Joint Transmit and Receive Beamforming Design in Full-Duplex Integrated Sensing and Communications

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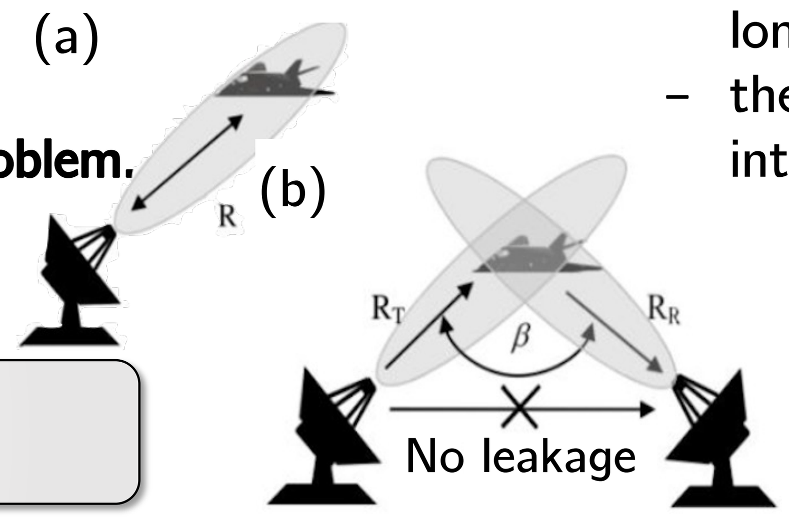
Background

- Mono-static:
  - Relative simplicity due to the known transmit (dual-function) waveform at the receiver.
  - Suffering from leakage (self interference).
  - **Most ISAC studies underestimate this leakage problem.**
- Bistatic:
  - Overhead cost associated with reference sharing.



Full-duplex Setup

- Physical separation of TX and RX antennas may not entirely solve the echo-miss problem (SI can be 100dB larger than thermal noise).
- To achieve ISAC, the transceiver should work in the full-duplex (FD) mode.

Challenge: Echo-miss

- **Echo-miss**: For a mono-static ISAC transceiver,
  - signal transmission durations (3GPP 38.211) are typically much longer than the radar echo round-trip times,
  - the radar returns are drowned by the strong residual self interference (SI) from the transmitter.

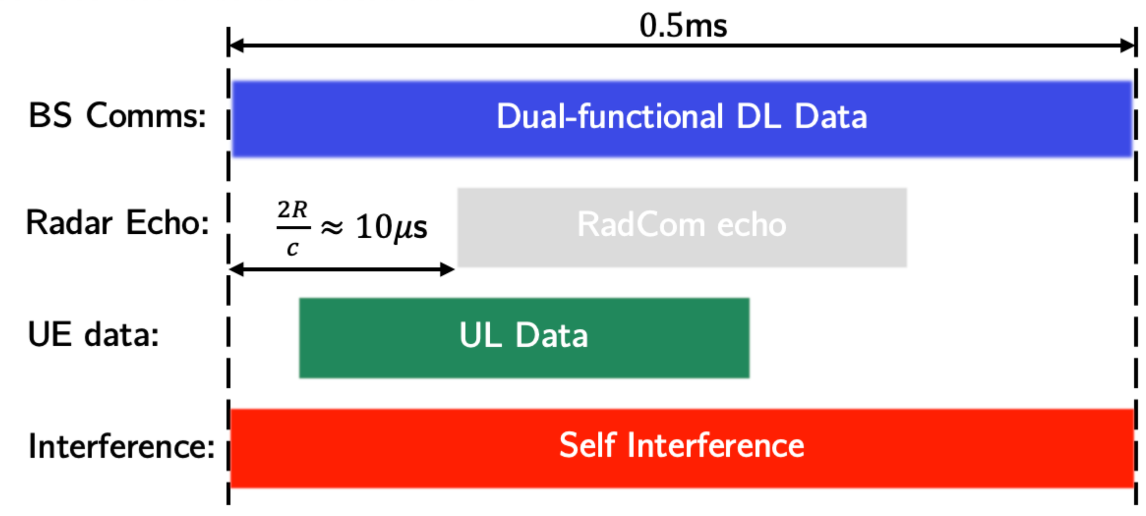
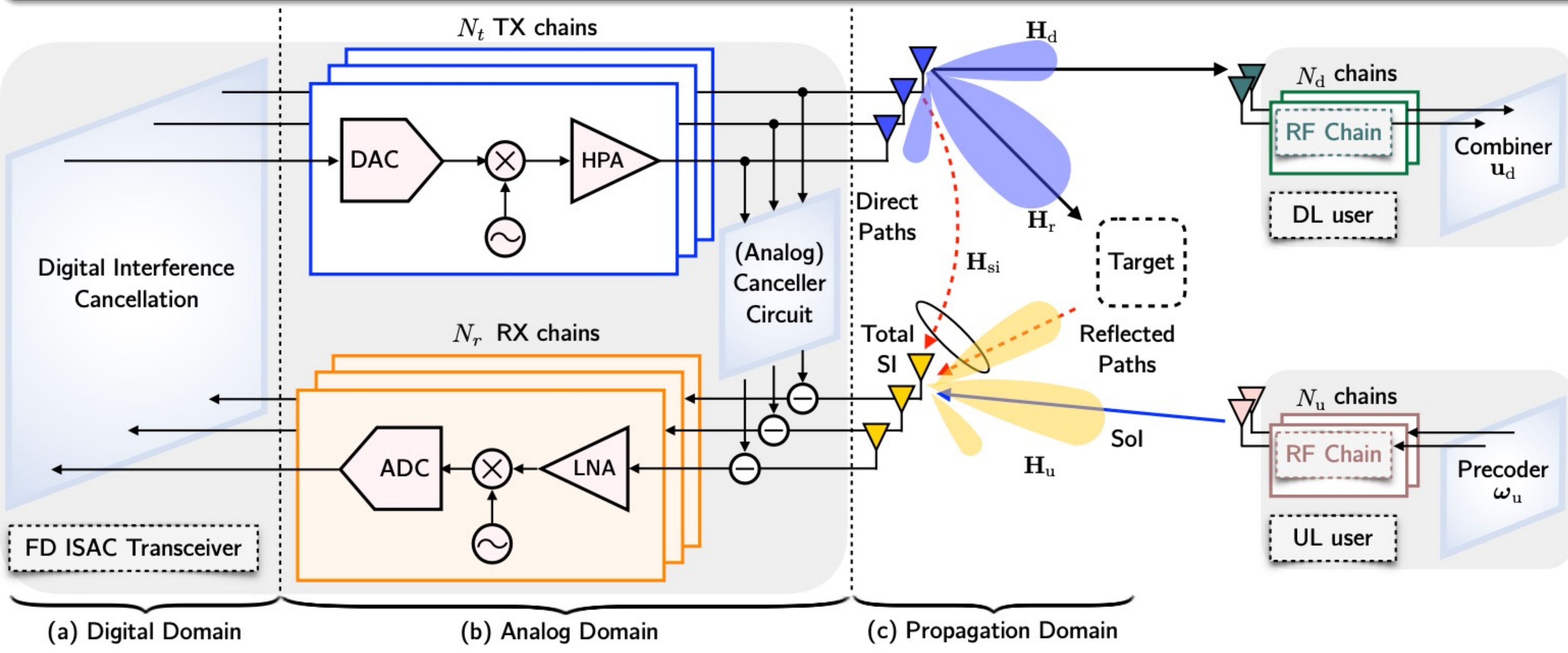


Fig: frames in a typical ISAC system.

Previous Approaches for SI Cancellation



- Taxonomy of SI cancellation techniques:
  - Propagation domain
  - Analog domain
  - Digital domain (e.g., modulo ADC [1], [2])

Difficulty in FD ISAC

- Radar echoes are correlated with the SI
- Previous approaches may distort SoI

$$\max_{\mathbf{p},\mathbf{w},\boldsymbol{\omega}_u,\mathbf{u}_d} \alpha_1 R_u + \alpha_2 R_d + \alpha_3 G_t + \alpha_4 G_r$$
$$\text{s.t.} \quad \|\mathbf{p}\|_2^2 \le P_d, \quad \|\mathbf{w}\|_2^2 = 1, \quad \|\boldsymbol{\omega}_u\|_2^2 \le P_u, \quad \mathbf{w}^H \mathbf{H}_{si}\mathbf{p} = 0.$$

- $R_u = \log_2(1+\gamma_u)$
- $R_d = \log_2(1+\gamma_d)$
- $\gamma_u = \frac{|\mathbf{w}^H \mathbf{H}_u \boldsymbol{\omega}_u|^2}{|\mathbf{w}^H \mathbf{H}\mathbf{p}|^2 + \|\mathbf{w}\|^2\sigma_u^2}$
- $\gamma_d = \frac{|\mathbf{u}_d^H \mathbf{H}_d \mathbf{p}|^2}{\|\mathbf{u}_d\|^2\sigma_d^2}$
- $G_r = |\mathbf{w}^H \mathbf{a}(\theta_r)|^2$
- $G_t = |\mathbf{b}^H(\theta_r)\mathbf{p}|^2$
- P_u, P_d: combiner at the downlink user

Our Approach: Joint ISAC TX-RX Design

- We aim to design
  - $\mathbf{p}, \mathbf{w}$: the transmit and receive beamformer at the transceiver,
  - $\boldsymbol{\omega}_u$: precoder at the uplink user,
  - $\mathbf{u}_d$: combiner at the downlink user

to simultaneously maximize
  - R_u, R_d: the uplink and downlink rate,
  - G_t, G_r: the transmit and receive radar beampattern power at the target,

suppress the residual SI.

Transformation and Penalty-based BCD Update

- Coupling Constraint Transformation by Penalty Term

  Constraint $\mathbf{w}^H \mathbf{H}_{si}\mathbf{p} = 0$ ➡ A penalty term $-\frac{1}{2\beta}\left\|\mathbf{w}^H \mathbf{H}_{si}\mathbf{p}\right\|_2^2$ in the objective function

- Communication Rate Transformation by (weighted minimize mean square error) WMMSE

  R_u ➡ $\log_2 \rho_u - \rho_u \mathrm{E}_{BS}$ R_d ➡ $\log_2 \rho_d - \rho_d \mathrm{E}_d$

  – ρ_u, ρ_d :auxiliary variables – $\mathrm{E}_{BS}, \mathrm{E}_d$: MSE matrices

- Beampattern Power Transformation to make it concave in the objective function

$$\max_{\substack{\{\mathbf{p},\mathbf{w}\},\{\boldsymbol{\omega}_u,\mathbf{u}_d\}\\ \{\rho_u,\rho_d\}}} \alpha_1\left(\log_2\rho_u - \rho_u \mathrm{E}_{BS}\right) + \alpha_2\left(\log_2\rho_d - \rho_d \mathrm{E}_d\right) + \alpha_3 \mathbf{p}^H Z_t(\theta_t)\mathbf{p} + \alpha_4 \mathbf{w}^H Z_r(\theta_r)\mathbf{w} - \frac{1}{2\beta}\left\|\mathbf{w}^H \mathbf{H}_{si}\mathbf{p}\right\|_2^2$$
$$\text{s.t.} \quad \|\mathbf{p}\|_2^2 \le P_d, \|\boldsymbol{\omega}_u\|_2^2 \le P_u, \|\mathbf{w}\|_2^2 = 1.$$

Algorithm 1: Proposed Penalty-based Joint Transmit and Receive Beamformer Design

Input: $\mathbf{H}_d, \mathbf{H}_u, \mathbf{H}_r, \mathbf{H}_{si}, P_d, P_u$.
Output: $\rho_u^*, \rho_d^*, \mathbf{p}^*, \mathbf{w}^*, \boldsymbol{\omega}_u^*, \mathbf{u}_d^*$.

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Initialize p, w, ω_u, u_d randomly, β = 10^{-25};
while no convergence of objective function do
    Update ρ_u^*. Complexity = O(N_r^2).
    Update ρ_d^*. Complexity = O(N_t N_d).
    Update ω_u^*. Complexity = O(I_1 N_r N_u).
    Update w^*. Complexity = O(N_r^3).
    Update u_d^*. Complexity = O(N_t N_d).
    Update p^*. Complexity = O(I_2 N_t^3).
end
Normalize w^*;
Return ρ_u^*, ρ_d^*, p^*, w^*, ω_u^*, u_d^*.
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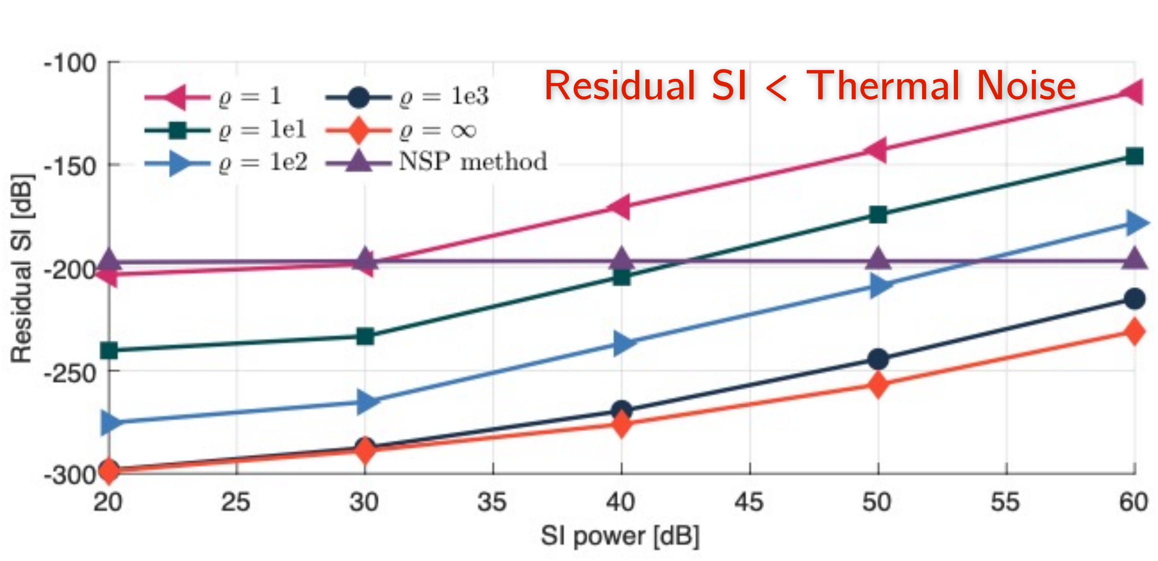
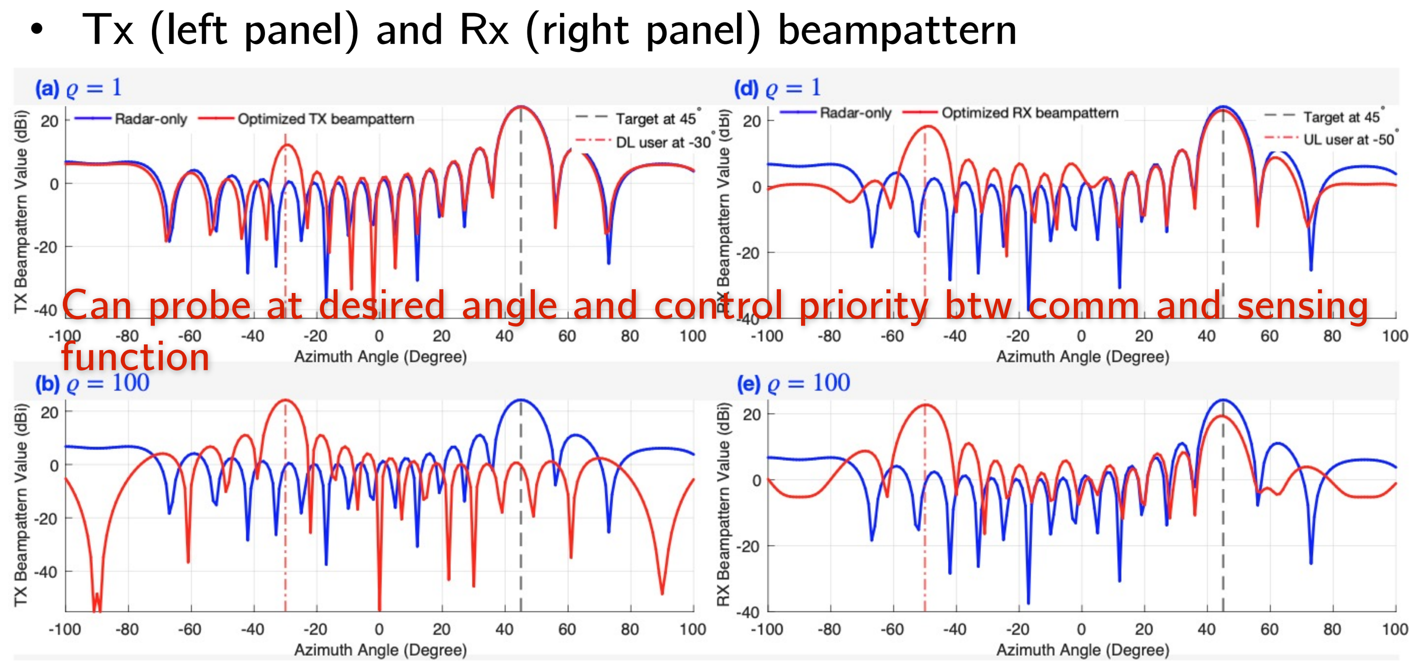
Numerical Evaluation

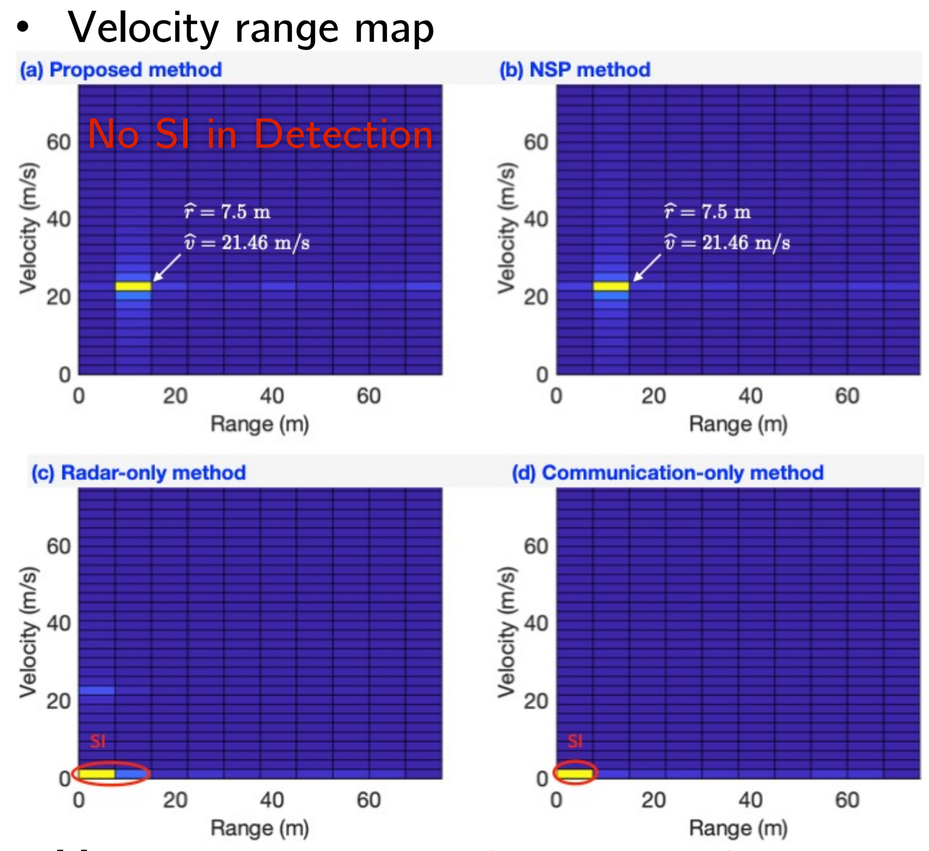
- SI cancellation performance



- Tx (left panel) and Rx (right panel) beampattern



- Velocity range map



Conclusion

- Our proposed joint TX-RX beamformer design method can effectively achieve up to 60 dB digital-domain SI cancellation, a higher average sum-rate, and more accurate radar parameter estimation compared with previous ISAC FD studies.

[1] Z. Liu, A. Bhandari, and B. Clerckx, "λ–MIMO: Massive MIMO via modulo sampling," accepted to *IEEE Trans. Commun.*
[2] A. Bhandari, F. Krahmer, and R. Raskar, "On unlimited sampling and reconstruction," *IEEE Trans. Sig. Proc.*, vol. 69, pp. 3827–3839, Dec. 2020.