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On the Spectral Efficiency and Fairness in Full-Duplex Cellular Networks

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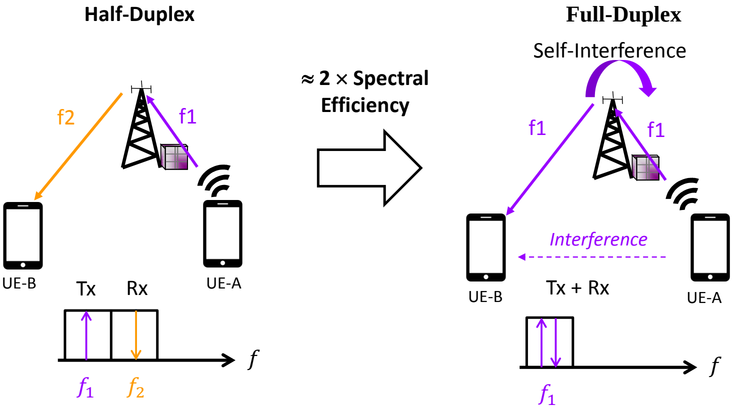
Why full-duplex in celllular networks?

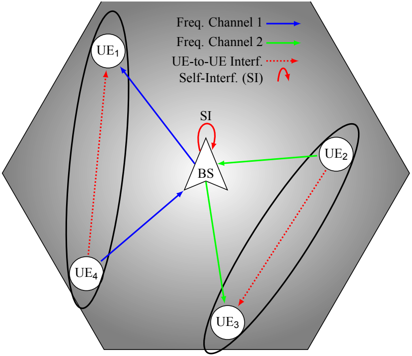


- Half-Duplex (HD) systems $\rightarrow$ Inefficient resource utilization
- Full-Duplex (FD) systems $\rightarrow \sim 2\times$ spectral efficiency

Outline

Outline

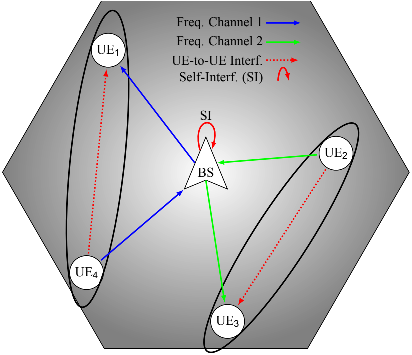
FD Characteristics in cellular networks



Benefits

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

FD Characteristics in cellular networks



Challenges

- Severe self-interference (SI)
- UE-to-UE interference
- Mitigate both interferences → user pairing and power allocation

Research Gap in FD cellular networks

Lack of fairness analysis in full-duplex

- How to ensure fairness in FD cellular networks?*†
  - ↑ minimum achieved spectral efficiency
  - Minimum quality-of-service constraints
  - Weights on the spectral efficiency

Lack of fair and spectral efficient cross-layer procedures

- How to maximize spectral efficiency and fairness?
  - Pairing → UL and DL users to share the frequency channel
  - Power allocation → mitigate interference
  - Multi-objective optimization

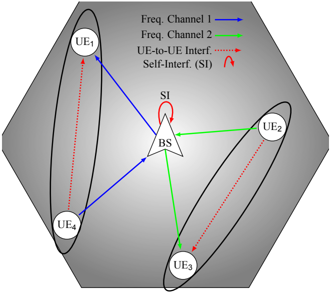
* J. Mairton B. da Silva Jr., G. Fodor, C. Fischione, "Spectral Efficient and Fair User Pairing for Full-Duplex Communication in Cellular Networks," IEEE TWC, Nov. 2016.
† J. Mairton B. da Silva Jr., Y. Xu, G. Fodor, C. Fischione, "Distributed Spectral Efficiency Maximization for Full-Duplex Communication in Cellular Networks," in Proc. of IEEE ICC, May 2016.

Contributions

- Study multi-objective optimization with weighted spectral efficiency and fairness
  - Joint pairing and power allocation → maximize weighted sum spectral efficiency + minimum achieved spectral efficiency
- Solve this MINLP problem
  - Scalarization + Lagrangian duality → optimal power allocation + centralized assignment
- Show gains over FD solutions
  - Realistic system simulations → Yes, spectral efficiency + fairness!
  - Disregard UE-to-UE interference → losses on fairness + spectral efficiency
  - Weights on spectral efficiency → no longer necessary

Outline

Definitions (1/2)



- Single-cell cellular system + only BS is FD-capable
- UL users → I; DL users → J; Frequency channels → F; Pair $n = (i, j)$
- 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 (2/2)

- Power vectors $\rightarrow$ $\mathbf{p^u} = [P_1^u \dots P_I^u]$, $\mathbf{p^d} = [P_1^d \dots P_J^d]$
- 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 rate maximization (SR)
  - $\alpha_i^u = G_{ib}^{-1}, \quad \alpha_j^d = G_{bj}^{-1} \rightarrow$ Path loss compensation (PL)

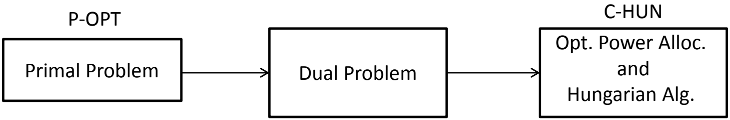
Multi-objective problem formulation

- How to maximize both weighted sum spectral efficiency and fairness?
  - Multi-objective optimization

$$
\begin{aligned}
\underset{\mathbf{X},\mathbf{p}^u,\mathbf{p}^d}{\text{maximize}} \quad & \Big(1-\mu\Big)\Big(\sum_{i=1}^{I}\alpha_i^u C_i^u + \sum_{j=1}^{J}\alpha_j^d C_j^d\Big) + \mu \min_{\forall i,j}\{C_i^u, C_j^d\} && \text{(Objective)}\\
\text{subject to} \quad & P_i^u \leq P_{\text{max}}^u,\ \forall\, i, && \text{(Maximum Tx. power UL)}\\
& P_j^d \leq P_{\text{max}}^d,\ \forall\, j, && \text{(Maximum Tx. power DL)}\\
& \sum_{i=1}^{I} x_{ij} \leq 1,\ \forall\, j, && \text{(User orthogonality UL)}\\
& \sum_{j=1}^{J} x_{ij} \leq 1,\ \forall\, i, && \text{(User orthogonality DL)}\\
& x_{ij} \in \{0,1\},\ \forall\, i,j. && \text{(Binary association)}
\end{aligned}
$$

- $\mu \rightarrow$ trades between both objectives

Solution approach



- Primal problem + hypograph formulation → dual problem
- High complexity of dual problem + insights → reformulation of the problem
  - Optimal power allocation → consider weakest user with higher weight
  - Assignment problem → centralized Hungarian solution

Outline

Lagrangian function

- Equivalent hypograph formulation

$$\underset{\mathbf{X},\mathbf{p}^u,\mathbf{p}^d}{\text{maximize}} \quad \Big(1-\mu\Big)\Big(\sum_{i=1}^{I} \alpha_i^u C_i^u + \sum_{j=1}^{J} \alpha_j^d C_j^d\Big) + \mu \ t \qquad \text{(Objective)}$$

$$\begin{aligned} \text{subject to} \quad & C_i^u \geq t, \forall i, && \text{(Min. UL)} \\ & C_j^d \geq t, \forall j, && \text{(Min. UL)} \\ & \text{Same constraints...} \end{aligned}$$

- Formulate partial Lagrangian function

$$L(\boldsymbol{\lambda}^u, \boldsymbol{\lambda}^d, \mathbf{X}, \mathbf{p}^u, \mathbf{p}^d, t) = t\Big(\sum_{i=1}^{I} \lambda_i^u + \sum_{j=1}^{J} \lambda_j^d - \mu\Big) - \sum_{i=1}^{I}\Big(\lambda_i^u + (1-\mu)\alpha_i^u\Big) C_i^u - \sum_{j=1}^{J}\Big(\lambda_j^d + (1-\mu)\alpha_j^d\Big) C_j^d.$$

Dual problem and closed-form solution for assignment

- The dual function is

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

$$g(\boldsymbol{\lambda}^u, \boldsymbol{\lambda}^d) = \begin{cases} \inf_{\mathbf{X}\in\mathcal{X}\ \mathbf{p}^u,\mathbf{p}^d\in\mathcal{P}} \Big[\sum_i q_i^u(\mathbf{X}, \mathbf{p}^u, \mathbf{p}^d) + \\ \sum_j q_j^d(\mathbf{X}, \mathbf{p}^u, \mathbf{p}^d) \Big], \quad \text{if } \sum_i \lambda_i^u + \sum_j \lambda_j^d = \mu \\ -\infty, \ \text{otherwise}, \end{cases}$$

with

$$q_i^u(\mathbf{X}, \mathbf{p}^u, \mathbf{p}^d) \triangleq -\Big(\lambda_i^u + (1-\mu)\alpha_i^u\Big) C_i^u,$$

$$q_j^d(\mathbf{X}, \mathbf{p}^u, \mathbf{p}^d) \triangleq -\Big(\lambda_j^d + (1-\mu)\alpha_j^d\Big) C_j^d.$$

Assignment and optimal power allocation

- Initial expression for the assignment

$$x_{ij}^{\star} = \begin{cases} 1, & \text{if } (i,j) = \arg\max_{i,j} \left(q_{i_n}^{u,\mathsf{max}} + q_{j_n}^{d,\mathsf{max}} \right) \\ 0, & \text{otherwise} \end{cases}$$

- Turn our attention to the power allocation problem

$$\begin{aligned} \underset{\mathbf{p}^u, \mathbf{p}^d}{\text{maximize}} \quad & \sum_{i=1}^{I} \left(\lambda_i^u + (1-\mu)\alpha_i^u \right) C_i^u + \sum_{j=1}^{J} \left(\lambda_j^d + (1-\mu)\alpha_j^d \right) C_j^d \\ \text{subject to} \quad & \mathbf{p}^u, \mathbf{p}^d \in \mathcal{P}. \end{aligned}$$

- Optimal solution for available⋆ $\rightarrow$ corner points of $\mathcal{P}$

⋆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

Dual problem analysis

- Analyse the dual problem

$$\underset{\boldsymbol{\lambda}^u,\ \boldsymbol{\lambda}^u}{\text{minimize}} \quad \sum\nolimits_{i=1}^{I} \lambda_i^u C_i^u + \sum\nolimits_{j=1}^{J} \lambda_j^d C_j^d$$
$$\text{subject to} \quad \sum\nolimits_{i=1}^{I} \lambda_i^u + \sum\nolimits_{j=1}^{J} \lambda_j^d = \mu,$$
$$\lambda_i^u,\ \lambda_j^d \geq 0, \forall i, j,$$

- Solution for λ^u, λ^d $\rightarrow$ Unique non-zero λ^* for all i, j
- High complexity solution to find λ^* $\rightarrow$ minimum achieved spectral efficiency in total
- Reformulate dual to select one λ_n^* per pair instead of λ^* for all i, j $\rightarrow$ minimum achieved spectral efficiency per pair

Problem reformulation

- Insights from the dual → reformulate closed-form assignment with optimal power allocation

$$\begin{aligned} \underset{\mathbf{X}}{\text{maximize}} \quad & \sum_{i=1}^{I} \sum_{j=1}^{J} s_{ij} x_{ij} \\ \text{subject to} \quad & \sum_{i=1}^{I} x_{ij} = 1, \ \forall j, \\ & \sum_{j=1}^{J} x_{ij} = 1, \ \forall i, \\ & x_{ij} \in \{0, 1\}, \ \forall i, j, \end{aligned}$$

with $s_{ij} = (1-\mu)(\alpha_i^u C_i^u + \alpha_j^d C_j^d) + \mu \min\{C_i^u, C_j^d\}$

- Centralized solution → Hungarian algorithm (C-HUN)

Overall solution approach

Centralized Hungarian Algorithm

- Input: α_i^u, α_i^u, G_{ib}, G_{bj}, G_{ij}, β, $P_{\max}^u$, $P_{\max}^d$
- Evaluate corner point (P_i^u, P_j^d) that maximizes s_{ij} for all i, j
- Evaluate optimal assignment using Hungarian algorithm

- CSI acquisition $\rightarrow$ reference signals standardized by 3GPP[⋆†]
- Complexity of $O(I^3)$

[*] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2," 3GPP, TS 36.300, Sep. 2015.

[†] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures," 3GPP, TS 36.313, Jun. 2016.

Outline

1. Introduction
2. System Model and Problem Formulation
3. Solution Approach Based on Lagrangian Duality
4. Numerical Results
5. Conclusions

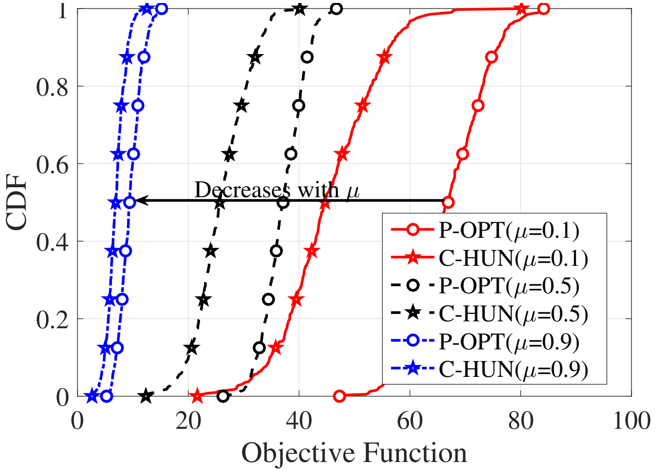
Simulation Parameters

- $I = J = F$ and $I + J = [8,\ 50]$
- SI cancellation $\beta = -100\text{dB}$
- Proposed algorithm
  - C-HUN: Centralized Hungarian + Optimal power allocation

compared to

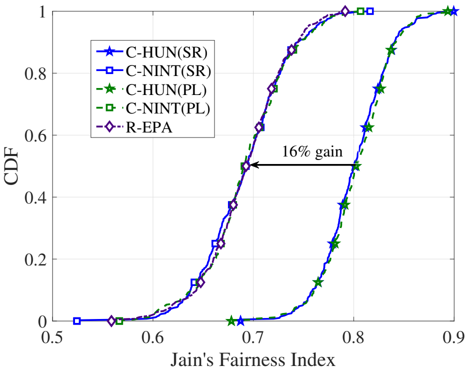
  - P-OPT: Primal optimal from brute-force solution
  - C-NINT: Centralized solution but without UE-to-UE interference knowledge
  - R-EPA: Random assignment + equal power allocation

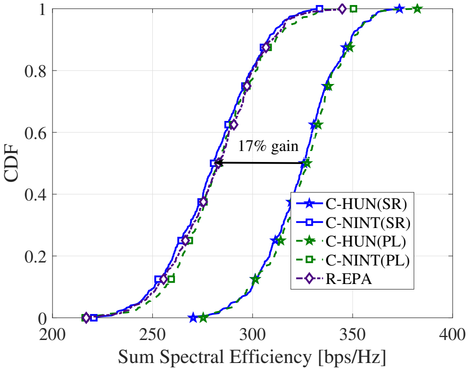
Optimality gap for different μ



- Objective function + optimality gap decrease with μ
- High μ $\rightarrow$ more fairness $\rightarrow$ lower gap

Fairness and sum spectral efficiency with $\mu = 0.9$





- C-HUN outperforms all other schemes
- Without proper UE-to-UE interference knowledge (C-NINT) $\rightarrow$ loss in fairness and spectral efficiency
- High μ $\rightarrow$ PL $\approx$ SR for fairness and spectral efficiency

Outline

Take home message

Conclusions

- Multi-objective optimization in FD cellular networks
  - Spectral efficiency and fairness maximization
  - Fair and efficient
  - Weights on spectral efficiency no longer necessary
- User-to-user interference knowledge is important
  - Limiting factor for fairness and spectral efficiency
  - If not considered $\rightarrow$ as good as random assignment and equal power allocation

Future works

- Distributed solution for the network
- Other scalarization techniques

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