Low Complexity Hybrid Beamforming for mmWave Full-Duplex Integrated Access and Backhaul

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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 IAB ($\mathbf{y}_\text{b}$) and UE ($\mathbf{y}_\text{a}$) are

$$\mathbf{y}_\text{b} = \underbrace{\sqrt{\rho_\text{b}}\mathbf{W}_\text{IAB}^*\mathbf{H}_\text{b}\mathbf{F}_\text{gNB}\mathbf{s}_\text{b}}_{\text{Desired Signal}} + \underbrace{\sqrt{\rho_\text{s}}\mathbf{W}_\text{IAB}^*\mathbf{H}_\text{s}\mathbf{F}_\text{IAB}\mathbf{s}_\text{a}}_{\text{Self-Interference Signal}} + \underbrace{\mathbf{W}_\text{IAB}^*\mathbf{n}_\text{IAB}}_{\text{AWGN}} \quad (1)$$

$$\mathbf{y}_\text{a} = \underbrace{\sqrt{\rho_\text{a}}\mathbf{W}_\text{UE}^*\mathbf{H}_\text{a}\mathbf{F}_\text{IAB}\mathbf{s}_\text{a}}_{\text{Desired Signal}} + \underbrace{\mathbf{W}_\text{UE}^*\mathbf{n}_\text{UE}}_{\text{AWGN}} \quad (2)$$

ITERATE

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

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

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

- IAB solutions to the coupled problems (3) and (4):

$$\mathbf{W}_\text{IAB}^\text{RF} = \alpha\mathbf{R}_\text{IAB}^{-1}\mathbf{H}_\text{b}\mathbf{F}_\text{gNB}^\text{RF}\left(\mathbf{F}_\text{gNB}^{\text{RF}*}\mathbf{H}_\text{b}^*\mathbf{R}_\text{IAB}^{-1}\mathbf{H}_\text{b}\mathbf{F}_\text{gNB}^\text{RF}\right)^{-1} \quad (5)$$

$$\mathbf{F}_\text{IAB}^\text{RF} = \beta\mathbf{S}_\text{IAB}^{-1}\mathbf{H}_\text{a}^*\mathbf{W}_\text{UE}^{\text{RF}*}\left(\mathbf{W}_\text{UE}^{\text{RF}*}\mathbf{H}_\text{a}\mathbf{S}_\text{IAB}^{-1}\mathbf{H}_\text{a}^*\mathbf{W}_\text{UE}^\text{RF}\right)^{-1} \quad (6)$$

- Select UE (MMSE) and gNB (Reg ZF) analog beamformers:

$$\mathbf{W}_\text{UE}^\text{RF} = \left(\mathbf{H}_\text{a}\mathbf{F}_\text{IAB}^\text{RF}\mathbf{F}_\text{IAB}^{\text{RF}*}\mathbf{H}_\text{a}^* + \frac{N_\text{UE}}{\text{SNR}_\text{a}}\mathbf{I}_{N_\text{UE}}\right)^{-1}\mathbf{H}_\text{a}\mathbf{F}_\text{IAB}^\text{RF} \quad (7)$$

$$\mathbf{F}_\text{gNB}^\text{RF} = \left(\mathbf{H}_\text{b}^*\mathbf{W}_\text{IAB}^\text{RF}\mathbf{W}_\text{IAB}^{\text{RF}*}\mathbf{H}_\text{b} + \frac{N_\text{IAB}}{\text{SNR}_\text{b}}\mathbf{I}_{N_\text{IAB}}\right)^{-1}\mathbf{H}_\text{b}^*\mathbf{W}_\text{IAB}^\text{RF} \quad (8)$$

- Apply unit modulus constraint to analog beamformers
- Design each of four digital beamformers $\mathbf{X}_\text{BB}$ optimally from its corresponding analog beamformer $\mathbf{X}_\text{RF}$:
  Compute SVD $\mathbf{X}_\text{RF} = \mathbf{U}_\text{RF}\mathbf{S}_\text{RF}\mathbf{V}_\text{RF}^*$.
  $\mathbf{X}_\text{BB} = \mathbf{V}_\text{RF}\mathbf{S}_\text{RF}^{-1}\mathbf{Q}$, where $\mathbf{Q}$ is a unitary matrix.

System Architecture

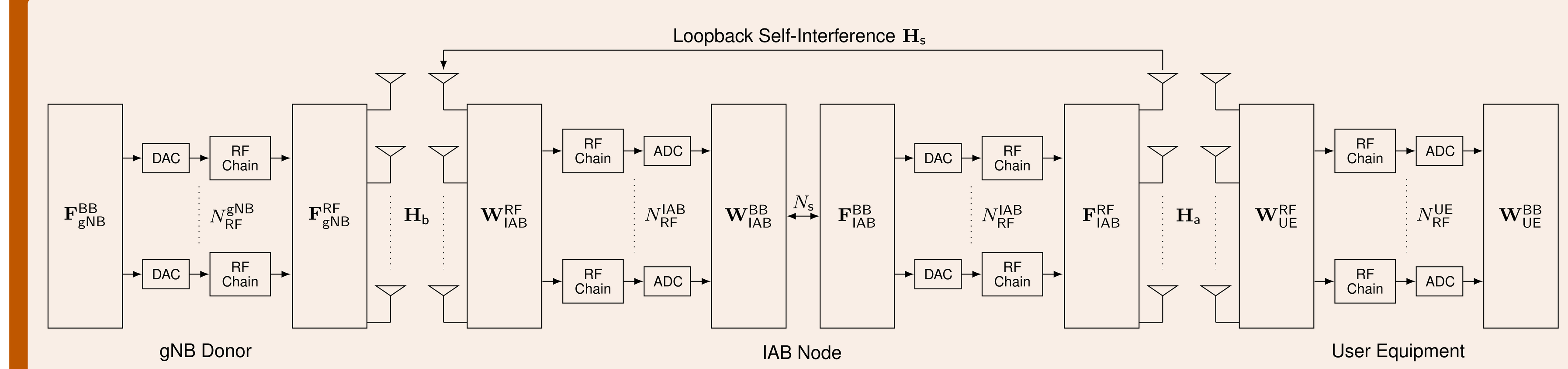

Figure: Hybrid analog/digital beamforming architecture of the full-duplex integrated access and backhaul (IAB) system. The backhaul channel is between the gNB donor and IAB node, and the access channel is between the IAB node and user equipment (UE).

Numerical Results

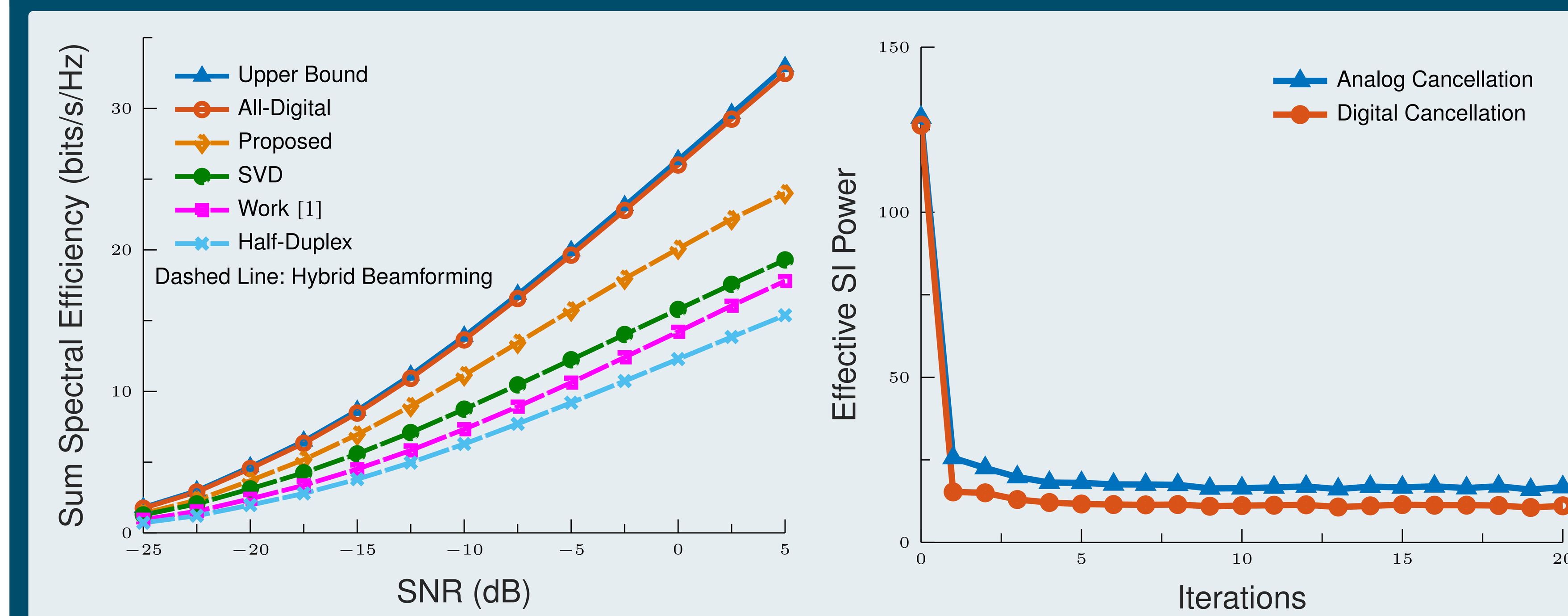

Figure: LEFT: Spectral efficiency vs. full-duplex methods, half-duplex method and benchmarks all-digital beamforming and upper bound. RIGHT: Convergence of proposed algorithm.

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
$\mathbf{W}_\text{IAB}^\text{RF}$	21165	$\frac{1}{3}N_\text{IAB}^3$	16.06%
$\mathbf{F}_\text{IAB}^\text{RF}$	19373	$\frac{1}{3}N_\text{IAB}^3$	16.06%
$\mathbf{F}_\text{gNB}^\text{RF}$	13995	$\frac{1}{3}N_\text{gNB}^3$	16.06%
$\mathbf{W}_\text{IAB}^\text{BB}$	4360	$N_\text{IAB}^2 N_\text{s}$	3.01%
$\mathbf{F}_\text{IAB}^\text{BB}$	4360	$N_\text{IAB}^2 N_\text{s}$	3.01%
$\mathbf{F}_\text{gNB}^\text{BB}$	4360	$N_\text{gNB}^2 N_\text{s}$	3.01%
$\mathbf{W}_\text{UE}^\text{BB}$	328	$9\left(N_\text{RF}^\text{UE}\right)^2 N_\text{UE}$	0.21%
$\mathbf{W}_\text{UE}^\text{RF}$	70	$\frac{3}{2}N_\text{UE}^2 N_\text{RF}^\text{UE}$	0.07%

Simulation Parameters

Parameter	Value
Carrier Frequency	28 GHz
Bandwidth	850 MHz
Number of gNB antennas (N_gNB)	32
Number of IAB antennas (N_IAB)	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
Number of spatial streams (N_s)	2
Number of RF chains (N_RF)	2

Hybrid Beamforming Design Algorithm

Better spectral efficiency than half-duplex, conventional approach (SVD) and related work [1]

Gap to bound due to unit modulus constraint

Analog beamforming (BF) drops SI power from 128 to 16 to prevent ADC saturation (8x)

Digital BF drops SI power from 16 to 10.6 (1.5x)

Converges in 10 iterations (0.7 Mflops in total)

Low complexity: dominated by N_IAB^3 and N_gNB^3

Reference

[1] I. P. Roberts, H. B. Jain and S. Vishwanath, "Frequency-Selective Beamforming Cancellation Design for Millimeter-Wave Full-Duplex," *IEEE Int. Conf. Communications*, 2020.