Spectral Efficiency and Fairness Maximization in Full-Duplex Cellular Networks

José Mairton B. da Silva Jr.

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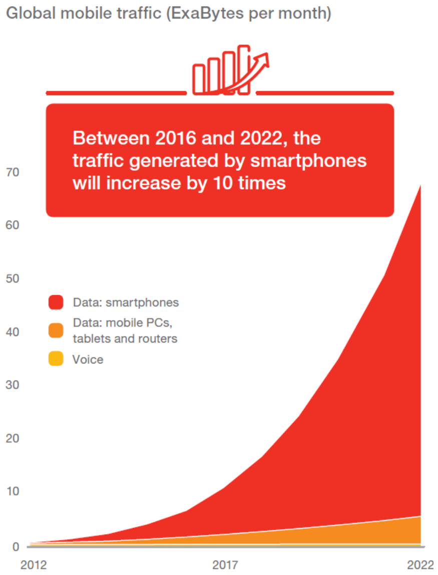
Department of Network and Systems Engineering
School of Electrical Engineering
KTH Royal Institute of Technology
Stockholm, Sweden

http://www.kth.se/profile/jmbdsj
jmbdsj@kth.se

Need for higher rates in 5G

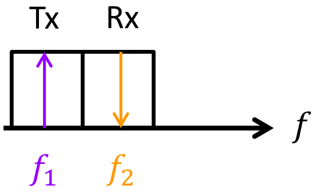


[Ericsson16]

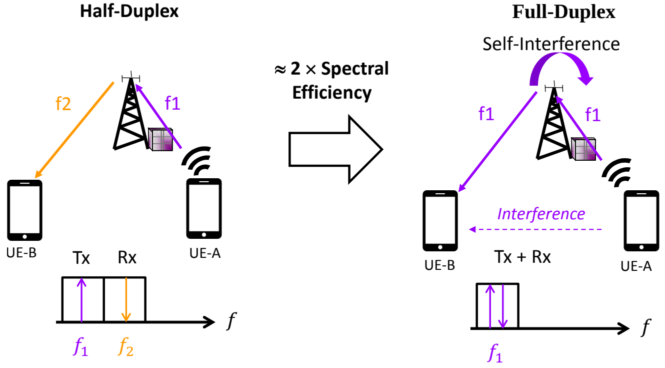
How to meet this demand?

- $\uparrow$ antennas at the base station $\rightarrow$ massive MIMO
- $\uparrow$ spectrum $\rightarrow$ mmWave
- $\uparrow$ cells $\rightarrow$ densification
- $\uparrow$ spectral efficient? $\rightarrow$ evolve half-duplex (HD)

Half-Duplex



Half-duplex versus Full-duplex

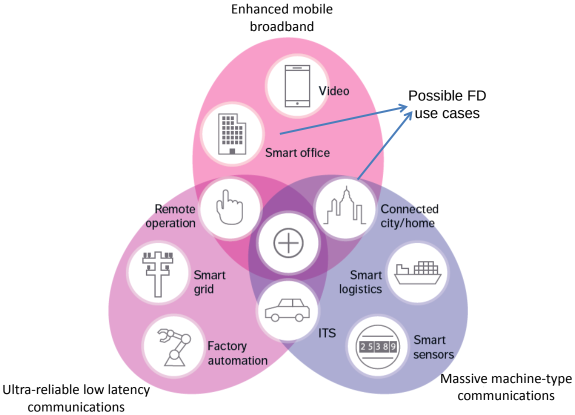


Why half-duplex so far? [Goldsmith05]

"It is generally not possible for radios to receive and transmit on the same frequency band due to the interference that results."

- Recent advances on self-interference (SI) [Bharadia,SIGCOMM13] → full-duplex is possible

The role of full-duplex in 5G



[Ericsson17]

- Full-duplex suitable for short distance + small cells

Outline

1. Overview of FD cellular networks & main contributions
2. Spectral efficiency maximization
3. Fairness maximization
4. Concluding remarks

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1. Overview of FD cellular networks & main contributions
2. Spectral efficiency maximization
3. Fairness maximization
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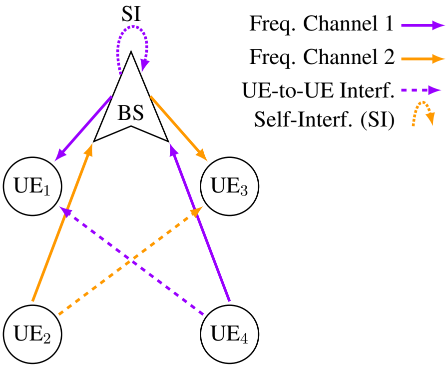
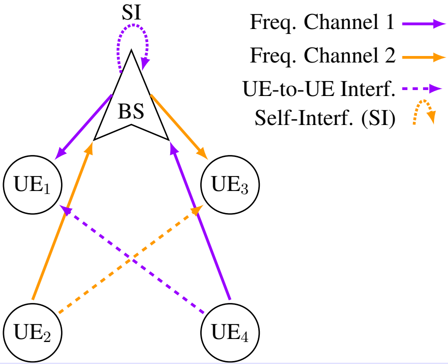
FD characteristics in cellular networks



Benefits

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

FD characteristics in cellular networks



Challenges

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

Research gap in FD cellular networks

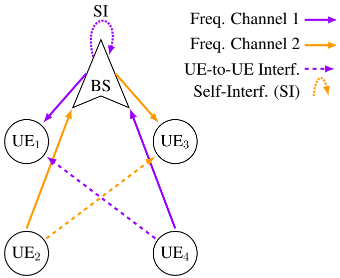
Need of distributed schemes

- Processing burden at the BS is high [Osseiran,COMMAG14]
  - Dense deployment of user
  - New SI cancellation mechanisms
  - Radio resource management

Lack of fair and efficient cross-layer procedures

- How to mitigate UE-to-UE interference and assess fairness?
  - Pairing $\rightarrow$ uplink to downlink users (flat fading)
  - Assignment $\rightarrow$ uplink/downlink users to frequency channel (frequency selective fading)
  - Power allocation $\rightarrow$ mitigate interference
  - Fairness $\rightarrow$ (weighted sum + min) spectral efficiency maximization

General problem formulation



$$\begin{aligned} \underset{\mathbf{X},\mathbf{p}^u,\mathbf{p}^d}{\text{maximize}} \quad & f_0(\mathbf{X},\mathbf{p}^u,\mathbf{p}^d) \\ \text{subject to} \quad & \mathbf{f}_m(\mathbf{X},\mathbf{p}^u,\mathbf{p}^d) \le \mathbf{b}_m, \ \forall m \in \mathcal{M}, \\ & \mathbf{h}_n(\mathbf{X}) \le \mathbf{c}_n, \ \forall n \in \mathcal{N}, \\ & \mathbf{X} \in \{0,1\}^S. \end{aligned}$$

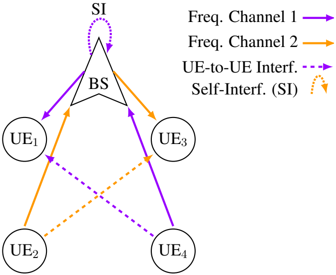
Optimization Variables

- Assignment matrix $\rightarrow \mathbf{X} \in \{0,1\}^S, S = I \times J$

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

- Transmitting powers $\rightarrow \ \mathbf{p}^u, \mathbf{p}^d$

General problem formulation



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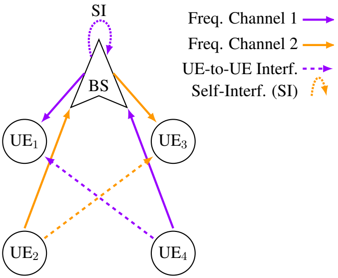
Optimization Variables

- Assignment matrix frequency selective fading $\rightarrow \mathbf{X} \in \{0,1\}^S$, $S = I \times J \times F$

$$x_{ijf} = \begin{cases} 1, & \text{if uplink UE}_i \text{ is paired with downlink UE}_j \text{ on freq. } f, \\ 0, & \text{otherwise.} \end{cases}$$

- Transmitting powers $\rightarrow \ \mathbf{p}^u, \mathbf{p}^d$

General problem formulation



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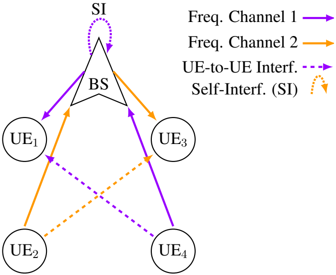
Objective function $f_0(\mathbf{X}, \mathbf{p}^u, \mathbf{p}^d)$

- Sum spectral efficiency $\rightarrow$ sum rate over a given bandwidth
- Fairness $\rightarrow$ worst users should also benefit
- Spectral efficiency + fairness $\rightarrow$ improve the system + the worst users

General problem formulation



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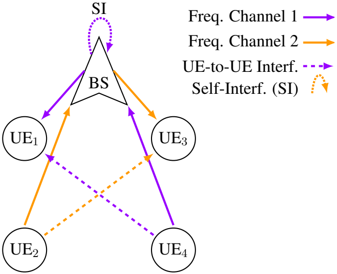
Constraint function $\mathbf{f}_m(\mathbf{X}, \mathbf{p}^u, \mathbf{p}^d)$

- Minimum quality of service requirements $\rightarrow \mathbf{f}_m(\mathbf{X}, \mathbf{p}^u, \mathbf{p}^d) \rightarrow$ Non-convex
- Maximum transmitting power $\rightarrow \mathbf{f}_m(\mathbf{p}^u, \mathbf{p}^d) \rightarrow$ Convex

General problem formulation



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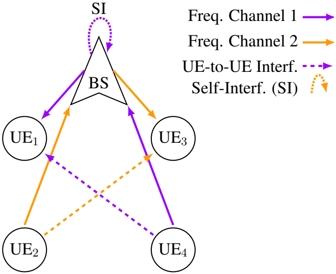
Constraint function $\mathbf{h}_n(\mathbf{X})$

- Binary constraints $\rightarrow$ orthogonality of UL/DL users and frequency channels
- Linear constraints

General problem formulation



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How difficult is this problem?

- Mixed integer nonlinear programming (MINLP) problem $\rightarrow$ difficult to solve
- Some cases of $\mathbf{X}$ $\rightarrow$ NP-hard $\rightarrow$ no polynomial-time solution known

Thesis contributions (1/3)

Spectral efficiency maximization

[C1] José Mairton B. da Silva Jr., Y. Xu, G. Fodor, C. Fischione, "Distributed Spectral Efficiency Maximization in Full-Duplex Cellular Networks", in *Proc. IEEE International Conference on Communications* (ICC'16), May 2016.

[J1] José Mairton B. da Silva Jr., G. Fodor, C. Fischione, "Fast-Lipschitz Power Control and User-Frequency Assignment in Full-Duplex Cellular Networks," submitted to *IEEE Transactions on Wireless Communications*, February 2017.

Fairness maximization

[J2] José Mairton B. da Silva Jr., G. Fodor, C. Fischione, "Spectral Efficient and Fair User Pairing for Full-Duplex Communication in Cellular Networks", *IEEE Transactions on Wireless Communications*, Vol. 15, No. 11, pp. 7578-7593, Nov. 2016.

[C2] José Mairton B. da Silva Jr., G. Fodor, C. Fischione, "On the Spectral Efficiency and Fairness in Full-Duplex Cellular Networks", in *Proc. IEEE International Conference on Communications* (ICC'17), May 2017, accepted.

Thesis contributions (2/3)

	[C1]	[J1]	[J2]	[C2]
User Pairing	✓	✓	✓	✓
Freq. Assignment	-	✓	✓	-
Power Alloc./Control	✓	✓	✓	✓
Distributed	✓	✓	-	-
Objective	Sum SE	Sum SE	Minimum SE	Sum SE + Minimum SE

Spectral efficiency maximization

- Distributed mechanisms for FD cellular networks
  - Auction algorithm [C1] → resource pairing
  - Power control [J1] → SINR and power settings
- SI or UE-to-UE interference → different roles for power allocation and assignment
- Spectral efficiency gains over HD
  - Realistic system simulations → Yes, + energy savings!

Thesis contributions (3/3)

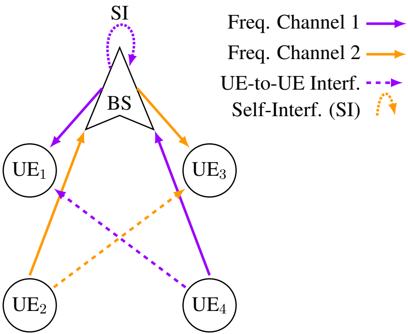
	[C1]	[J1]	[J2]	[C2]
User Pairing	✓	✓	✓	✓
Freq. Assignment	-	✓	✓	-
Power Alloc./Control	✓	✓	✓	✓
Distributed	✓	✓	-	-
Objective	Sum SE	Sum SE	Minimum SE	Sum SE + Minimum SE

Fairness maximization

- Role of assignment and power allocation in fairness
  - Assignment and power allocation → used jointly and should not be split
- Weights to increase fairness [C2] → not necessary if multi-objective optimization
- Fairness gains over simple FD solutions [J2,C2]
  - Realistic system simulations → Yes, + user connectivity!

Outline

System Model (1/3)



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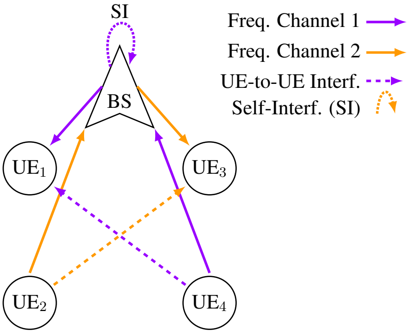
Objective	Sum SE	Sum SE	Minimum SE	Sum SE + Minimum SE

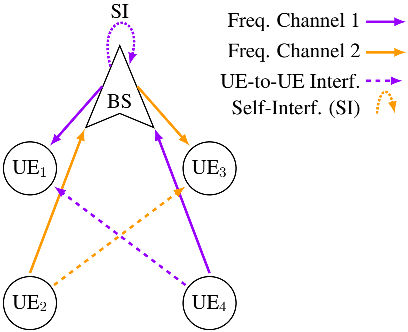
System Model (2/3)



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

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

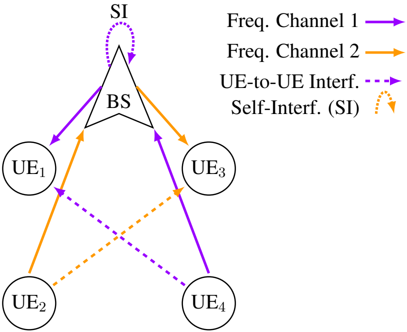
System Model (2/3)



- Single-cell cellular system → only BS is FD-capable
- # UL users → I; # DL users → J; # Frequency channels → F
- Path gain for frequency selective fading → G_{ibf}, G_{bjf}, G_{ijf}
- SI cancellation coefficient → β fixed
- Assignment matrix freq. selective fading → $\mathbf{X} \in \{0,1\}^{I \times J \times F}$

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

System Model (3/3)



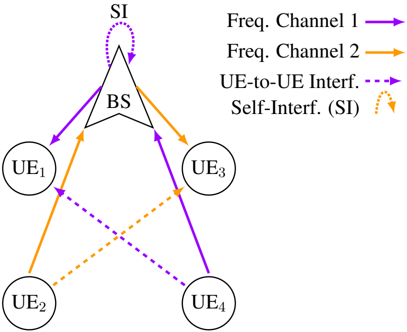
- Power vectors → $\mathbf{p^u} = [P_1^u \dots P_I^u], \quad \mathbf{p^d} = [P_1^d \dots P_J^d]$
- Signal-to-interference noise ratio (SINR)

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

- Achievable spectral efficiency

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

System Model (3/3)



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- Achievable spectral efficiency

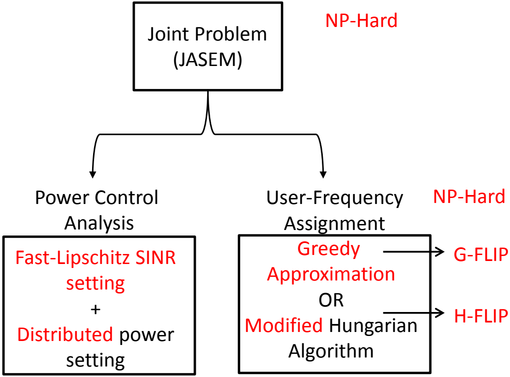
$$C_i^u = \sum_{f=1}^F \log_2(1 + \gamma_{if}^u), \quad C_j^d = \sum_{f=1}^F \log_2(1 + \gamma_{jf}^d).$$

Problem formulation

- Joint assignment and spectral efficiency maximization (JASEM)

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

Solution approach for JASEM



- Power control analysis → fixed $\mathbf{X}$ and variables $\mathbf{p}^u, \mathbf{p}^d$
  - Power allocation problem → vector transformation + hypograph equivalent form
- User-frequency assignment → fixed $\mathbf{p}^u, \mathbf{p}^d$ and variable $\mathbf{X}$
  - NP-Hard → greedy approximation

Power control analysis (1/2)

Power allocation problem

$$\underset{\mathbf{p}^u,\mathbf{p}^d}{\text{maximize}} \quad \sum_{i=1}^{I} C_i^u + \sum_{j=1}^{J} C_j^d$$
$$\text{subject to} \quad \mathbf{p}^u, \mathbf{p}^d \in \mathcal{P}.$$

$\longleftrightarrow$

Power + spectral efficiency problem

$$\underset{\mathbf{p},\mathbf{t}}{\text{maximize}} \quad \sum_{k=1}^{K} t_k$$
$$\text{subject to} \quad t_k \leq \alpha_k \log(1 + \gamma_k(\mathbf{p})), \forall k,$$
$$P_k \leq P_{\text{max}}^{(k)}, \forall k.$$

Lemma on t_k

The diagonal matrix $\mathbf{T} = [\exp(t_k/\alpha_k) - 1]_k$ of adaptive SINR targets is feasible if and only if

$$\rho(\mathbf{TF}) < 1.$$

- Lemma on t_k $\rightarrow$ target inequality for pair (k, l) sharing resource

$$\exp\left(\frac{t_k}{\alpha_k} + \frac{t_l}{\alpha_l}\right) - \exp\left(\frac{t_k}{\alpha_k}\right) - \exp\left(\frac{t_l}{\alpha_l}\right) \leq \epsilon\left(\frac{G_{kb}^u G_{bl}^d}{\beta G_{lk}} - 1\right).$$

Power control analysis (2/2)

Spectral efficiency target

$$\begin{aligned} \underset{t_k, t_l}{\text{maximize}} \quad & t_k + t_l \\ \text{subject to} \quad & (\text{target inequality}), \\ & t_k, t_l \geq 0. \end{aligned}$$

$\longleftrightarrow$

Fast-Lipschitz form [Fischione, TAC11]

$$\begin{aligned} \underset{t_k, t_l}{\text{maximize}} \quad & t_k + t_l \\ \text{subject to} \quad & t_k \leq t_k - \gamma h(t_k, t_l), \\ & \mathbf{x} = [t_k \; t_l] \in \mathcal{X}, \end{aligned}$$

Lemma on t_k

If $\frac{\partial h(t_k,t_l)}{\partial t_l} < \frac{\partial h(t_k,t_l)}{\partial t_k}$, and the parameter γ is constrained as $\left(2\frac{\partial h(t_k,t_l)}{\partial t_k}\right)^{-1} < \gamma < \left(\frac{\partial h(t_k,t_l)}{\partial t_k}\right)^{-1}$, then problem above is Fast-Lipschitz.

Distributed spectral efficiency target + power setting

- t_k $\rightarrow$ Fast-Lipschitz optimization
- t_l $\rightarrow$ use t_k with golden search optimization
- Use t_k, t_l to find P_k, P_l that minimizes $P_k + P_l$
- $\therefore \rightarrow$ Close-to-optimal spectral efficiency + min. sum power

User-frequency assignment solutions

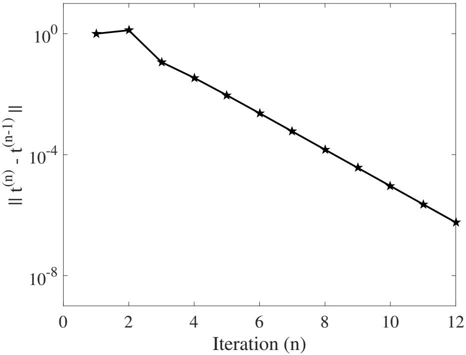
- Axial 3D Assignment problem → NP-Hard

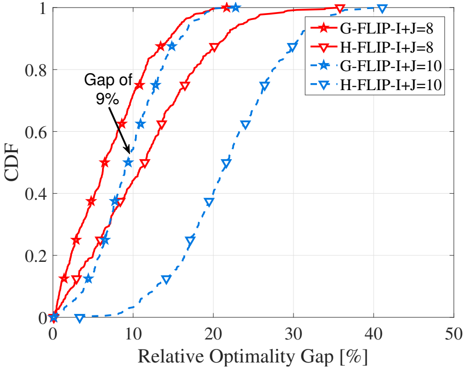
$$\begin{aligned}
&\underset{\mathbf{X}}{\text{maximize}} && \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{f=1}^{F}\left(C_{if}^{u}+C_{jf}^{d}\right)x_{ijf} && \text{(Objective)}\\
&\text{subject to} && \sum_{j=1}^{J}\sum_{f=1}^{F} x_{ijf}=1,\ \forall i, && \text{(User orthogonality UL)}\\
& && \sum_{i=1}^{I}\sum_{f=1}^{F} x_{ijf}=1,\ \forall j, && \text{(User orthogonality DL)}\\
& && \sum_{i=1}^{I}\sum_{j=1}^{J} x_{ijf}=1,\ \forall f, && \text{(User orthogonality freq)}\\
& && x_{ijf}\in\{0,1\},\ \forall i,j,f, && \text{(Binary association)}
\end{aligned}$$

Solution approach

- Start with best pair and continue until all users are paired
- Greedy approximation → performance guarantee of $1/3$
- Modified Hungarian algorithm → transforms 3D into 2D + Hungarian algorithm

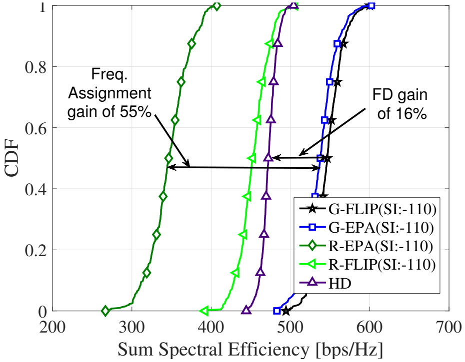
Optimality of G-FLIP

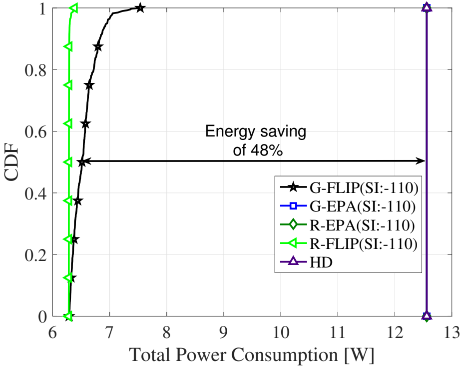




- Convergence with accuracy 10^{-6} in 12 iterations
- G-FLIP $\rightarrow$ close to optimality
- H-FLIP $\rightarrow$ large optimality gap for high number of users

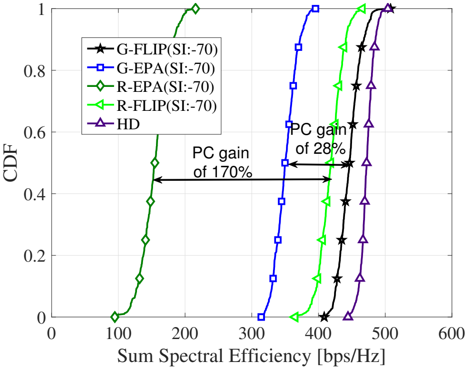
Results for interference-limited regime -25 UL/DL UEs

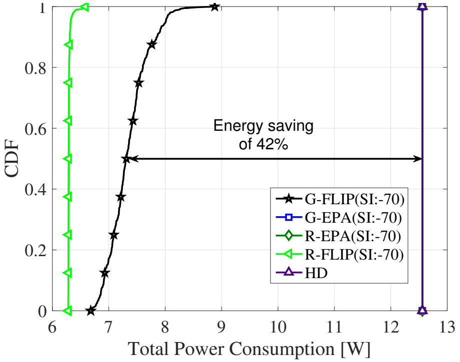




- Most of the gains (G-FLIP & G-EPA) → greedy assignment
- Power control (FLIP) + poor assignment (R) → still no gains
- Expected → large gains in energy efficiency

Results for SI-limited regime - 25 UL/DL UEs





- Most of the gains (G-FLIP & R-FLIP) → power control (FLIP)
- Power control + greedy assignment → still no gains over HD
- Expected → large gains in energy efficiency

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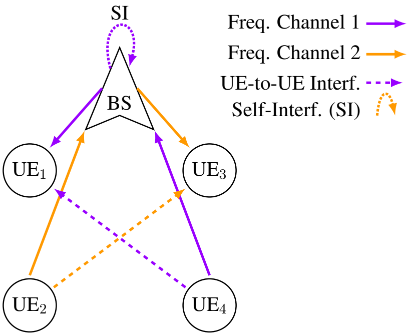


	[C1]	[J1]	[J2]	[C2]
User Pairing	✓	✓	✓	✓
Freq. Assignment	-	✓	✓	-
Power Alloc./Control	✓	✓	✓	✓
Distributed	✓	✓	-	-
Objective	Sum SE	Sum SE	Minimum SE	Sum SE + Minimum SE

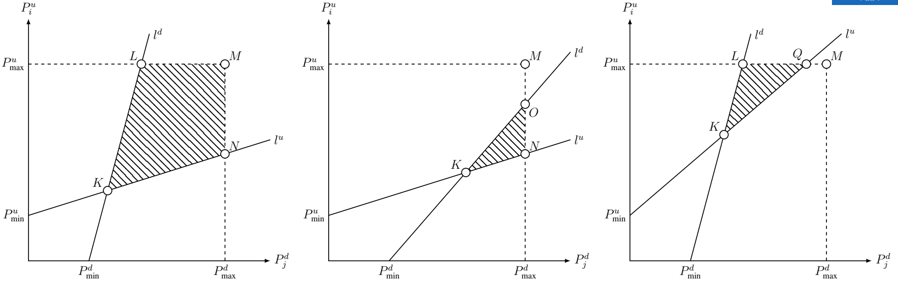
Problem formulation

- Joint assignment and fairness maximization (JAFM)

$$\underset{\mathbf{X}^u,\mathbf{X}^d,\mathbf{p}^u,\mathbf{p}^d}{\text{maximize}} \quad \min_{\forall i,j}\{C_i^u, C_j^d\} \qquad \text{(Objective)}$$

$$\begin{aligned}
\text{subject to} \quad & \sum_{f=1}^{F} \gamma_{if}^u \geq \gamma_{\text{th}}^u,\ \forall i, && \text{(Minimum SINR constraint UL)}\\
& \sum_{f=1}^{F} \gamma_{jf}^d \geq \gamma_{\text{th}}^d,\ \forall j, && \text{(Minimum SINR constraint DL)}\\
& P_i^u \leq P_{\text{max}}^u,\ \forall i, && \text{(Maximum Tx. power UL)}\\
& P_j^d \leq P_{\text{max}}^d,\ \forall j, && \text{(Maximum Tx. power DL)}\\
& \sum_{i=1}^{I} x_{if}^u \leq 1,\ \forall f, && \text{(User-frequency orthogonality UL)}\\
& \sum_{f=1}^{F} x_{if}^u \leq 1,\ \forall i, && \text{(Frequency orthogonality in UL)}\\
& \sum_{j=1}^{J} x_{jf}^d \leq 1,\ \forall f, && \text{(User-frequency orthogonality DL)}\\
& \sum_{f=1}^{F} x_{jf}^d \leq 1,\ \forall j, && \text{(Frequency orthogonality in DL)}\\
& x_{if}^u,\ x_{jf}^d \in \{0,1\},\ \forall i,j,f. && \text{(Binary association)}
\end{aligned}$$

Admissible area



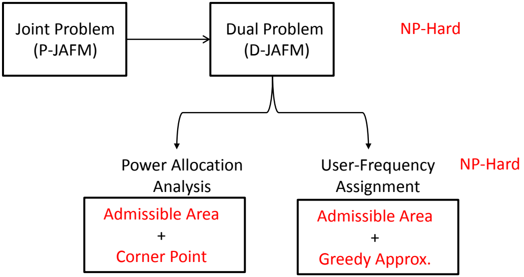
$\gamma_{iMf}^u > \gamma_{\text{th}}^u,\ \gamma_{jMf}^d \geq \gamma_{\text{th}}^d$ $\qquad$ $\gamma_{iMf}^u > \gamma_{\text{th}}^u,\ \gamma_{jMf}^d < \gamma_{\text{th}}^d$ $\qquad$ $\gamma_{iMf}^u \leq \gamma_{\text{th}}^u,\ \gamma_{jMf}^d \geq \gamma_{\text{th}}^d$

Lemma on admissible β

Pair (i,j) on frequency f is an *admissible* if the SI is $\beta \leq \beta_{ijf}^{\max}$

$$\beta_{ijf}^{\max} = \begin{cases} \dfrac{G_{bjf}(P_{\max}^u G_{ibf} - \gamma_{\text{th}}^u \sigma^2)}{\gamma_{\text{th}}^u \gamma_{\text{th}}^d (P_{\max}^u G_{ijf} + \sigma^2)}, \text{if } \gamma_{jMf}^d > \gamma_{\text{th}}^d, \\ \dfrac{P_{\max}^d G_{bjf} G_{ibf} - \sigma^2 \gamma_{\text{th}}^d (G_{ijf} \gamma_{\text{th}}^u + G_{ibf})}{\gamma_{\text{th}}^u \gamma_{\text{th}}^d P_{\max}^d G_{ijf}}, \text{if } \gamma_{jMf}^d \leq \gamma_{\text{th}}^d. \end{cases}$$

Solution approach for JAFM (1/2)



- Lagrangian duality → power allocation + user-frequency assignment
- Power allocation analysis → optimal allocation in corner point of admissible area
- User-frequency assignment → greedy approximation for users in the admissible area

Solution approach for JAFM (2/2)

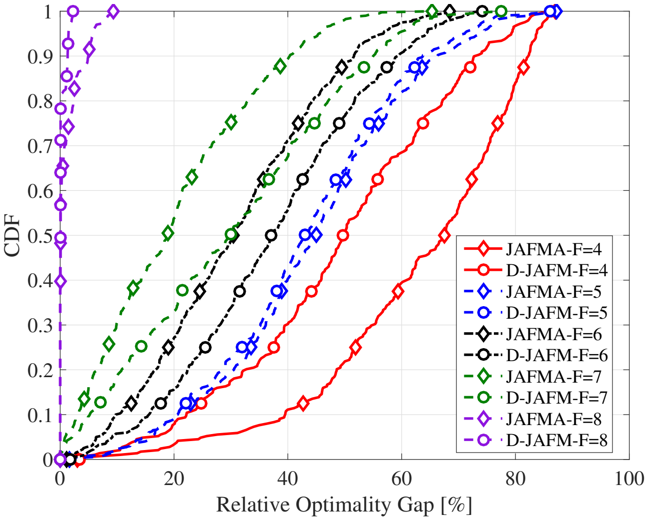
$$\begin{aligned}
\underset{\mathbf{X}}{\text{maximize}} \quad & \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{f=1}^{F}\Big(\min\{C_{if}^{u}, C_{jf}^{d}\}\Big)x_{ijf} && \text{(Objective)}\\
\text{subject to} \quad & \sum_{j=1}^{J}\sum_{f=1}^{F} x_{ijf} = 1,\ \forall i, && \text{(User orthogonality UL)}\\
& \sum_{i=1}^{I}\sum_{f=1}^{F} x_{ijf} = 1,\ \forall j, && \text{(User orthogonality DL)}\\
& \sum_{i=1}^{I}\sum_{j=1}^{J} x_{ijf} = 1,\ \forall f, && \text{(User orthogonality freq)}\\
& x_{ijf} \in \{0,1\},\ \forall i,j,f, && \text{(Binary association)}
\end{aligned}$$

- Start with best admissible pair and continue until all users are paired
- Performance guarantee of $1/3$
- Power allocation $+$ greedy approximation $\rightarrow$ JAFMA

JAFMA

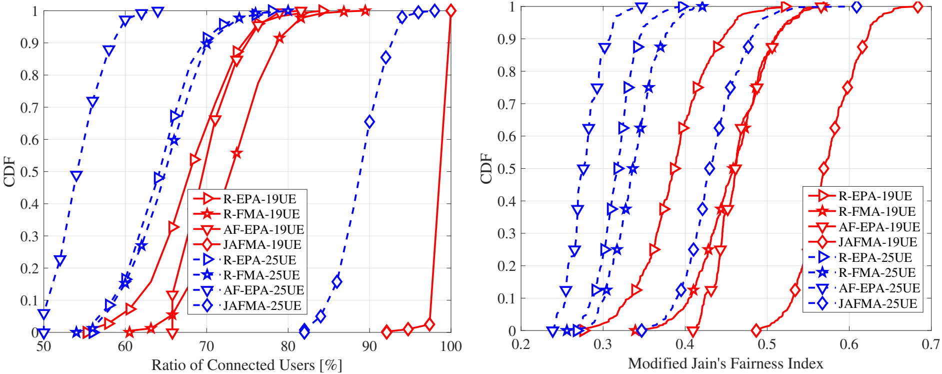
- Duality gap $\downarrow$ as number of frequency channel $\uparrow$
- JAFMA $\rightarrow$ approximate solution to JAFM

Optimality gap for JAFMA - $\beta = -100$dB



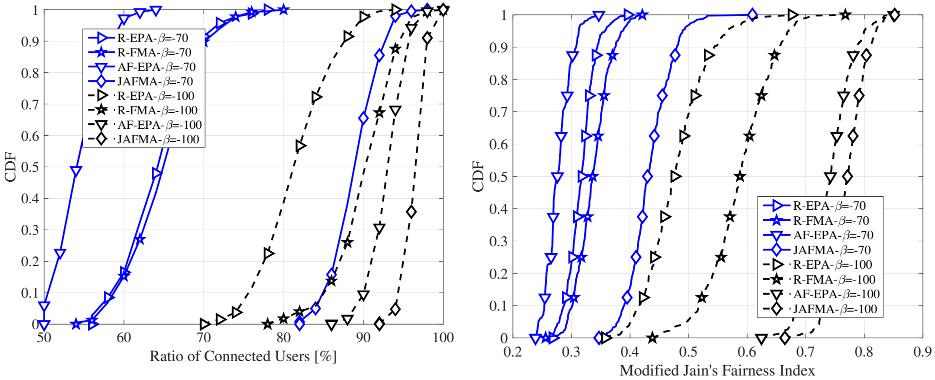
- JAFMA → optimality gap decreases with increasing F

Analysis for different users' loads - $\beta = -70\text{dB}$



- JAFMA $\rightarrow$ highest user connectivity + fairness
- Greedy assignment (AF) + equal power allocation $\rightarrow$ still no gains
- Optimal power allocation (FMA) + poor assignment $\rightarrow$ still no gains

Analysis for different β - 25 UL/DL UEs



- β =-100 dB
  - JAFMA → gains in user connectivity + fairness
  - Split JAFMA → still good performance
- β =-70 dB
  - JAFMA → large gains in user connectivity + fairness
  - Split JAFMA → poor performance

Outline

Some takeaways

Sum spectral efficiency maximization

- Gains over HD with distributed solutions
  - Auction theory + optimal power allocation → weighted sum spectral efficiency
  - Fast-Lipschitz optimization + greedy approximation → spectral and energy efficiency
- Different roles of assignment and power control → interference- or SI-limited regime

Fairness maximization

- Gains for minimum achieved spectral efficiency + connectivity
- Joint solutions + UE-to-UE interference consideration → higher fairness
- Multi-objective optimization → PL weights not necessary

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Thanks for your attention!

ROYAL INSTITUTE OF TECHNOLOGY

Spectral Efficiency and Fairness Maximization in Full-Duplex Cellular Networks

José Mairton B. da Silva Jr.

April 28th, 2017

Department of Network and Systems Engineering
School of Electrical Engineering
KTH Royal Institute of Technology
Stockholm, Sweden

http://www.kth.se/profile/jmbdsj
jmbdsj@kth.se