Distributed Spectral Efficiency Maximization in Full-Duplex Cellular Networks

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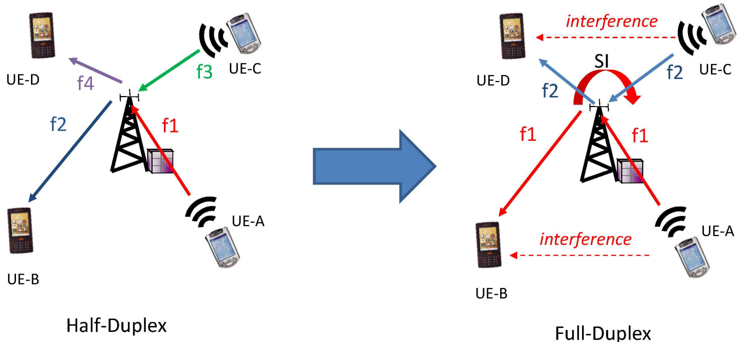
Why full-duplex at the base station?



- Half-Duplex (HD) systems $\rightarrow$ Inefficient resource utilization
- Full-Duplex (FD) systems $\rightarrow \sim 2\times$ spectral efficiency

Outline

1. Introduction
2. System Model for Spectral Efficiency Maximization
3. Centralized Solution Based on Lagrangian Duality
4. Distributed Solution Based on Auction Theory
5. Numerical Results
6. Conclusions

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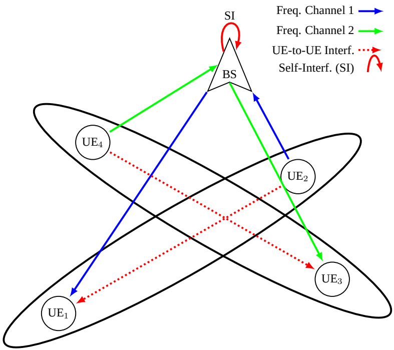
FD Characteristics in cellular networks



Benefits

- Spectral efficiency: $\sim 2\times$
- MAC layer: hidden terminal, collision avoidance, reduced end-to-end delay...

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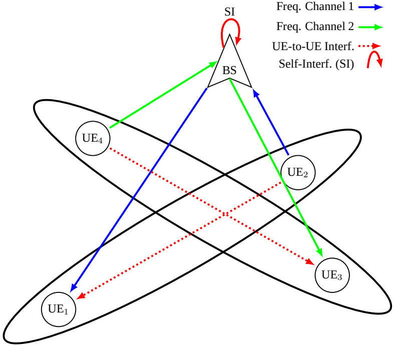

Challenges

- Severe self-interference (SI)
- UE-to-UE interference
- User to frequency channels pairing and power allocation

Research Gap in FD cellular networks

Need of distributed schemes

- Processing burden at the BS is high*
  - Dense deployment of user
  - New SI cancellation mechanisms
  - Radio Resource Management

Lack of fair and efficient PHY procedures

- How to mitigate UE-to-UE interference and assess fairness?
  - Pairing → UL and DL users to share the frequency resource
  - Power allocation → mitigate interference
  - Fairness → weighted sum spectral efficiency maximization

*A. Osseiran et al., "Scenarios for 5G mobile and wireless communications: the vision of the METIS project," IEEE Communications Magazine, vol. 52, no. 5, pp. 26-35, May 2014.

Contributions

- Study sum spectral efficiency maximization and fairness problem
  - Joint pairing and power allocation $\rightarrow$ maximize weighted sum spectral efficiency
- Solve this MINLP problem
- Provide distributed mechanisms for FD cellular networks
- Show spectral efficiency gains over HD with distributed schemes

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  - Lagrangian duality $\rightarrow$ optimal power allocation $+$ optimal centralized assignment
- Provide distributed mechanisms for FD cellular networks
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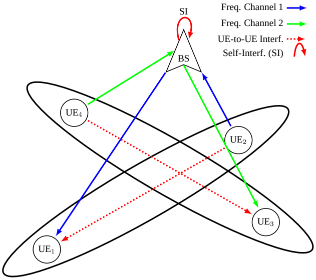
- Show spectral efficiency gains over HD with distributed schemes
  - Realistic system simulations $\rightarrow$ Yes, 89%!

Outline

Definitions (1)



- Single-cell cellular system + only BS is FD-capable
- UL users → I; DL users → J; Frequency channels → F
- Effective path gain values → G_{ib}, G_{bj}, G_{ij}
- SI cancellation coefficient → β
- Assignment matrix → $\mathbf{X} \in \{0,1\}^{I \times J}$

$$x_{ij} = \begin{cases} 1, & \text{if the UL UE}_i \text{ is paired with the DL UE}_j, \\ 0, & \text{otherwise.} \end{cases}$$

Definitions (2)

- Power vectors $\rightarrow \quad \mathbf{p^u} = [P_1^u \dots P_I^u], \quad \mathbf{p^d} = [P_1^d \dots P_J^d]$
- SINR at the BS and at DL user

$$\gamma_i^u = \frac{P_i^u G_{ib}}{\sigma^2 + \sum_{j=1}^{J} x_{ij} P_j^d \beta}, \ \gamma_j^d = \frac{P_j^d G_{bj}}{\sigma^2 + \sum_{i=1}^{I} x_{ij} P_i^u G_{ij}}.$$

- Achievable spectral efficiency

$$C_i^u = \log_2(1 + \gamma_i^u), \qquad C_j^d = \log_2(1 + \gamma_j^d).$$

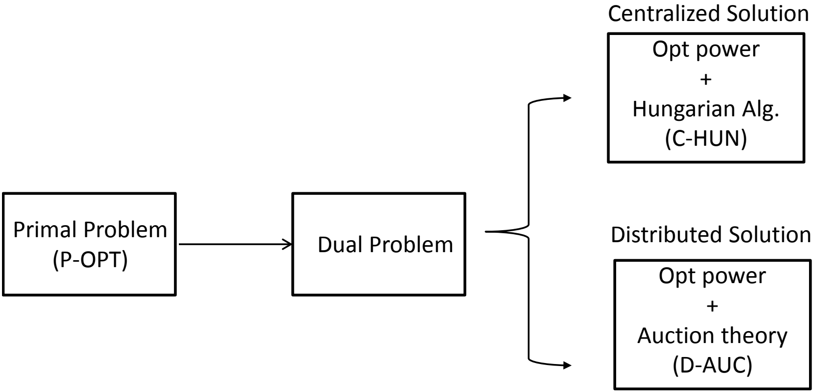
- Weights α_i^u, α_j^d
  - $\alpha_i^u = \alpha_j^d = 1, \forall i, j \rightarrow$ Sum spectral efficiency maximization
  - $\alpha_i^u = G_{ib}^{-1}, \quad \alpha_j^d = G_{bj}^{-1} \rightarrow$ Path loss compensation

Problem Formulation

- Weighted sum spectral efficiency maximization (P-OPT)

$$
\begin{aligned}
\underset{\mathbf{X},\mathbf{p}^u,\mathbf{p}^d}{\text{maximize}} \quad & \sum_{i=1}^{I} \alpha_i^u C_i^u + \sum_{j=1}^{J} \alpha_j^d C_j^d \\
\text{subject to} \quad & \gamma_i^u \geq \gamma_{\text{th}}^u, \ \forall i, \\
& \gamma_j^d \geq \gamma_{\text{th}}^d, \ \forall j, \\
& P_i^u \leq P_{\text{max}}^u, \ \forall i, \\
& P_j^d \leq P_{\text{max}}^d, \ \forall j, \\
& \sum_{i=1}^{I} x_{ij} \leq 1, \ \forall j, \\
& \sum_{j=1}^{J} x_{ij} \leq 1, \ \forall i, \\
& x_{ij} \in \{0, 1\}, \ \forall i, j.
\end{aligned}
$$

Problem solution approaches



Outline

Lagrangian function

- Formulate partial Lagrangian function

$$L(\boldsymbol{\lambda}^u, \boldsymbol{\lambda}^d, \mathbf{X}, \mathbf{p}^u, \mathbf{p}^d) \triangleq -\sum_{i=1}^{I} \alpha_i^u C_i^u - \sum_{j=1}^{J} \alpha_j^d C_j^d + \\ + \sum_{i=1}^{I} \lambda_i^u \left(\gamma_{\mathsf{th}}^u - \gamma_i^u\right) + \sum_{j=1}^{J} \lambda_j^d \left(\gamma_{\mathsf{th}}^d - \gamma_j^d\right)$$

- The dual function is

$$g(\boldsymbol{\lambda}^u, \boldsymbol{\lambda}^d) = \inf_{\mathbf{X} \in \mathcal{X}\ \mathbf{p}^u, \mathbf{p}^d \in \mathcal{P}} L(\boldsymbol{\lambda}^u, \boldsymbol{\lambda}^d, \mathbf{X}, \mathbf{p}^u, \mathbf{p}^d)$$

Dual problem and closed-form solution for assignment

- Rewrite the dual as

$$g(\boldsymbol{\lambda}^u, \boldsymbol{\lambda}^d) = \inf_{\mathbf{X}\in\mathcal{X}} \inf_{\mathbf{p}^u, \mathbf{p}^d \in \mathcal{P}} \sum_{n=1}^{N} \left(q^u_{i_n}(\mathbf{X}, \mathbf{p}^u, \mathbf{p}^d) + q^d_{j_n}(\mathbf{X}, \mathbf{p}^u, \mathbf{p}^d) \right),$$

with

$$q^u_{i_n}(\mathbf{X}, \mathbf{p}^u, \mathbf{p}^d) \triangleq \lambda^u_{i_n}\left(\gamma^u_{\mathsf{th}} - \gamma^u_{i_n}\right) - \alpha^u_i C^u_{i_n},$$

$$q^d_{j_n}(\mathbf{X}, \mathbf{p}^u, \mathbf{p}^d) \triangleq \lambda^d_{j_n}\left(\gamma^d_{\mathsf{th}} - \gamma^d_{j_n}\right) - \alpha^d_{j_n} C^d_{j_n}.$$

- Closed-form expression for the assignment

$$x^*_{ij} = \begin{cases} 1, & \text{if } (i,j) = \arg\max_{i,j} \left(q^{u,\max}_{i_n} + q^{d,\max}_{j_n} \right) \\ 0, & \text{otherwise} \end{cases}$$

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Dual problem and optimal power allocation

- Analyse the dual problem

$$\underset{\boldsymbol{\lambda}^u,\, \boldsymbol{\lambda}^u}{\text{maximize}} \quad g(\boldsymbol{\lambda}^u, \boldsymbol{\lambda}^d)$$

$$\text{subject to} \quad \lambda_i^u,\ \lambda_j^d, \geq 0, \forall i, j,$$

- Turn our attention to the power allocation problem

$$\underset{\mathbf{p}^u, \mathbf{p}^d}{\text{minimize}} \quad -\sum_{i=1}^{I} \alpha_i^u C_i^u - \sum_{j=1}^{J} \alpha_j^d C_j^d \qquad (1a)$$

$$\text{subject to} \quad \mathbf{p}^u, \mathbf{p}^d \in \mathcal{P}. \qquad (1b)$$

- Optimal solution for (1) available[*†]

[*] A. Gjendemsjø, D. Gesbert, G. E. Øien and S. G. Kiani, "Binary Power Control for Sum Rate Maximization over Multiple Interfering Links," IEEE TWC, vol. 7, no. 8, pp. 3164-3173, August 2008

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Outline

Problem Reformulation

- Reformulate closed-form assignment with optimal power allocation as

$$
\begin{aligned}
\underset{\mathbf{X}}{\text{maximize}} \quad & \sum_{i=1}^{I}\sum_{j=1}^{J} c_{ij}x_{ij} \\
\text{subject to} \quad & \sum_{i=1}^{I} x_{ij} = 1, \ \forall j, \\
& \sum_{j=1}^{J} x_{ij} = 1, \ \forall i, \\
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- Centralized solution $\rightarrow$ Hungarian Algorithm
- Distributed solution $\rightarrow$ Auction Theory

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Distributed Auction

- Input: c_{ij}, and tolerance ϵ

Bidding Phase

- UL bids for a DL user that maximizes $c_{ij} - \hat{p}_j$
- Wait for acknowledgement on assignment or update price

Assignment Phase

- BS is responsible for DL users
- BS selects the highest bid and update the prices $\hat{p}_j$
- Send updates and wait until the assignment matrix X is feasible

- Messages exchanged using control channels, e.g., PUCCH or PDCCH

Outline

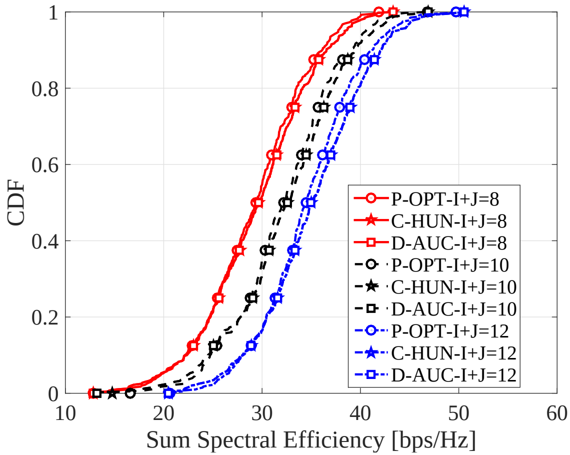
Simulation Parameters

- $F = I = J$ and $I + J = 8, \ldots, 50$
- Path-loss compensation $\rightarrow \alpha_i^u = G_{ib}^{-1}, \quad \alpha_j^d = G_{bj}^{-1}$
- SI cancellation $\beta = [-70, -100]$dB
- Proposed algorithm
  - D-AUC: Dual solution with distributed Auction

compared to

  - P-OPT: Primal optimal from brute-force solution
  - C-HUN: Centralized solution based on Duality and Hungarian algorithm
  - R-EPA: Random assignment + equal power allocation
  - HD: Traditional Half-Duplex scheme

Optimality Gap Comparison with $\beta = -100\text{dB}$



- Negligible difference between P-OPT, C-HUN and D-AUC
- Possible to use distributed solutions without losing too much

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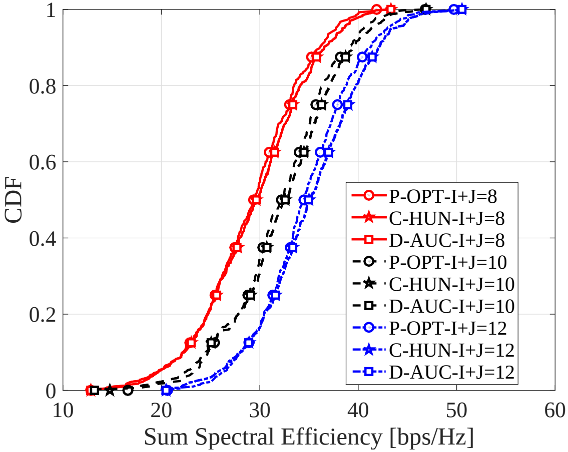

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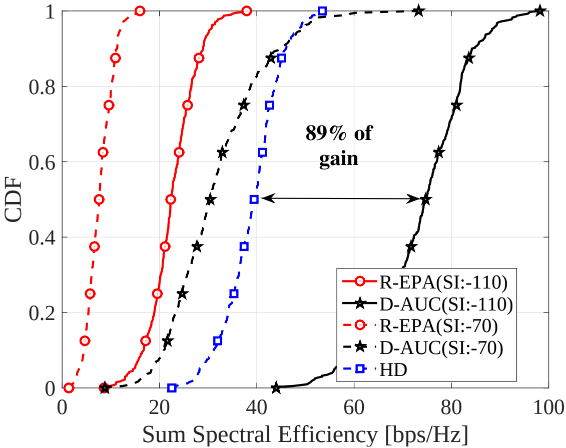
Sum Spectral Efficiency Comparison for different β



- $\beta = -110$dB $\rightarrow$ UE-to-UE interference is the limiting factor
- $\beta = -70$dB $\rightarrow$ residual SI is the limiting factor

Outline

Take home message

- Distributed algorithms to FD cellular networks
  - Perform close to centralized schemes
  - Fair and efficient
  - Almost double spectral efficiency ([illegible])

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  - UE-to-UE interference is the limiting factor for low β
  - Residual SI is the limiting factor for high β

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