Advanced Signal Processing Techniques For Full-Duplex Systems [1]

Overview of Ph.D. Research

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Introduction

- Full duplex (FD) systems transmit and receive in the same time/frequency resource block
- Potential benefits
  - Double spectral efficiency
  - Reduce latency
  - Enhance reliability/coverage
- Problem: Loop-back self-interference (SI)
  - Transmitted signal received by co-located receiver
  - Saturates receiver analog-to-digital converters (ADCs)
  - ADC saturation results in poor spectral efficiency
- Approach: Use the degrees of freedom to mitigate interference and improve communication performance

Contribution I: Point-to-Point Systems

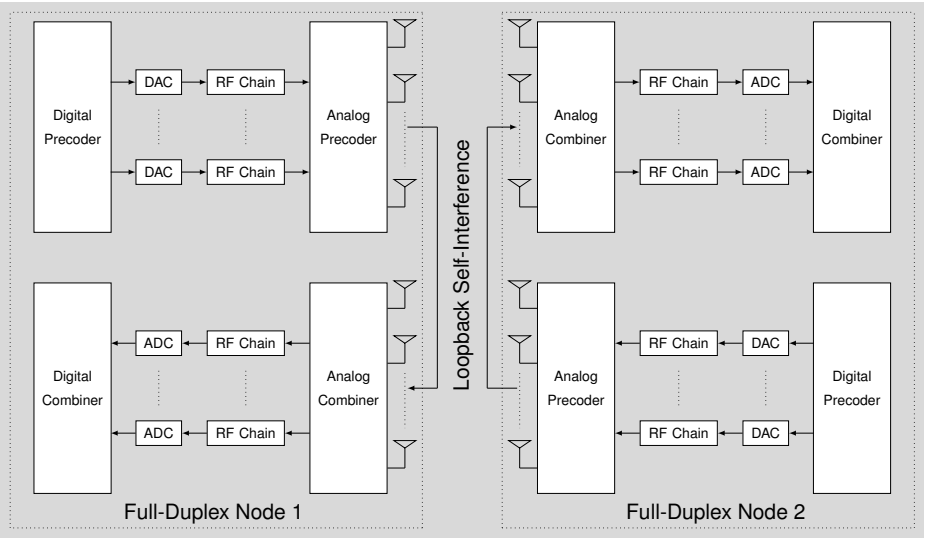


Figure 1: Hybrid analog/digital architecture of a point-to-point two-node FD system.

- Bi-directional communications to double spectral efficiency
- Decompose hybrid beamformers into analog and digital
- SI incurred by LOS and NLOS external reflections
- SI fading captured by Rician channel
- SI channel model dependent on operating frequency

Hybrid Beamforming

- The optimization problem has the following generic form:

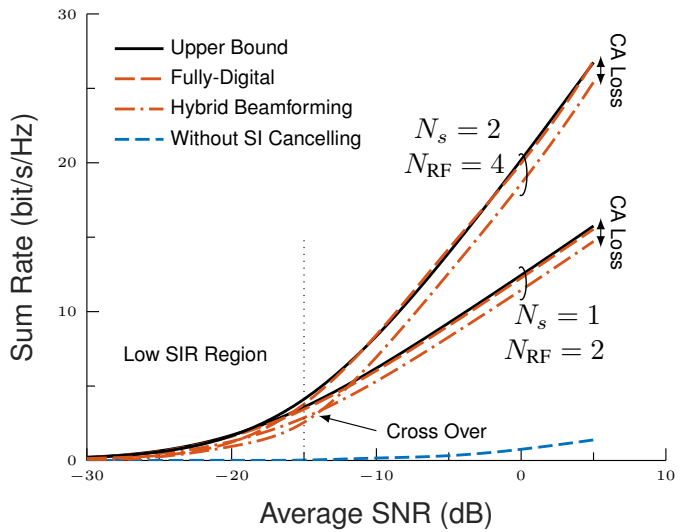
$$\begin{aligned} \mathscr{P}_1 : \max_{X_{BB}, X_{RF}} \quad & \log\det\left(I_N + \rho X_{BB}^* X_{RF}^* A A^* X_{RF} X_{BB}\right) \\ \text{s.t. } & X_{BB}^* X_{RF}^* X_{RF} X_{BB} = I_N \\ & X_{RF}^* C = 0 \text{ (SI null space)}, \\ & X_{RF} \in \mathbb{V}^{M \times L} \text{ (Constant amplitude space)} \end{aligned} \tag{1}$$

- $P_\perp \leftarrow I - CC^*$, compute $P_\perp A$,
  $X_{RF} \leftarrow N$ Dominant left singular vectors of $P_\perp A$
- Alternating projections: matched filtering -> SI null space -> Constant Amplitude space
- Baseband beamforming design: matched filtering

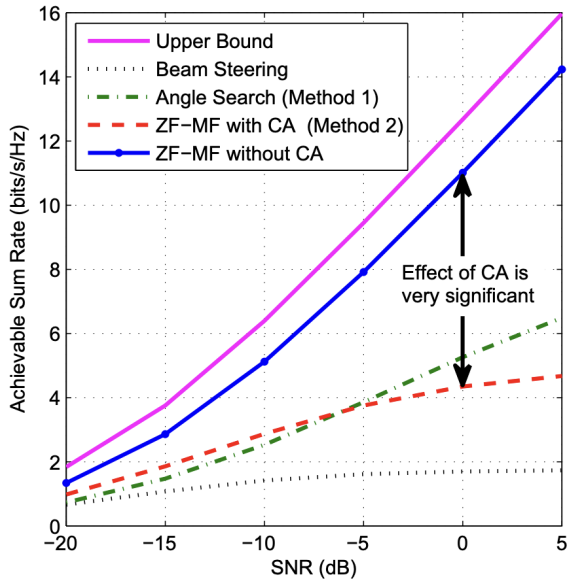
Elyes Balti, Salam Akoum, Iyad Alfalujah, and Brian L Evans. Hybrid Beamforming Design for Wideband mmWave Full-Duplex Systems. In: *IEEE JSAC Special Issue on Full Duplex and its Applications* (2023), submitted.

Elyes Balti and Neji Mensi. Zero-Forcing Max-Power Beamforming for Hybrid mmWave Full-Duplex MIMO Systems. In: *Int. Conf. Adv. Sys. and Emergent Technologies*. 2020, pp. 344–349.

Numerical Results



(a)



(b)

Figure 2: Narrowband results: (a) Proposed joint hybrid beamforming [1] and (b) loss due to CA constraint in [2].

- Proposed joint hybrid beamforming design satisfies SI null space constraint while minimizing loss incurred by CA
- Proposed (practical) very close to full-digital (impractical)
- Fewer RF chains to attain same spectral spectral efficiency

Balti and Mensi 2020.

Zhenyu Xiao, Pengfei Xia, and Xiang-Gen Xia. Full-Duplex Millimeter-Wave Communication. In: *IEEE Wireless Communications* 24.6 (2017), pp. 136–143.

Conclusion

- **Problem**: Communication performance limited by loopback self-interference
- **Approach**: Use degrees of freedom to design hybrid analog-digital beamformers to cancel self-interference
- **Proposed**: Joint analog-digital beamforming design for narrowband and wideband cases
  - Minimize loss incurred by CA constraint
  - Without violating SI null space constraint
- **Takeaways**: Our proposed solution achieves at 0 dB SNR
  - 2x spectral efficiency vs. decoupling the constraints
  - 90% of impractical all-digital beamformer benchmark
- **Future**: Extend proposed full-duplex hybrid beamforming algorithm to support joint communication and sensing

Contribution II: Single-User MIMO Systems

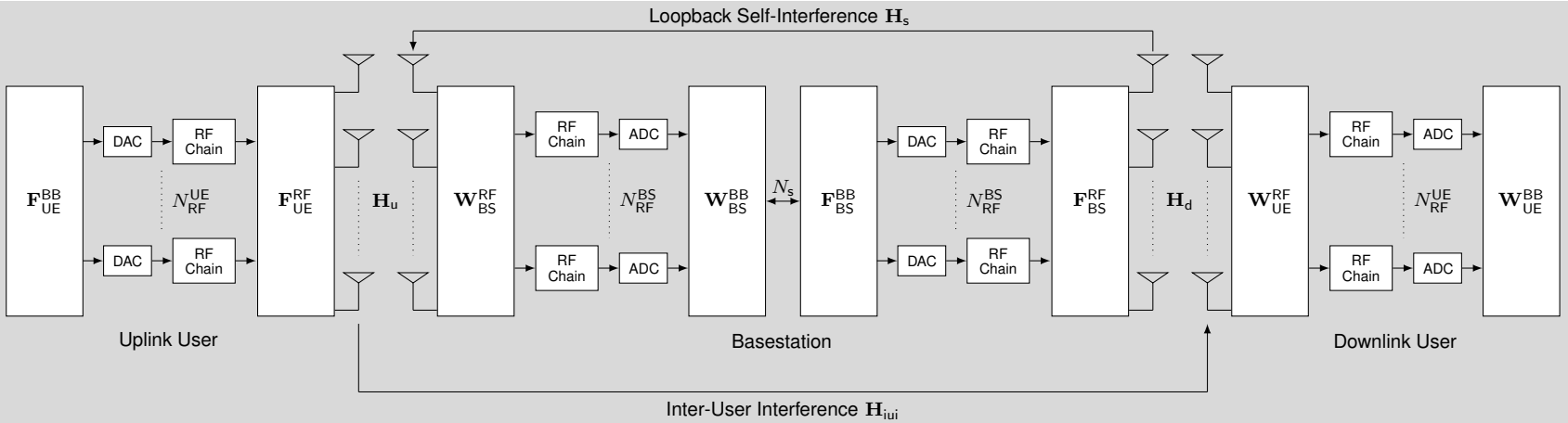


Figure 3: Hybrid analog/digital beamforming architecture of a single-user MIMO system.

- FD base station (BS) simultaneously communicates with uplink and downlink users in the same resource block
- Decompose hybrid beamformers into analog & baseband
- Uplink user is corrupted by loopback SI
- Downlink user has inter-user interference from uplink user

Elyes Balti, Salam Akoum, Iyad Alfallujah, and Brian L. Evans. Hybrid Beamforming and Interference Cancellation in mmWave Full-Duplex Single-User MIMO Systems. In: *in preparation*. 2023.

Elyes Balti, Chris Dick, and Brian L. Evans. Low Complexity Hybrid Beamforming for mmWave Full-Duplex Integrated Access and Backhaul. In: *IEEE Global Comm. Conf.* 2022, pp. 1606–1611.

Convergence

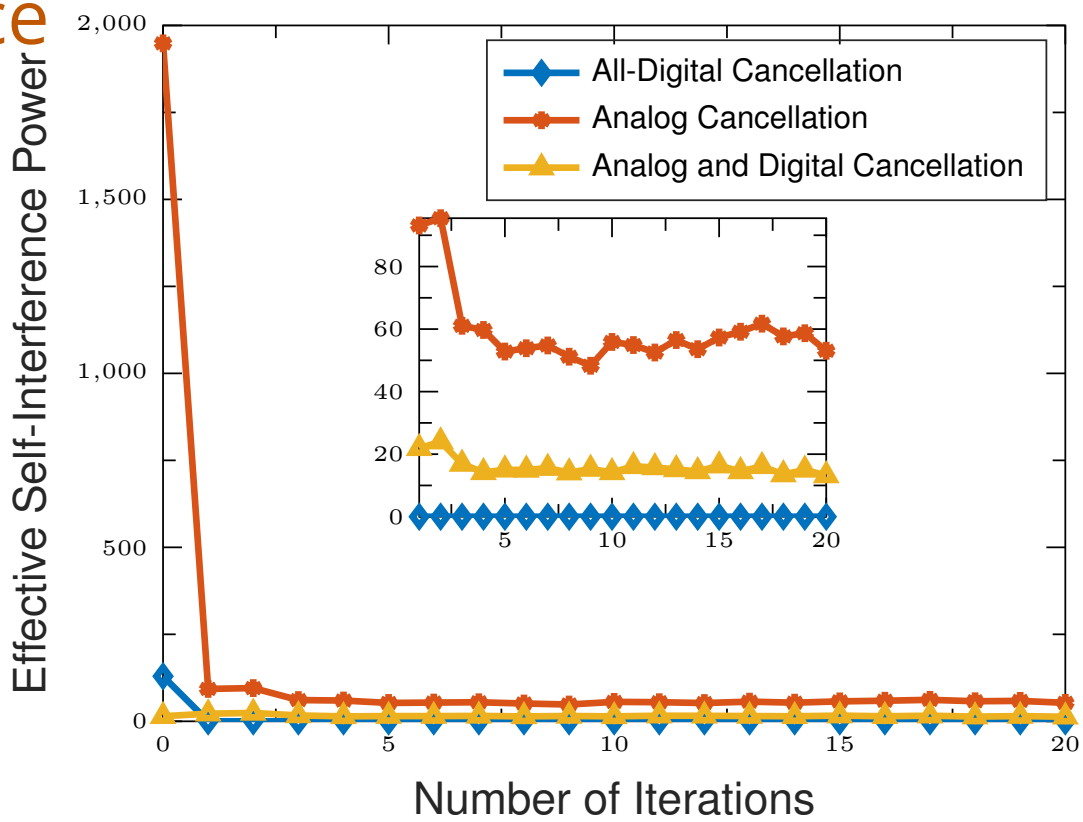


Figure 4: Convergence of objective function (effective SI power) with **SNR 5 dB**, SI power **15 dB**, IUI power **5 dB**.

- Algorithm converges in a few iterations
- SI power reduced 40x from 2000 to 53 in analog BF to prevent ADC saturation and 4x from 53 to 13 in digital BF

Conclusion and Future Directions

- **Problem**: Self- and inter-user interference saturate ADCs
- **Approach**: Use degrees of freedom to cancel interference and maintain high multiplexing gain
- **Proposed**: Joint analog-digital beamforming design
  - Reduce interference in analog to avoid ADC saturation
  - Allocate degrees of freedom between interference cancellation and spatial multiplexing gain
- **Takeaways**: Proposed joint analog-digital beamforming
  - 40x reduction in interference in analog domain
  - 4x rejection of residual interference in digital domain
  - Converges in 3-5 iterations
  - Low comp. complexity (number BS antennas cubed)
- **Future**: Design hybrid analog/digital beamformers for *multiuser* full-duplex integrated access and backhaul for wideband MIMO-OFDM systems

Contribution III: Massive MIMO Cellular Networks

Numerical Results

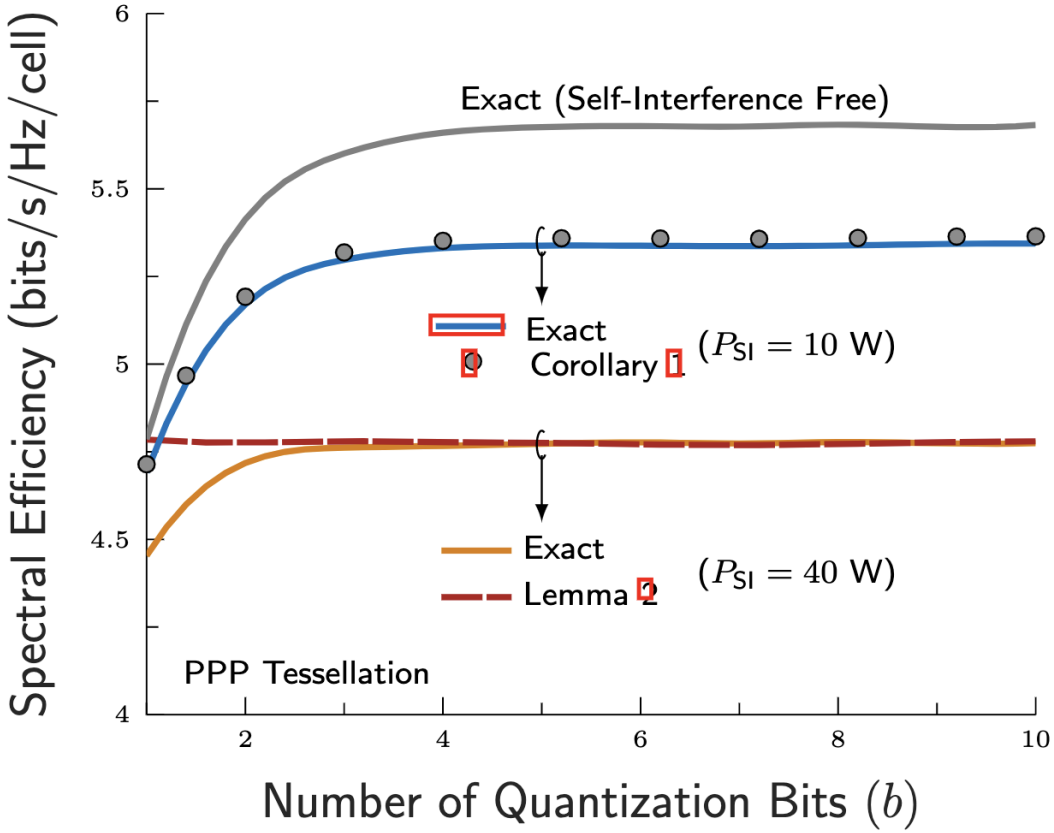


Figure 5: Spectral efficiency vs. number of quantization bits for large-scale distribution $\overline{\mathbf{sqinr}}^{\mathbf{MF}}$ in the reverse link for a Poisson Point Process (PPP) network with **1000** BS antennas.

- SI power degrades the performance
- 4 quantization bits achieves the full-resolution results

Conclusion and Future Directions

- **Problem**: FD systems for practical cellular scenarios
- **Proposed**: Unify analytical framework for communication performance in sub-6 GHz and mmWave bands
  - Hardware impairments such as quantization noise
  - Pilot contamination
  - Self-, inter-user, and inter-cell interference
  - Power scaling laws, asymptotic analysis, special cases
- **Takeaways**:
  - Reverse link: 4 bits achieve full-resolution results
  - Forward link: Using more antennas can eliminate interference, pilot contamination, noise
- **Future**: Model antenna correlation and user scheduling

Elyes Balti and Brian L. Evans. A Unified Framework for Full-Duplex Massive MIMO Cellular Networks With Low Resolution Data Converters. In: *IEEE Open J. Communications Society* 4 (2023), pp. 1–28.

Current Research

- **In-depth survey** on full-duplex communication systems (*in preparation*)
  - Self-interference channel models
  - Self-interference cancellation techniques
  - Hardware impairments
  - Applications
- **Magazine article** on full-duplex joint communication and sensing in mmWave bands (*in preparation*)
- **Journal paper** on designing low-complexity hybrid analog/digital beamformers to support multiuser wideband mmWave integrated access and backhaul (*in preparation*)

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