Hybrid Beamforming and Interference Cancellation in mmWave Full-Duplex Single-User MIMO Systems

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SCAN ME

Full Duplex

- Simultaneous transmission and reception in same resource block (time/frequency).
- Efficient use of spectrum and latency reduction.
- Loopback self-interference (SI) saturates ADC.
- Use degrees freedom in beamforming to cancel SI.

Hybrid Beamforming Design

- Received signals at the BS ($\mathbf{y}_\mathsf{u}$) and UE ($\mathbf{y}_\mathsf{d}$) are

$$\mathbf{y}_\mathsf{u} = \underbrace{\sqrt{\rho_\mathsf{u}}\mathbf{W}_\mathsf{BS}^*\mathbf{H}_\mathsf{u}\mathbf{F}_\mathsf{UE}\mathbf{s}_\mathsf{u}}_{\text{Desired Signal}} + \underbrace{\sqrt{\rho_\mathsf{s}}\mathbf{W}_\mathsf{BS}^*\mathbf{H}_\mathsf{s}\mathbf{F}_\mathsf{BS}\mathbf{s}_\mathsf{d}}_{\text{Self-Interference Signal}} + \underbrace{\mathbf{W}_\mathsf{BS}^*\mathbf{n}_\mathsf{BS}}_{\text{AWGN}} \quad (1)$$

$$\mathbf{y}_\mathsf{d} = \underbrace{\sqrt{\rho_\mathsf{d}}\mathbf{W}_\mathsf{UE}^*\mathbf{H}_\mathsf{d}\mathbf{F}_\mathsf{BS}\mathbf{s}_\mathsf{d}}_{\text{Desired Signal}} + \underbrace{\sqrt{\rho_\mathsf{iui}}\mathbf{W}_\mathsf{UE}^*\mathbf{H}_\mathsf{iui}\mathbf{F}_\mathsf{UE}\mathbf{s}_\mathsf{u}}_{\text{Inter-User Interference Signal}} + \underbrace{\mathbf{W}_\mathsf{UE}^*\mathbf{n}_\mathsf{UE}}_{\text{AWGN}} \quad (2)$$

ITERATE

- Minimize SI power in analog and preserve eff. channel rank:

$$\mathscr{P}_1 : \min_{\mathbf{W}_\mathsf{BS}^\mathsf{RF}} \operatorname{Tr}\left(\mathbf{W}_\mathsf{BS}^{\mathsf{RF}*}\mathbf{R}_1\mathbf{W}_\mathsf{BS}^\mathsf{RF}\right) \quad \text{s.t. } \mathbf{W}_\mathsf{BS}^{\mathsf{RF}*}\mathbf{H}_\mathsf{u}\mathbf{F}_\mathsf{UE}^\mathsf{RF} = \alpha\mathbf{I}_{N_\mathsf{RF}} \quad (3)$$

$$\mathscr{P}_2 : \min_{\mathbf{F}_\mathsf{BS}^\mathsf{RF}} \operatorname{Tr}\left(\mathbf{F}_\mathsf{BS}^{\mathsf{RF}*}\mathbf{R}_2\mathbf{F}_\mathsf{BS}^\mathsf{RF}\right) \quad \text{s.t. } \mathbf{W}_\mathsf{UE}^{\mathsf{RF}*}\mathbf{H}_\mathsf{d}\mathbf{F}_\mathsf{BS}^\mathsf{RF} = \beta\mathbf{I}_{N_\mathsf{RF}} \quad (4)$$

$$\mathscr{P}_3 : \min_{\mathbf{W}_\mathsf{UE}^\mathsf{RF}} \operatorname{Tr}\left(\mathbf{W}_\mathsf{UE}^{\mathsf{RF}*}\mathbf{R}_3\mathbf{W}_\mathsf{UE}^\mathsf{RF}\right) \quad \text{s.t. } \mathbf{W}_\mathsf{UE}^{\mathsf{RF}*}\mathbf{H}_\mathsf{d}\mathbf{F}_\mathsf{BS}^\mathsf{RF} = \gamma\mathbf{I}_{N_\mathsf{RF}} \quad (5)$$

$$\mathscr{P}_4 : \min_{\mathbf{F}_\mathsf{UE}^\mathsf{RF}} \operatorname{Tr}\left(\mathbf{F}_\mathsf{UE}^{\mathsf{RF}*}\mathbf{R}_4\mathbf{F}_\mathsf{UE}^\mathsf{RF}\right) \quad \text{s.t. } \mathbf{W}_\mathsf{BS}^{\mathsf{RF}*}\mathbf{H}_\mathsf{u}\mathbf{F}_\mathsf{UE}^\mathsf{RF} = \zeta\mathbf{I}_{N_\mathsf{RF}} \quad (6)$$

- Apply Lagrange approach to solve these problems.
- Apply unit modulus constraint to analog beamformers.
- Define hybrid analog/digital decomposition problem as

$$\mathscr{P}_5 : \min_{\mathbf{F}_\mathsf{BB},\mathbf{F}_\mathsf{RF}} \|\mathbf{F}_\mathsf{opt} - \mathbf{F}_\mathsf{RF}\mathbf{F}_\mathsf{BB}\|_F^2 \quad \text{s.t. } \mathbf{F}_\mathsf{RF} \in \mathcal{F}_\mathsf{RF}, \quad \|\mathbf{F}_\mathsf{RF}\mathbf{F}_\mathsf{BB}\|_F^2 = N_\mathsf{s} \quad (7)$$

- Design digital precoder using the Least Square routine as

$$\mathbf{F}_\mathsf{BB} = \mathbf{F}_\mathsf{RF}^\dagger\mathbf{F}_\mathsf{opt} \quad (8)$$

System Architecture

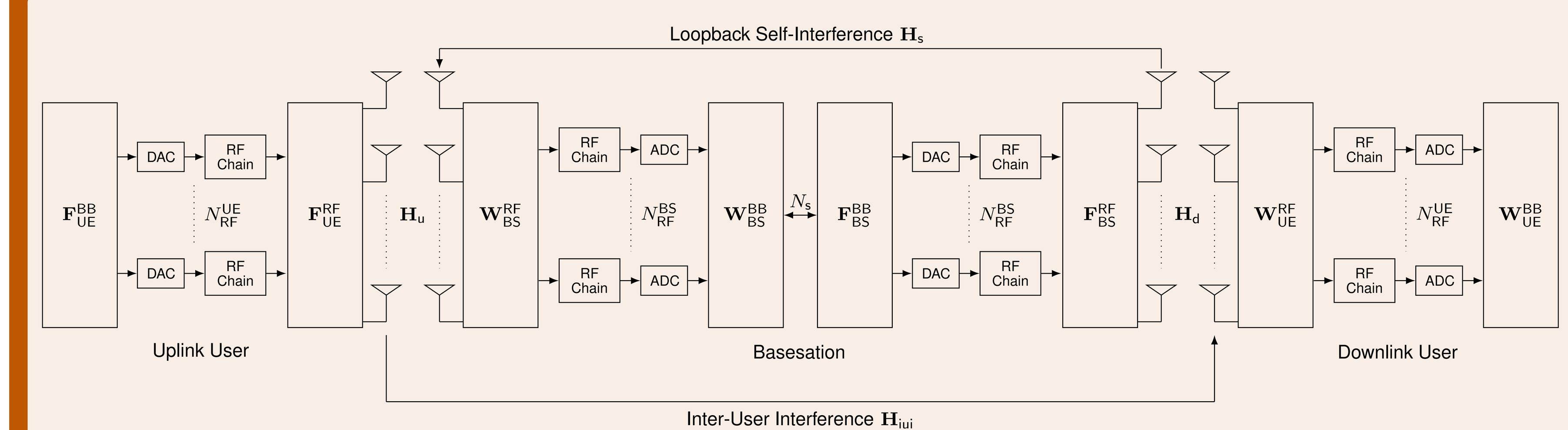

Figure: Basic abstraction of the hybrid analog/digital architecture of the FD BS and the uplink/downlink users. The loopback self-interference at the BS is denoted by the channel $\mathbf{H}_\mathsf{s}$ while the inter-user interference channel from the uplink to the downlink user is denoted by $\mathbf{H}_\mathsf{iui}$.

Numerical Results

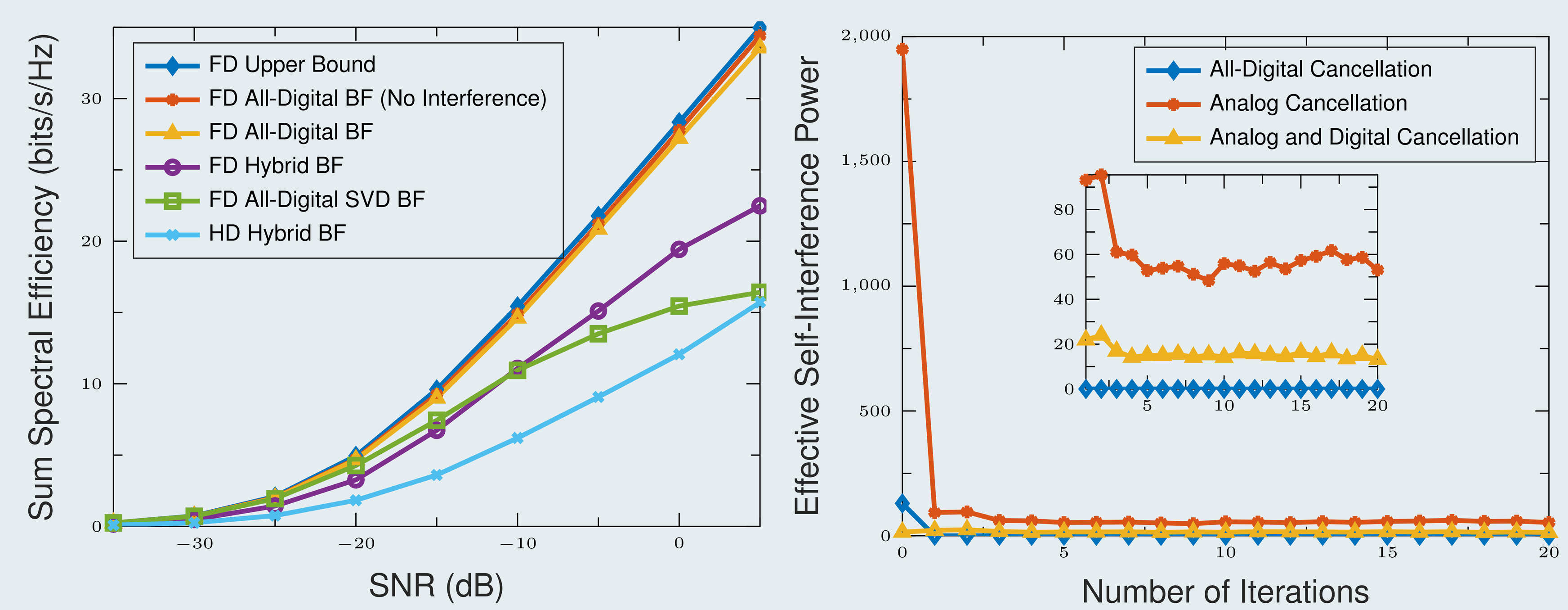

Figure: LEFT: Spectral efficiency vs. full-duplex methods, half-duplex method and benchmarks all-digital beamforming and upper bound. RIGHT: Convergence of proposed algorithm.

Table: Computational complexity of the hybrid beamforming algorithm per iteration. Parameters values are selected from the table of simulation parameters.

Operation	Flops	Dominant Term	% Computation
$\mathbf{W}_\mathsf{BS}^\mathsf{RF}$	16309	$\frac{1}{3}N_\mathsf{BS}^3$	32.41%
$\mathbf{F}_\mathsf{BS}^\mathsf{RF}$	16309	$\frac{1}{3}N_\mathsf{BS}^3$	32.41%
$\mathbf{W}_\mathsf{UE}^\mathsf{RF}$	368	$N_\mathsf{BS}N_\mathsf{UE}N_\mathsf{RF}^\mathsf{BS}$	0.76%
$\mathbf{F}_\mathsf{UE}^\mathsf{RF}$	368	$N_\mathsf{BS}N_\mathsf{UE}N_\mathsf{RF}^\mathsf{BS}$	0.76%
$\mathbf{W}_\mathsf{BS}^\mathsf{BB}$	143	$(N_\mathsf{RF}^\mathsf{BS})^2N_\mathsf{BS}$	0.38%
$\mathbf{F}_\mathsf{BS}^\mathsf{BB}$	143	$(N_\mathsf{RF}^\mathsf{BS})^2N_\mathsf{BS}$	0.38%
$\mathbf{W}_\mathsf{UE}^\mathsf{BB}$	31	$\left(N_\mathsf{RF}^\mathsf{UE}\right)^2N_\mathsf{UE}$	0.04%
$\mathbf{F}_\mathsf{UE}^\mathsf{BB}$	31	$\left(N_\mathsf{RF}^\mathsf{UE}\right)^2N_\mathsf{UE}$	0.04%

Simulation Parameters

Parameter	Value
Carrier frequency	28 GHz
Bandwidth	850 MHz
Number of BS antennas (N_BS)	32
Number of UE antennas (N_UE)	4
Number of clusters (C)	6
Number of rays per cluster (R_c)	8
AoA/AoD Angular spread	$20°$
Transceivers gap (d)	2λ
Transceivers incline (ω)	$\frac{\pi}{6}$
Rician factor (κ)	5 dB
SI power (ρ_s)	15 dB
IUI power (ρ_iui)	5 dB
Number of spatial streams (N_s)	2
Number of RF chains (N_RF)	2

Hybrid Beamforming Design Algorithm

- Better spectral efficiency than half-duplex and conventional approach (SVD).
- Gap from bound due to unit modulus constraint.
- Analog beamforming (BF) drops SI power from 2000 to 53 to prevent ADC saturation (40x).
- Digital BF drops SI power from 53 to 13 (4x).
- Converges in 10 iterations.
- Low complexity: dominated by N_BS^3.

Reference

- E. Balti, C. Dick and B. L. Evans "Low Complexity Hybrid Beamforming for mmWave Full-Duplex Integrated Access and Backhaul," *IEEE GLOBECOM*, 2022.