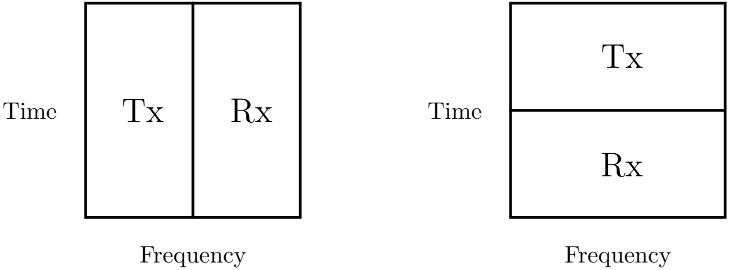
June 2020

Ian P. Roberts, Hardik B. Jain, and Sriram Vishwanath
GenXComm, Inc., Austin, Texas

http://genxcomm.com

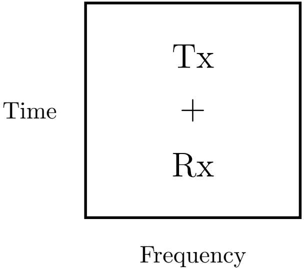
Introduction

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.



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.

Communication at mmWave is characterized by:

- wide bandwidth, high-rate communication
- high path loss, low diffraction, high reflectivity
- dense antenna arrays for beamforming gains

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
- digital self-interference cancellation

There are significant challenges in translating these solutions to mmWave systems.

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

- "beamforming cancellation"

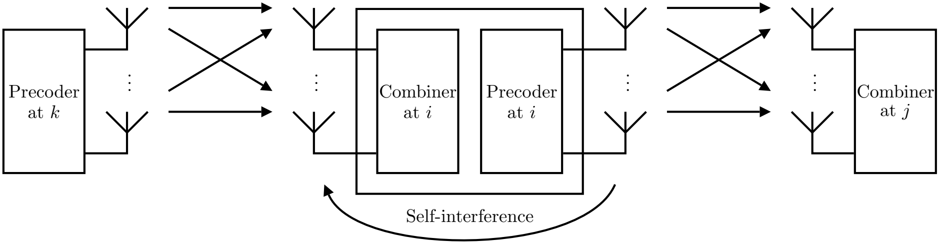
This work is an extension of our GLOBECOM work* to frequency-selective settings.

---

*I. P. Roberts and S. Vishwanath, "Beamforming cancellation design for millimeter-wave full-duplex," in *Proceedings of the IEEE Global Communications Conference*, Waikoloa, HI, USA, Dec. 2019.

System Model & Problem Statement

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



How to handle the self-interference? $\rightarrow$ beamforming cancellation

System Model & Problem Statement

In this work, we create MIMO precoding and combining designs that sufficiently:

- transmit to j
- receive from k
- mitigate self-interference

Two main challenges at mmWave:

1. hybrid digital/analog beamforming
2. frequency-selectivity

System Model & Problem Statement

Three frequency-selective (multi-tap) channels of concern:

- $\mathbf{H}_{ij}[d]$ — transmit channel
- $\mathbf{H}_{ki}[d]$ — receive channel
- $\mathbf{H}_{ii}[d]$ — self-interference channel

With OFDM, we can transform these into U frequency-domain subchannels via

$$\mathbf{H}[u] = \sum_{d=0}^{D-1} \mathbf{H}[d] \ e^{-\mathrm{j}\frac{2\pi u d}{U}} \tag{1}$$

We will be precoding and combining on frequency-domain subchannels.

System Model & Problem Statement

Each transmitter has digital precoders $\{\mathbf{F}_{\mathsf{BB}}[u]\}$ and an analog precoder $\mathbf{F}_{\mathsf{RF}}$.

Each receiver has a digital combiner $\{\mathbf{W}_{\mathsf{BB}}[u]\}$ and an analog combiner $\mathbf{W}_{\mathsf{RF}}$.

The RF beamformers are (relatively) frequency-flat (i.e., are not tunable per-subcarrier).

System Model & Problem Statement

The symbol vector from i to j is

$$\mathbf{y}^{(j)}[u] = \mathbf{W}_{\mathsf{BB}}^{(j)*}[u]\mathbf{W}_{\mathsf{RF}}^{(j)*}\left(\sqrt{P_{\mathrm{tx}}^{(i)}}G_{ij}\mathbf{H}_{ij}[u]\mathbf{F}_{\mathsf{RF}}^{(i)}\mathbf{F}_{\mathsf{BB}}^{(i)}[u]\mathbf{s}^{(i)}[u] + \mathbf{n}^{(j)}[u]\right) \tag{2}$$

- $P_{\mathrm{tx}}^{(i)} \rightarrow$ transmit power
- $G_{ij} \rightarrow$ large-scale gain
- $\mathbf{H}_{ij}[u] \rightarrow$ channel
- $\mathbf{s}^{(i)}[u] \rightarrow$ symbol vector
- $\mathbf{n}^{(j)}[u] \rightarrow$ noise vector

System Model & Problem Statement

The symbol vector received by i from k is

$$\mathbf{y}^{(i)}[u] = \mathbf{W}_{\mathsf{BB}}^{(i)*}[u]\mathbf{W}_{\mathsf{RF}}^{(i)*}\left(\sqrt{P_{\mathrm{tx}}^{(k)}}G_{ki}\mathbf{H}_{ki}[u]\mathbf{F}_{\mathsf{RF}}^{(k)}\mathbf{F}_{\mathsf{BB}}^{(k)}[u]\mathbf{s}^{(k)}[u]\right. \left. + \underbrace{\sqrt{P_{\mathrm{tx}}^{(i)}}G_{ii}\mathbf{H}_{ii}[u]\mathbf{F}_{\mathsf{RF}}^{(i)}\mathbf{F}_{\mathsf{BB}}^{(i)}[u]\mathbf{s}^{(i)}[u]}_{\mathrm{self-interference}} + \mathbf{n}^{(i)}[u]\right) \tag{3}$$

The goal of our beamforming cancellation design is to mitigate self-interference per-subcarrier.

Contribution

To handle frequency-selective beamforming design, we take inspiration from orthogonal matching pursuit (OMP)-based hybrid beamforming design*.

$$(\mathbf{X}_{\mathsf{RF}}, \mathbf{X}_{\mathsf{BB}}) = \mathsf{omp\_hybrid}\,(\mathbf{X}, \mathbf{A}_{\mathsf{RF}}, N_{\mathrm{RF}}) \tag{4}$$

- $\mathbf{X} \rightarrow$ fully-digital beamforming matrix
- $\mathbf{A}_{\mathsf{RF}} \rightarrow$ analog beamforming codebook
- $N_{\mathrm{RF}} \rightarrow$ number of RF chains

- $\mathbf{X}_{\mathsf{RF}} \rightarrow$ analog beamforming matrix
- $\mathbf{X}_{\mathsf{BB}} \rightarrow$ digital beamforming matrix

*O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Transactions on Wireless Communications*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

Contribution

To utilize omp_hybrid() for frequency-selective beamforming, we stack per-subcarrier fully-digital beamformers in the following fashion.

$$\bar{\mathbf{X}} = \left[\mathbf{X}[0] \quad \mathbf{X}[1] \quad \cdots \quad \mathbf{X}[U-1]\right] \in \mathbb{C}^{N_{\mathrm{a}} \times U N_{\mathrm{s}}} \tag{5}$$

Calling OMP-based hybrid approximation on this will yield

$$\left(\mathbf{X}_{\mathsf{RF}}, \bar{\mathbf{X}}_{\mathsf{BB}}\right) = \text{omp\_hybrid}\left(\bar{\mathbf{X}}, \mathbf{A}_{\mathsf{RF}}, N_{\mathrm{RF}}\right) \tag{6}$$

where we can simply unstack the digital result according to

$$\bar{\mathbf{X}}_{\mathsf{BB}} = \left[\mathbf{X}_{\mathsf{BB}}[0] \quad \mathbf{X}_{\mathsf{BB}}[1] \quad \cdots \quad \mathbf{X}_{\mathsf{BB}}[U-1]\right] \tag{7}$$

We have a frequency-selective hybrid approximation algorithm.

Contribution

Precoding and combining at the half-duplex devices j and k is done so using so-called eigen-beamforming.

Taking the singular value decomposition (SVD), we get

$$\mathbf{H}_{ki}[u] = \mathbf{U}_{\mathbf{H}_{ki}}[u]\ \mathbf{\Sigma}_{\mathbf{H}_{ki}}[u]\ \mathbf{V}^{*}_{\mathbf{H}_{ki}}[u] \tag{8}$$

$$\mathbf{H}_{ij}[u] = \mathbf{U}_{\mathbf{H}_{ij}}[u]\ \mathbf{\Sigma}_{\mathbf{H}_{ij}}[u]\ \mathbf{V}^{*}_{\mathbf{H}_{ij}}[u], \tag{9}$$

which allows us to transmit and receive along the strongest subchannels.

$$\mathbf{F}^{(k)}[u] = \left[\mathbf{V}_{\mathbf{H}_{ki}}[u]\right]_{:,0:N_{\mathrm{s}}^{(k)}-1} \tag{10}$$

$$\mathbf{W}^{(j)}[u] = \left[\mathbf{U}_{\mathbf{H}_{ij}}[u]\right]_{:,0:N_{\mathrm{s}}^{(i)}-1}, \tag{11}$$

Contribution

We now hybrid-approximate these fully-digital beamformers.

We build $\bar{\mathbf{F}}^{(k)}$ from $\{\mathbf{F}^{(k)}[u]\}$ and $\bar{\mathbf{W}}^{(j)}$ from $\{\mathbf{W}^{(j)}[u]\}$, as described by (5), and execute OMP-based hybrid approximation.

$$\left(\mathbf{F}_{\mathsf{RF}}^{(k)}, \bar{\mathbf{F}}_{\mathsf{BB}}^{(k)}\right) = \mathsf{omp\_hybrid}\left(\bar{\mathbf{F}}^{(k)}, \mathbf{A}_{\mathsf{RF}}^{(k)}, L_{\mathrm{t}}^{(k)}\right) \tag{12}$$

$$\left(\mathbf{W}_{\mathsf{RF}}^{(j)}, \bar{\mathbf{W}}_{\mathsf{BB}}^{(j)}\right) = \mathsf{omp\_hybrid}\left(\bar{\mathbf{W}}^{(j)}, \mathbf{A}_{\mathsf{RF}}^{(j)}, L_{\mathrm{r}}^{(j)}\right), \tag{13}$$

Contribution

Precoding and combining at the full-duplex device i aims to serve j and k while suppressing self-interference.

We initialize the precoder and combiner at i as its eigenbeamformers

$$\mathbf{W}^{(i)}[u] = \left[\mathbf{U}_{\mathbf{H}_{ki}}[u]\right]_{:,0:N_{\mathrm{s}}^{(k)}-1} \tag{14}$$

$$\mathbf{F}^{(i)}[u] = \left[\mathbf{V}_{\mathbf{H}_{ij}}[u]\right]_{:,0:N_{\mathrm{s}}^{(i)}-1}. \tag{15}$$

We then hybrid-approximate them using our OMP-based approach to get

$$\left(\mathbf{W}_{\mathsf{RF}}^{(i)}, \left\{\mathbf{W}_{\mathsf{BB}}^{(i)}[u]\right\}\right) \tag{16}$$

$$\left(\mathbf{F}_{\mathsf{RF}}^{(i)}, \left\{\mathbf{F}_{\mathsf{BB}}^{(i)}[u]\right\}\right). \tag{17}$$

Contribution

We will be tailoring solely the per-subcarrier digital precoder at i to reject self-interference in an MMSE fashion.

We define the effective self-interference channel as

$$\mathbf{H}_{\mathrm{int}}[u] \triangleq \mathbf{W}_{\mathsf{BB}}^{(i)*}[u]\mathbf{W}_{\mathsf{RF}}^{(i)*}\mathbf{H}_{ii}[u]\mathbf{F}_{\mathsf{RF}}^{(i)} \tag{18}$$

and the effective desired channel from i to j as

$$\mathbf{H}_{\mathrm{des}}[u] \triangleq \mathbf{W}_{\mathsf{BB}}^{(j)*}[u]\mathbf{W}_{\mathsf{RF}}^{(j)*}\mathbf{H}_{ij}[u]\mathbf{F}_{\mathsf{RF}}^{(i)} \tag{19}$$

Contribution

We can now build our MMSE-based per-subcarrier precoder as follows

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

This concludes our design, having set all digital and analog beamformers at each device.

Simulation & Results

We evaluate the sum spectral efficiency achieved by our design in three scenarios.

Scenario	U	$L_{\mathrm{t}}^{(i)}$	$L_{\mathrm{r}}^{(i)}$	$L_{\mathrm{r}}^{(j)}$	$L_{\mathrm{t}}^{(k)}$
Equal users, low selectivity	8	6	2	2	2
Equal users, high selectivity	128	8	4	4	4
Disparate users, low selectivity	8	6	2	2	2

Simulation & Results

Important benchmarks:

1. ideal full-duplex (fully-digital beamforming, no self-interference)
2. ideal hybrid full-duplex (no self-interference)
3. half-duplex (fully-digital beamforming, equal time sharing)
4. hybrid half-duplex (equal time sharing)

Simulation & Results — Equal Users, Low Selectivity

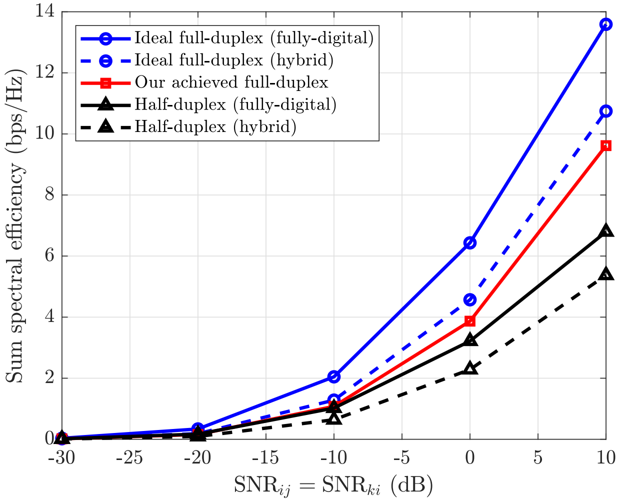


Figure 1: Results of simulating Scenario #1 showing sum spectral efficiency as a function of $\mathrm{SNR}_{ij} = \mathrm{SNR}_{ki}$ when $\mathrm{SNR}_{ii} = 80$ dB.

Simulation & Results — Equal Users, High Selectivity

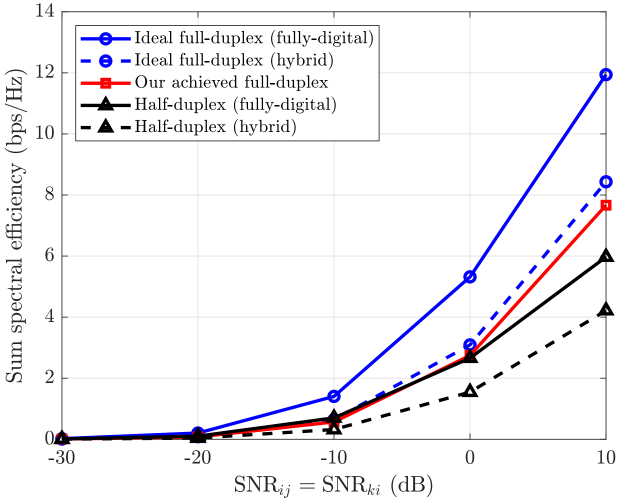


Figure 2: Results of simulating Scenario #2 showing sum spectral efficiency as a function of $\mathrm{SNR}_{ij} = \mathrm{SNR}_{ki}$ when $\mathrm{SNR}_{ii} = 80$ dB.

Simulation & Results — Disparate Users, Low Selectivity

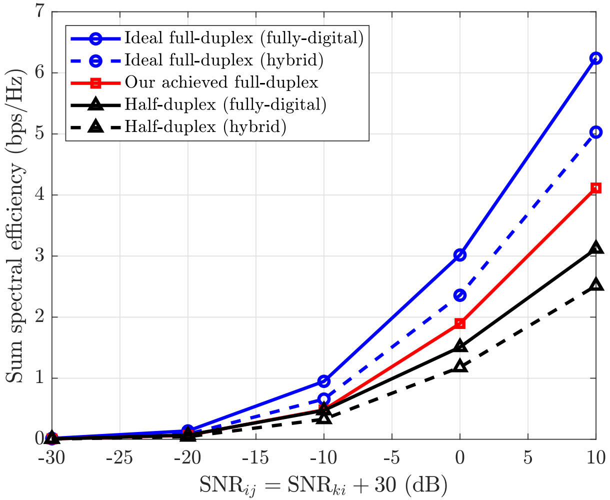


Figure 3: Results of simulating Scenario #3 showing sum spectral efficiency as a function of $\mathrm{SNR}_{ij} = \mathrm{SNR}_{ki} + 30$ dB when $\mathrm{SNR}_{ii} = 80$ dB.

Simulation & Results

Takeaway points:

- Beamforming-based self-interference mitigation can be achieved in frequency-selective settings, even with the constraints of hybrid beamforming.
- Appreciable spectral efficiency gains can be had in various scenarios.
- The number of RF chains can play a significant role in highly selective settings.

Future work:

- Characterize the self-interference channel and its frequency-selectivity.
- Explore the impacts of beam squint.
- Create robust designs that handle channel estimation errors.

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

ianroberts@genxcomminc.com

GenXComm

http://genxcomm.com

Bonus Slides

$$\mathbf{H} = \sqrt{\frac{N_{\mathrm{t}} N_{\mathrm{r}}}{N_{\mathrm{rays}} N_{\mathrm{cl}}}} \sum_{m=1}^{N_{\mathrm{cl}}} \sum_{n=1}^{N_{\mathrm{rays}}} \beta_{m,n} \mathbf{a}_{\mathrm{r}}(\theta_{m,n}) \mathbf{a}_{\mathrm{t}}^{*}(\phi_{m,n}) \tag{20}$$

Bonus Slides

$$\mathbf{H}_{\mathrm{SI}} = \sqrt{\frac{\kappa}{\kappa + 1}}\mathbf{H}_{\mathrm{SI}}^{\mathrm{LOS}} + \sqrt{\frac{1}{\kappa + 1}}\mathbf{H}_{\mathrm{SI}}^{\mathrm{NLOS}} \qquad (21)$$

Bonus Slides

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

$$\left[\mathbf{H}_{\mathrm{SI}}^{\mathrm{LOS}}\right]_{n,m} = \frac{\rho}{r_{m,n}} \exp\left(-\mathrm{j}2\pi \frac{r_{m,n}}{\lambda}\right) \tag{22}$$

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 (20).

Bonus Slides

Algorithm 1: OMP-based hybrid approximation.

Input: $\mathbf{A}_{\mathsf{RF}} \leftarrow$ analog beamforming codebook matrix
Input: $\mathbf{F} \leftarrow$ desired fully-digital beamformer
Input: $N_{\mathrm{RF}} \leftarrow$ number of RF chains
Output: $\mathbf{F}_{\mathrm{RF}}, \mathbf{F}_{\mathrm{BB}} \leftarrow$ analog and digital beamformers

$[N_{\mathrm{a}}, N_{\mathrm{s}}] = \mathsf{size}(\mathbf{F})$
$\mathbf{Y} = \mathbf{F}$
$\mathbf{Z} = [\ ]$
for $r = 0 \ldots N_{\mathrm{RF}} - 1$ **do**
    $\mathbf{\Phi} = \mathbf{A}_{\mathsf{RF}}^{*} \mathbf{Y}$
    $k = \arg\max_{m} \left([\mathbf{\Phi}\mathbf{\Phi}^{*}]_{m,m} \right)$
    $\mathbf{Z} = \left[\mathbf{Z} \mid \ [\mathbf{A}_{\mathsf{RF}}]_{:,k} \right]$
    $\mathbf{F}_{\mathrm{BB}} = \left(\mathbf{Z}^{*} \mathbf{Z} \right)^{-1} \mathbf{Z}^{*} \mathbf{F}$
    $\mathbf{Y} = \mathbf{F} - \mathbf{Z}\mathbf{F}_{\mathrm{BB}}$
    $\mathbf{Y} = \mathbf{Y} / \left\| \mathbf{Y} \right\|_{\mathrm{F}}$
end
$\mathbf{F}_{\mathrm{RF}} = \mathbf{Z}$
return $\mathbf{F}_{\mathrm{RF}}, \mathbf{F}_{\mathrm{BB}}$