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How to Split UL/DL Antennas in Full-Duplex Cellular Networks

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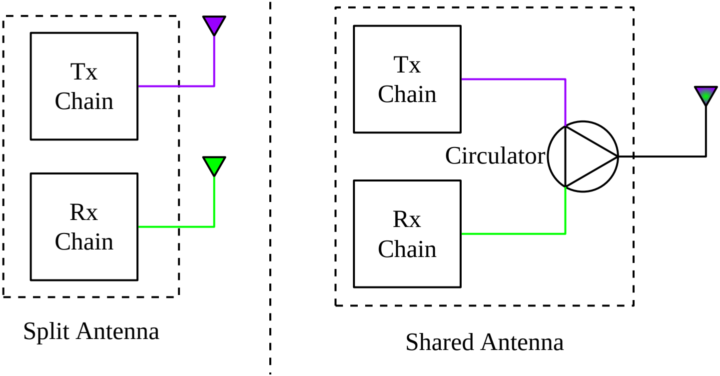
Architectures in full-duplex cellular networks



- Split architecture → current radios + select UL/DL antennas
- Shared architecture → circulator + bad with # of antennas

Why select UL/DL antennas?

- Severe self-interference (SI) → reduce # DL antennas
- Severe UE-to-UE interference → reduce # UL antennas

Outline

1. Introduction
2. System Model & Problem Formulation
3. Solution Approach: Parallel Successive Convex Approximation
4. Numerical Results
5. Conclusion

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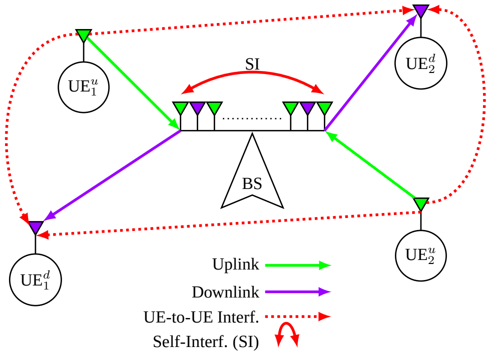
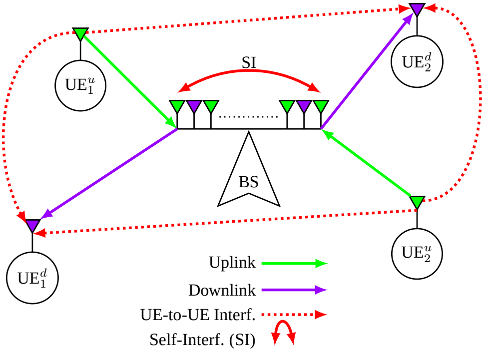
FD characteristics in cellular networks



Benefits

- Spectral efficiency: $\sim 2\times$
- Medium access layer: mitigate hidden terminal, collision avoidance, low latency...

FD characteristics in cellular networks



Challenges

- Severe SI
- UE-to-UE interference
- Mitigate both interferences → user-frequency assignment, power allocation and antenna splitting

Research gap in FD cellular networks

Understand impact of split antennas

- How to split the antennas?
  - Everett2016 → fixed splitting based on array geometry
  - Gowda2018 → split to minimize gap between demand and achievable rates

Lack of efficient splitting algorithms

- Initial assumption on the # split antennas
  - If SI high → reduce # DL antennas
  - If UE-to-UE interference high → reduce # UL antennas
  - If UL/DL asymmetry → increase # antennas with higher demand

[Everett2016] E. Everett et al., "SoftNull: Many-Antenna Full-Duplex Wireless via Digital Beamforming," IEEE TWC, Dec. 2016.
[Gowda2018] N. M. Gowda et al., "JointNull: Combining Partial Analog Cancellation With Transmit Beamforming for Large-Antenna Full-Duplex Wireless Systems," IEEE TWC, Mar. 2018.

Contributions

- Antenna splitting with UE-to-UE interference + distortions
  - Sum MSE minimization → maximize sum spectral efficiency
- Combinatorial problem for UL/DL antenna splitting
  - Equivalent problem reformulation → quadratic and biquadratic terms + first-order Taylor approximation
- NP-hard binary quadratic problem
  - Binary relaxation to hypercube $[0,1]^{M\times 1}$ → solve with Parallel Successive Convex Approximation (PSCA)
- Show spectral efficiency gains over simple splitting
  - Realistic system simulations → Yes, 23% with high SI cancellation!
  - How and when to split → Yes, $\#$ antennas is the key!

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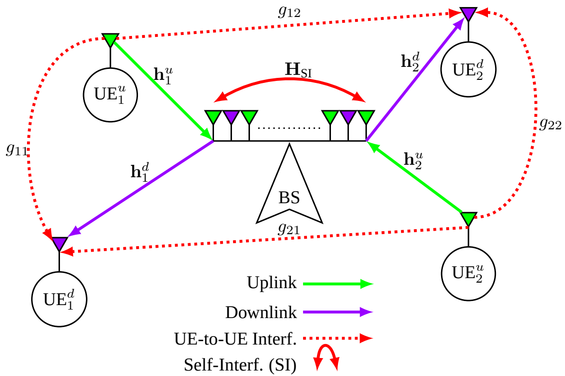
Definitions (1/2)



- Single-cell cellular system → only BS is FD-capable
- # M/1 antennas at BS/UE; # UL users → I; # DL users → J
- Channel for flat fading → $\mathbf{h}_i^u$, $\mathbf{h}_j^d$, g_{ij}
- SI cancellation matrix → $\mathbf{H}_{\mathsf{SI}} \in \mathbb{C}^{M\times M}$
- Tx and Rx distortion signals are present → c_j^u, $\mathbf{c}_i^d$, $\mathbf{e}_i^u$, e_j^d

Definitions (2/2)

- Tx beamforming and UL power → fixed $\mathbf{w}_j^d,\ q_i^u$
- UL and DL antenna assignment vector → $\mathbf{x}^u,\ \mathbf{x}^d \in \{0,1\}^{M\times 1}$

$$x_k^{u(d)} = \begin{cases} 1, & \text{if antenna } k \text{ is Rx (Tx) in the UL (DL)},\\ 0, & \text{otherwise.}\end{cases}$$

- UL and DL received signals

$$\mathbf{y}^u = \sum_{i=1}^{I} \mathbf{h}_i^u \left(\sqrt{q_i^u} s_i^u + c_i^u\right) + \mathbf{H}_{\mathsf{SI}} \left(\sum_{j=1}^{J} \mathbf{w}_j^d s_j^d + \mathbf{c}^d\right) + \boldsymbol{\eta}^u + \mathbf{e}^u,$$

$$y_j^d = \mathbf{h}_j^{d^{\mathrm{H}}} \left(\sum_{m=1}^{J} \mathbf{w}_m^d s_m^d + \mathbf{c}^d\right) + \sum_{i=1}^{I} g_{ij} \left(\sqrt{q_i^u} s_i^u + c_i^u\right) + \eta_j^d + e_j^d,$$

- Effective channels and received signals

$$\widetilde{\mathbf{h}}_i^u = \mathbf{X}^u \mathbf{h}_i^u, \quad \widetilde{\mathbf{h}}_j^d = \mathbf{X}^d \mathbf{h}_j^d, \quad \widetilde{\mathbf{H}}_{\mathsf{SI}} = \mathbf{X}^u \mathbf{H}_{\mathsf{SI}} \mathbf{X}^d, \quad \widetilde{\boldsymbol{\eta}}^u = \mathbf{X}^u \boldsymbol{\eta}^u,$$

$$\widetilde{\mathbf{e}}^u = \mathbf{X}^u \mathbf{e}^u, \quad \underbrace{\mathbf{X}^d \left(\sum_{m=1}^{J} \mathbf{w}_m^d s_m^d + \mathbf{c}^d\right)}_{\text{DL Tx signal}}, \widetilde{\mathbf{y}}^u = \mathbf{X}^u \mathbf{y}^u.$$

Problem formulation

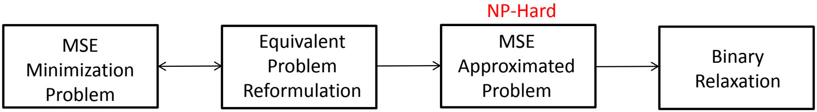
- MSE for UL and DL users with optimal MSE receivers $\mathbf{r}_i^u$, r_j^d

$$E_i^u = \left|\sqrt{q_i^u}\mathbf{r}_i^{u^{\mathrm{H}}}\widetilde{\mathbf{h}}_i^u - 1\right|^2 + \mathbf{r}_i^{u^{\mathrm{H}}}\mathbf{\Psi}_i^u\mathbf{r}_i^u,$$
$$E_j^d = \left|r_j^{d^{\mathrm{H}}}\widetilde{\mathbf{h}_j^{d^H}}\mathbf{w}_j^d - 1\right|^2 + \left|r_j^d\right|^2 \Psi_j^d.$$

- MSE minimization with UL/DL antenna assignment

$$\begin{array}{lll} \underset{\mathbf{x}^u,\mathbf{x}^d}{\text{minimize}} & \sum_{i=1}^{I} E_i^u + \sum_{j=1}^{J} E_j^d & (\text{Objective}) \\ \text{subject to} & \mathbf{x}^u + \mathbf{x}^d = \mathbf{1}, & (\text{UL/DL orthogonality}) \\ & \mathbf{x}^u, \mathbf{x}^d \in \{0,1\}^{M\times 1}. & (\text{Binary association}) \end{array}$$

General solution approach


NP-Hard

MSE Minimization Problem

Equivalent Problem Reformulation

MSE Approximated Problem

Binary Relaxation

- Equivalent problem reformulation
  - Sum MSE as two quadratic and one biquadratic terms of $\mathbf{X}^u, \mathbf{X}^d$
  - One quadratic and one quartic in terms of $\mathbf{x}^u$
- Quartic term $\rightarrow$ complicated
  - First-order Taylor approximation $\rightarrow$ quartic becomes linear in $\mathbf{x}^u$
- NP-Hard binary quadratic problem
  - Relaxation into unit hypercube $[0,1]^{M\times 1}$
  - Successive convex approximation

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Problem reformulation

MSE minimization

$$\underset{\mathbf{x}^u,\mathbf{x}^d}{\text{minimize}} \quad \sum_{i=1}^{I} E_i^u + \sum_{j=1}^{J} E_j^d$$
$$\text{s. t.} \quad \mathbf{x}^u + \mathbf{x}^d = \mathbf{1},$$
$$\mathbf{x}^u, \mathbf{x}^d \in \{0,1\}^{M\times 1}.$$

$$\longleftrightarrow$$

Equivalent problem

$$\underset{\mathbf{x}^u,\mathbf{x}^d}{\text{minimize}} \quad f^u(\mathbf{x}^u) + \color{red}{f^{u,d}(\mathbf{x}^u,\mathbf{x}^d)} + f^d(\mathbf{x}^d)$$
$$\text{s. t.} \quad \mathbf{x}^u + \mathbf{x}^d = \mathbf{1},$$
$$\mathbf{x}^u, \mathbf{x}^d \in \{0,1\}^{M\times 1}.$$

- Biquadratic $f^{u,d}(\mathbf{x}^u,\mathbf{x}^d)$ → quartic $f^{u,d}(\mathbf{x}^u)$
- First-order approximation of $f^{u,d}(\widetilde{\mathbf{X}}^u)$

$$g^u(\mathbf{x}^u) = f^{u,d}(\widetilde{\mathbf{x}}^u) + \text{Diag}\left(\nabla f^{u,d}(\widetilde{\mathbf{X}}^u)\right)^{\mathrm{T}} \mathbf{x}^u.$$

Binary quadratic problem→NP-Hard

$$\underset{\mathbf{x}^u}{\text{minimize}} \quad {\mathbf{x}^u}^T \mathbf{\Lambda} \mathbf{x}^u - 2\mathbf{b}^T \mathbf{x}^u$$
$$\text{subject to} \quad \mathbf{x}^u \in \{0,1\}^{M\times 1}.$$

Iterative solution approach

- Relaxation into unit hypercube → $\mathbf{x}^u \in [0,1]^{M\times 1}$
- Iterative convex approximation required → Taylor approx. for neighbourhood of $\mathbf{x}^u$
- PSCA includes proximal operator $\frac{\alpha}{2}\left\|\mathbf{x}^u - \mathbf{x}^{u(n)}\right\|_2^2$ → minimize objective and stay close to previous iteration

Relaxed MSE minimization problem (RLX-PROX)

$$\begin{aligned} \underset{\mathbf{x}^u}{\text{minimize}} \quad & {\mathbf{x}^u}^T \mathbf{\Lambda} \mathbf{x}^u - \mathbf{b}^T \mathbf{x}^u + \frac{\alpha}{2}\left\|\mathbf{x}^u - \mathbf{x}^{u(n)}\right\|_2^2 \\ \text{subject to} \quad & \mathbf{x}^u \in [0,1]^M. \end{aligned}$$

- Centralized solution with low computational complexity

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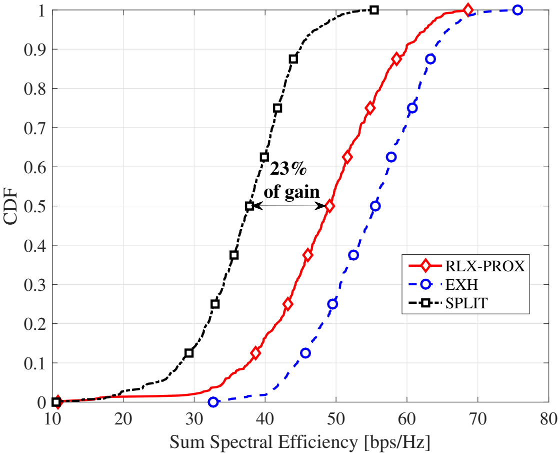
Simulation Parameters

- Small cell with $I = J = 4$ and $M = 8, \dots, 128$
- SI cancellation $\beta = [-50, \dots, -100]$dB
- BS/UL user maximum power → 30/23 dBm
- Proposed algorithm
  - RLX-PROX: Relaxed solution to MSE minimization problem

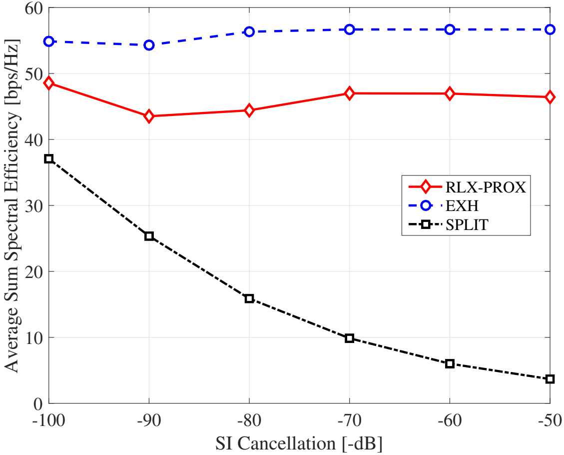
  compared to
  - EXH: exhaustive search
  - SPLIT: equal splitting between UL and DL antennas
- 600 Monte Carlo iterations

Optimality gap - $M = 8$, SI$= -100$ dB



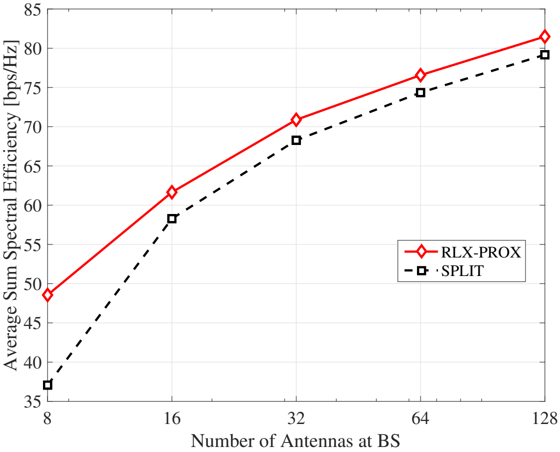
- UL/DL antenna splitting → substantial gains of 23% to 32%
- RLX-PROX close to optimal solution → 9% difference

Average sum spectral efficiency × SI cancellation



- Naive splitting → performance decreases quickly with SI
- UL/DL antenna splitting
  - Maintains performance across SI
  - Crucial for low SI cancellation

Average sum spectral efficiency × # antennas



- RLX-PROX and naive splitting → gap decreases with # antennas
- Role of antenna splitting small for large # antennas

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Some takeaways

Conclusions

- Combinatorial problem to split UL/DL antennas
    - MSE minimization → sum spectral efficiency maximization
    - NP-hard problem → solved with successive convex approximation
- Gains with UL/DL antenna splitting
    - Gains for spectral efficiency
    - Reduced role for large number of antennas
- Low and high SI cancellation → maintains spectral efficiency

Future works

- Impact of DL/UL beamforming in the splitting → joint beamforming and antenna splitting

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