Inter-Cell Interference Coordination in Wireless Networks

PhD Defense, IRISA, Rennes, 2015

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Background

- Mobile data traffic is exponentially increasing
    - 70% growth in 2012[1] and 81% growth in 2013[2]
    - Mobile data traffic in 2017 will be 13 times that of 2012
- METIS project technical objectives[3] for 5G networks:
    - 1,000 times higher mobile data volume per area
    - 10 to 100 times higher user data rate
    - 10 to 100 times higher number of connected devices
- Need to increase network capacity and spectral efficiency
    - Network densification
    - *Aggressive frequency reuse*

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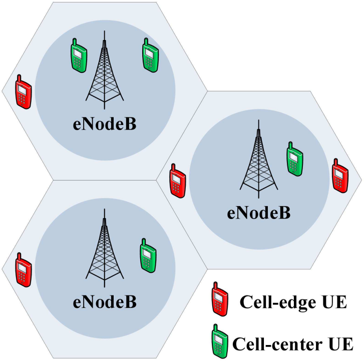
[1] Cisco Systems. *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012-2017.*

[2] Cisco Systems. *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2013-2018.*

[3] METIS D6.6. *Final Report on the METIS 5G System Concept and Technology Roadmap.* 2015.

Frequency Reuse-1 Model

- Orthogonal Frequency Division Multiple Access (OFDMA)
- Frequency reuse-1 model is used
  - Improve network capacity
  - Combat spectrum scarcity
  - Inter-cell interference problems



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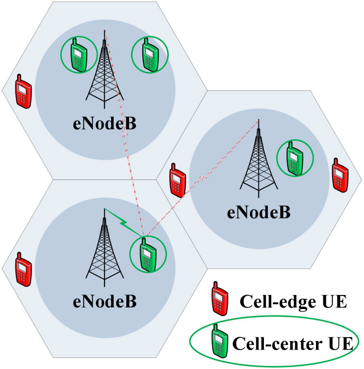

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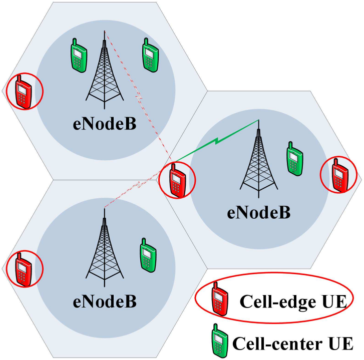

Inter-Cell Interference Coordination (ICIC)

- Negative impact of interference on system performance
- Multi-cell radio resource management function[4]
    - Reduce inter-cell interference
    - Alleviate throughput degradation
- 3GPP allows non-standardized ICIC techniques

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[4] 3GPP. *E-UTRAN Overall Description, Stage 2.* Technical Specification. 3GPP TS 36.300, 2012.

Classes of ICIC Techniques

Cooperation	Centralized
	Decentralized
	Hybrid
Objective	Throughput maximization
	Power minimization
	Satisfaction maximization
Mathematical tools	Convex optimization
	Graph theory
	Game theory
Technology	LTE/LTE-A networks
	Cloud-RAN

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Overview

Frequency Reuse Techniques[5]

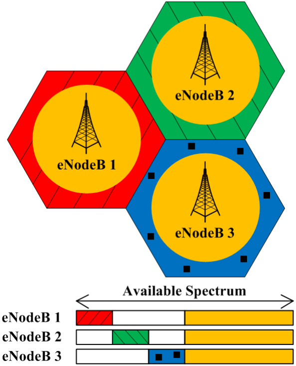

Figure 1: Fractional Frequency Reuse (FFR)

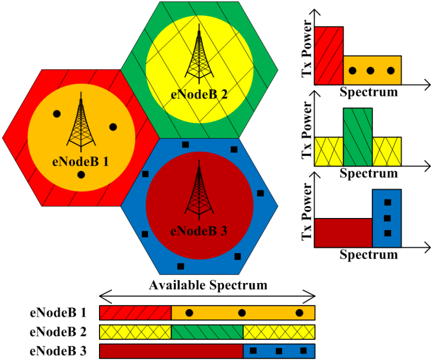

Figure 2: Soft Frequency Reuse (SFR)

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[5] M. Yassin et al. "Survey of ICIC Techniques in LTE Networks under Various Mobile Environment Parameters". In: *Springer Wireless Networks* (accepted for publication, 2015).

Simulation Parameters

- LTE downlink system level simulator[6]
- Seven LTE cells with 10 UEs per cell
- Random UE positions and radio conditions
- UE Classification
    - Good Radio (GR) UEs
    - Bad Radio (BR) UEs

Parameter	**Value**
Inter-eNodeB distance	500 m
Bandwidth	5 MHz
Resource Blocks (RBs)	25
Scheduler	Round Robin
Traffic model	Full buffer

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[6] J.C. Ikuno, M. Wrulich, and M. Rupp. “System Level Simulation of LTE Networks”. In: *IEEE* 71st *Vehicular Technology Conf.* Taipei, 2010, pp. 1–5.

Mean Throughput per Zone

- Mean throughput is calculated for 100 simulation runs

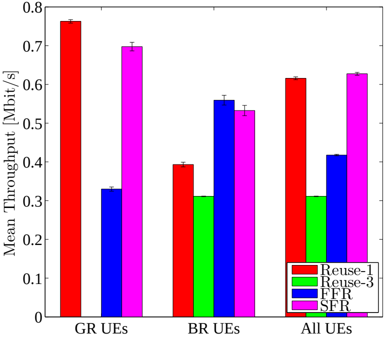

Figure 3: Mean throughput per GR, BR, and all UEs[7]

- The frequency reuse-3 model shows the lowest throughput
- SFR improves BR UEs throughput and mean UE throughput

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[7] M. AboulHassan et al. "Classification and Comparative Analysis of Inter-Cell Interference Coordination Techniques in LTE Networks". In: 7th *IFIP Int. Conf. New Technologies, Mobility, and Security*. Paris, 2015.

Throughput Cumulative Distribution Function

- $CDF(x) = P(X < x)$

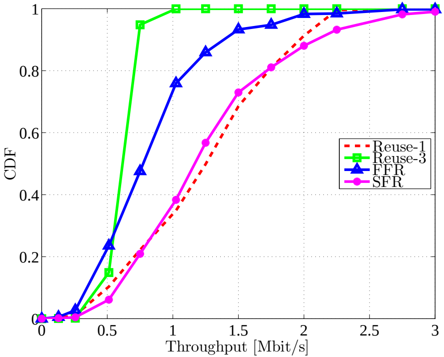

Figure 4: Throughput cumulative distribution function

- Reuse-3 CDF curve is the first to reach its maximum
- Throughput CDF is improved when using SFR

UE Satisfaction

- If R_k is less than 512 kbit/s $\Rightarrow$ UE k is unsatisfied

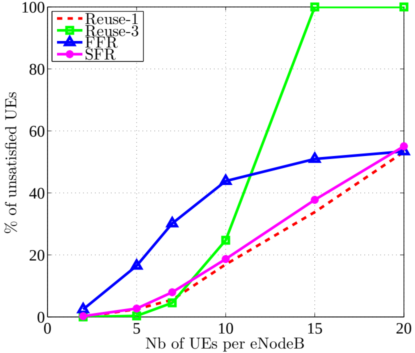

Figure 5: UE satisfaction versus network load

- Reuse-3 improves UE satisfaction for low network loads
- UE satisfaction is reduced when network load increases

Spectral Efficiency

- Spectral efficiency is evaluated for various UE distributions

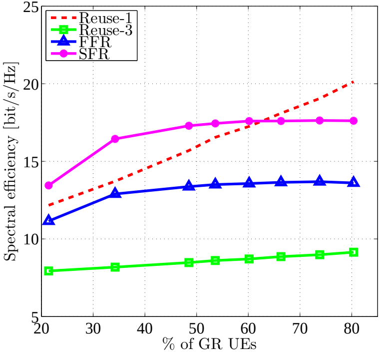

Figure 6: Spectral efficiency versus percentage of GR UEs

- Reuse-3 shows the lowest spectral efficiency
- SFR improves spectral efficiency for less than 60% GR UEs

Limitations of Static ICIC Techniques

- Spectrum underutilization
- Non-uniform UE distributions
- UE throughput demands
- Throughput fairness

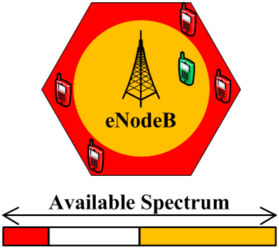

Figure 7: FFR limitations

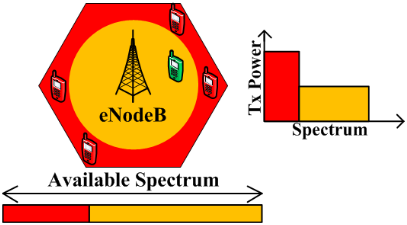

Figure 8: SFR limitations

Overview

Multi-Cell Resource and Power Allocation

- State-of-the-art contributions on resource and power allocation
  - Formulate a single cell problem
  - Neglect inter-cell interference
  - Do not guarantee throughput fairness
  - Introduce suboptimal approaches
- Centralized joint resource and power allocation
  - Formulate a multi-cell problem
  - Address inter-cell interference
  - Guarantee throughput fairness
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Optimization Variables and Objective Function

- Optimization variables:
  - $\pi_{i,n}$: transmit power of cell i on RB n
  - $\theta_{k,n}$: percentage of time UE k is associated with RB n
- Signal to Interference and Noise Ratio (SINR):

$$\sigma_{k,i,n} = \frac{\pi_{i,n} G_{k,i,n}}{N_0 + \sum_{i' \neq i} \pi_{i',n} G_{k,i',n}} \quad (1)$$

- Peak rate of UE k associated with RB n on cell i:

$$\rho_{k,i,n} = \log\left(1 + \sigma_{k,i,n}\right) \quad (2)$$

- Objective function:

$$\eta = \sum_{i \in \mathcal{I}} \sum_{k \in \mathcal{K}(i)} \log\left(\sum_{n \in \mathcal{N}} \theta_{k,n} . \log\left(1 + \sigma_{k,i,n}\right) \right) \quad (3)$$

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Proportional fairness

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Rate of UE k

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Problem Decomposition

Joint resource and power allocation

$$\underset{\boldsymbol{\theta},\boldsymbol{\pi}}{\text{maximize}}\ \eta = \sum_{i\in\mathcal{I}} \sum_{k\in\mathcal{K}(i)} \log\left(\sum_{n\in\mathcal{N}} \theta_{k,n}.\rho_{k,i,n}\right)$$

Centralized power allocation

$$\eta_1 = \sum_{i\in\mathcal{I}} \sum_{k\in\mathcal{K}(i)} \sum_{n\in\mathcal{N}} \log\left(\rho_{k,i,n}\right)$$

Per cell resource allocation

$$(\eta_2)_i = \sum_{k\in\mathcal{K}(i)} \sum_{n\in\mathcal{N}} \log(\theta_{k,n})$$

Convex optimization problem

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- Optimal solution to the resource and power allocation problem

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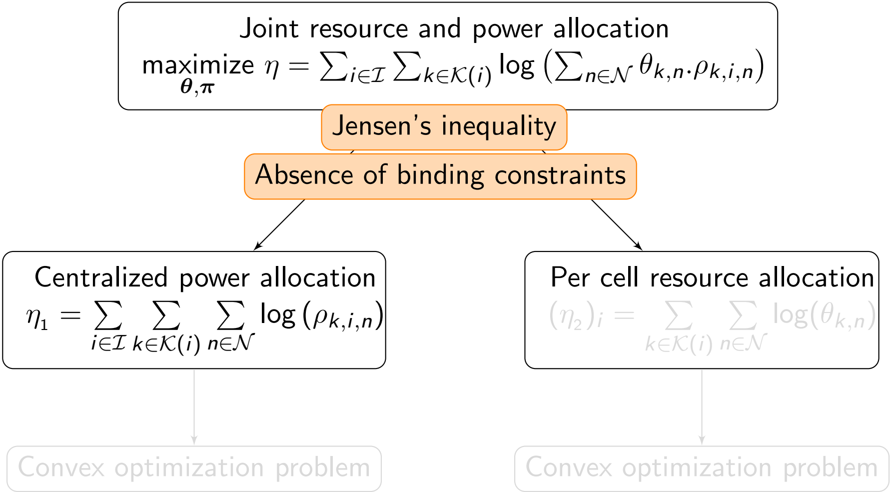

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Jensen's inequality

Absence of binding constraints

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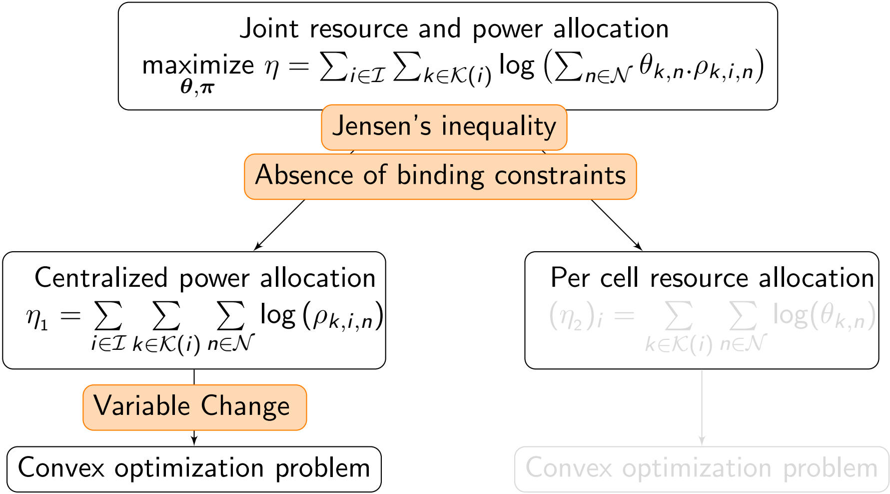

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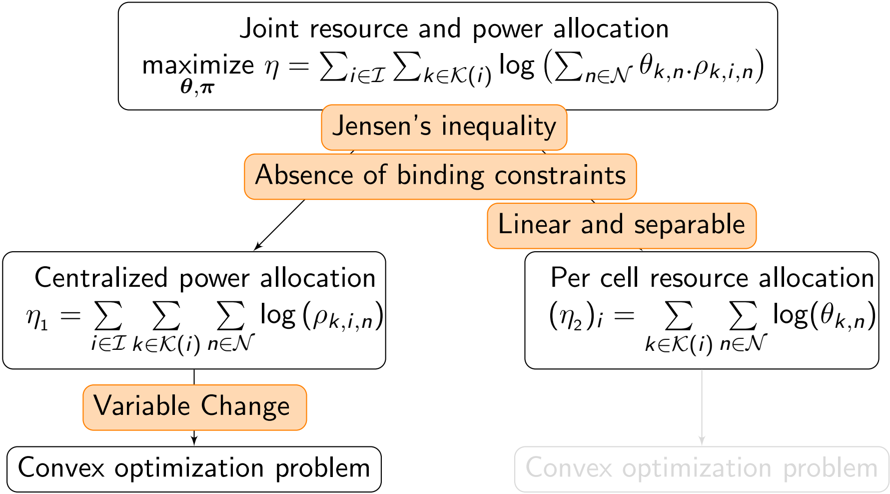

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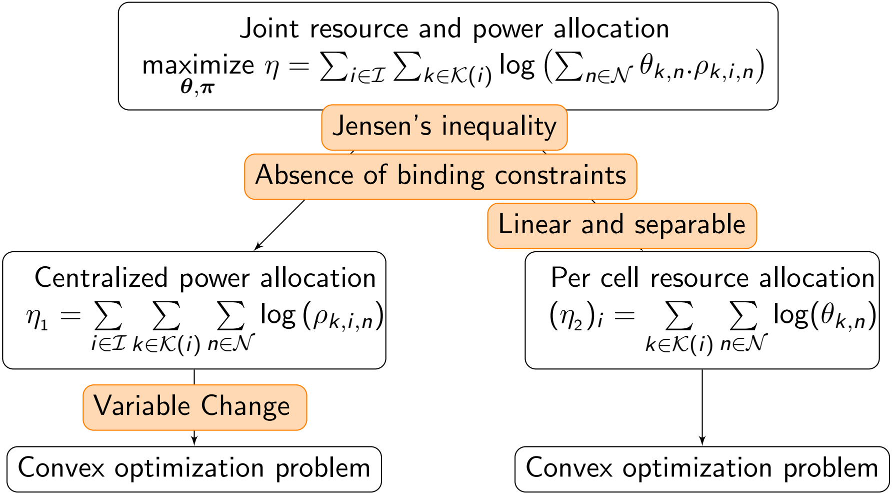

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Centralized Power Allocation Problem

- Variable change:

$$\widehat{\pi}_{i,n} = \log(\pi_{i,n}),\ \forall\, i \in \mathcal{I}, \forall\, n \in \mathcal{N}. \tag{4}$$

- Solved using Lagrange duality properties[8]
  - Constraints are transferred to the objective
  - Primal and dual optimization problems
- Primal iterations of the subgradient projection method:

$$\widehat{\pi}_{i,n}(t+1) = \widehat{\pi}_{i,n}(t) + \delta(t) \times \frac{\partial L}{\partial \widehat{\pi}_{i,n}}, \forall i \in \mathcal{I}, \forall n \in \mathcal{N} \tag{5}$$

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[8] M. Yassin et al. "Centralized Multi-Cell Resource and Power Allocation for Multiuser OFDMA Networks". In: *Submitted for publication in IFIP Networking Conf.* Vienna, 2016.

Centralized Power Allocation Algorithm

```
1: Initialization: set $t = t_{primal} = t_{dual} = 0$, and $\pi_{i,n}(0) \geq \pi_{min}$.
2: Set $\lambda_{k,i,n}(0)$ and $\nu_i(0) \geq 0$
3: $(\widehat{\boldsymbol{\pi}}^\star(t+1), \widehat{\boldsymbol{\rho}}^\star(t+1)) \leftarrow \textsc{PrimalProblem}(\boldsymbol{\nu}^\star(t), \boldsymbol{\lambda}^\star(t))$
4: $(\boldsymbol{\nu}^\star(t+1), \boldsymbol{\lambda}^\star(t+1)) \leftarrow \textsc{DualProblem}(\widehat{\boldsymbol{\pi}}^\star(t+1), \widehat{\boldsymbol{\rho}}^\star(t+1))$
5: if $(\Delta\widehat{\boldsymbol{\pi}}^\star(t+1) > \epsilon)$ or $(\Delta\widehat{\boldsymbol{\rho}}^\star(t+1) > \epsilon)$ or $(\Delta\boldsymbol{\nu}^\star(t+1) > \epsilon)$
   or $(\Delta\boldsymbol{\lambda}^\star(t+1) > \epsilon)$ then
6:     $t \leftarrow t+1$
7:     go to 3
8: end if
```

Centralized Power Allocation Algorithm

Primal variables: $\widehat{\boldsymbol{\pi}}, \widehat{\boldsymbol{\rho}}$
Dual variables: $\boldsymbol{\nu}, \boldsymbol{\lambda}$

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Centralized Power Allocation Convergence

- Convergence of the primal variables $\widehat{\pi}_{i,1}$

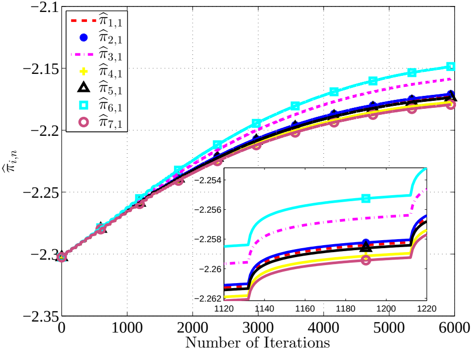

Figure 9: Convergence of the primal variables $\widehat{\pi}_{i,n}$

- Optimal solution to the power allocation problem

Solution to the Resource Allocation Problem

Theorem

The optimal solution to the resource allocation problem in cell i is:
$\theta^{\star}_{k,n} = \frac{1}{\max(|\mathcal{K}(i)|,|\mathcal{N}|)}, \forall k \in \mathcal{K}(i), \forall n \in \mathcal{N},$
$|\mathcal{K}(i)|$: number of active UEs in cell i,
$|\mathcal{N}|$: number of available RBs in cell i.

Example: $|\mathcal{K}(i)| < |\mathcal{N}| \Rightarrow \theta^{\star}_{k,n} = \frac{1}{|\mathcal{N}|}$.

Decentralized Power Allocation

- Multi-player game where the players are the cells
- Utility function U_i for cell i:

$$U_i = \sum_{k \in \mathcal{K}(i)} \sum_{n \in \mathcal{N}} \log\left(\log\left(1 + \sigma_{k,i,n}\right)\right)$$

- A Nash Equilibrium (NE) exists
- Subgradient projection method

Decentralized Power Allocation

Centralized power allocation:

$$\eta_1 = \sum_{i \in \mathcal{I}} \sum_{k \in \mathcal{K}(i)} \sum_{n \in \mathcal{N}} \log\left(\log\left(1 + \sigma_{k,i,n}\right)\right)$$

- Multi-player game where the players are the cells
- Utility function U_i for cell i:

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- A Nash Equilibrium (NE) exists
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Decentralized Power Allocation Convergence[9]

- Optimization variables: $\pi_{i,n}$
- Cluster of seven adjacent cells

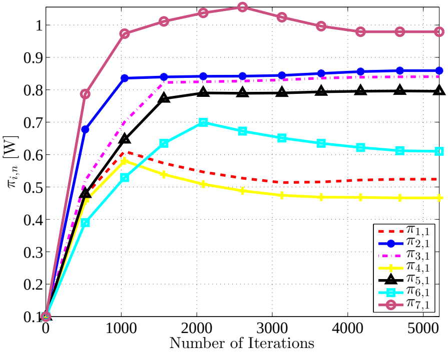

Figure 10: Optimization variables $\pi_{i,1}$

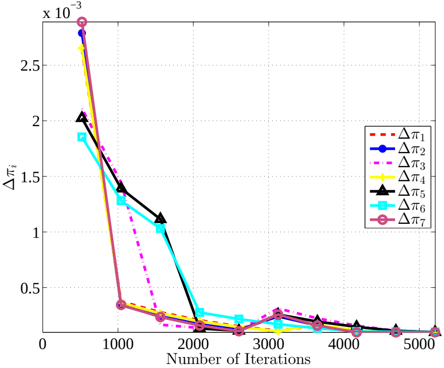

Figure 11: $\Delta\pi_i$ versus number of iterations

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[9] M. Yassin et al. "Centralized versus Decentralized Multi-Cell Resource and Power Allocation for Multiuser OFDMA Networks". In: *Submitted for publication in IEEE Trans. Wireless Commun.* (2015).

Comparison with State-of-the-Art Approaches

- Compared techniques:
    - Reuse-1, reuse-3, FFR, SFR, centralized, and decentralized

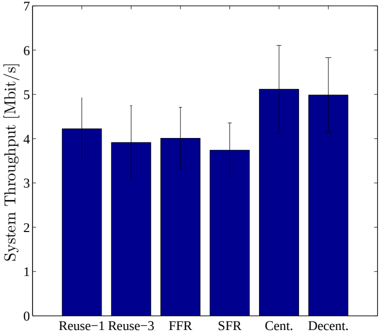


Figure 12: System throughput comparison

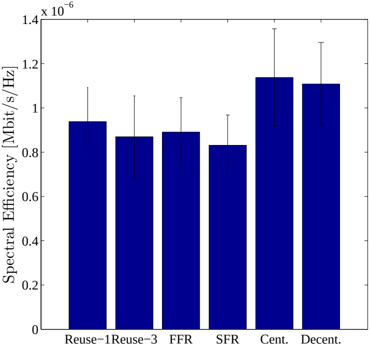


Figure 13: Spectral efficiency comparison

- The centralized power allocation outperforms the other approaches
- Centralized approach ⇒ high processing load and high complexity

Overview

1 Introduction

2 ICIC Techniques Comparison

3 Centralized versus Decentralized ICIC

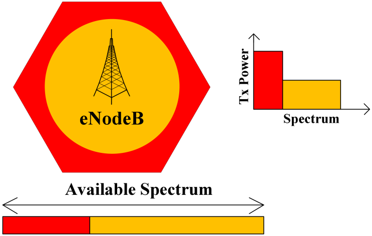
4 Autonomous ICIC

5 Cooperative ICIC

6 Conclusion

Autonomous Dynamic ICIC

- Self-organized networks ⇒ less signaling messages
- Overcome the limitations of static ICIC techniques
  - Adjust resource allocation between cell zones[10]
  - No additional signaling load is generated
- Initial resource and power allocation:



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[10] M. Yassin et al. "Non-Cooperative Inter-Cell Interference Coordination Technique for Increasing Throughput Fairness in LTE Networks". In: *IEEE* 81*st* *Vehicular Technology Conf.* Glasgow, 2015.

Autonomous Dynamic ICIC

- Self-organized networks ⇒ less signaling messages
- Overcome the limitations of static ICIC techniques
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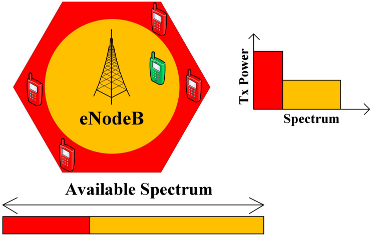
  - No additional signaling load is generated
- When BR UEs are unsatisfied:



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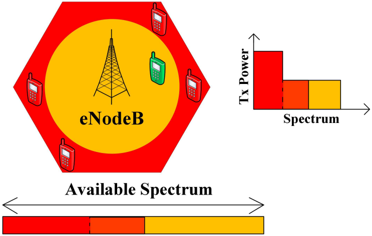

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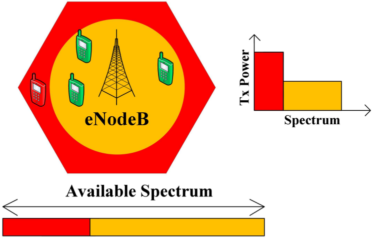

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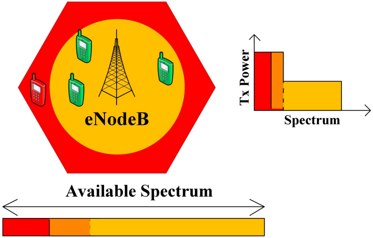

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[10] M. Yassin et al. "Non-Cooperative Inter-Cell Interference Coordination Technique for Increasing Throughput Fairness in LTE Networks". In: *IEEE 81st Vehicular Technology Conf.* Glasgow, 2015.

Autonomous ICIC Algorithm

```
Allocate RBs and power according to SFR
Every $T$ TTIs:
if ($\overline{R}_{GR} - \overline{R}_{BR} > \Delta_{th}$) then
    Borrow the RB with the highest CQI from GR to BR zone
else if ($\overline{R}_{BR} - \overline{R}_{GR} > \Delta_{th}$) then
    Borrow the RB with the lowest CQI from BR to GR zone
else
    Keep the same RB distribution
end if
```

Throughput Cumulative Distribution Function

- Seven adjacent cells with 10 active UEs per cell

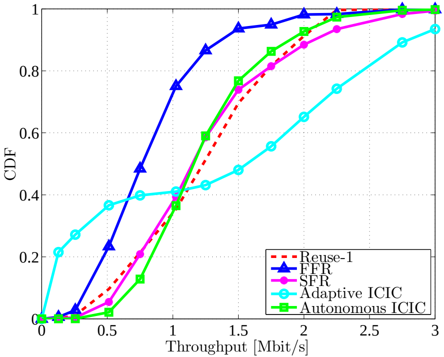

Figure 14: Throughput cumulative distribution function

- Negative impact of single cell resource and power allocation[11]
- Autonomous ICIC: lowest CDF for throughput less than 1 Mbit/s

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[11] T.Q.S. Quek, Zhongding Lei, and Sumei Sun. "Adaptive Interference Coordination in Multi-Cell OFDMA Systems". In: *IEEE 20th Int. Symp. Personal, Indoor and Mobile Radio Communications*. 2009.

Fairness Index

- Jain's fairness index:
  - $J(R_1, ..., R_K) = \frac{(\sum_{k=1}^{K} R_k)^2}{K.\sum_{k=1}^{K} R_k^2}$

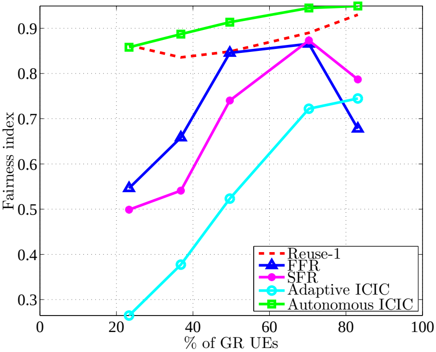

Figure 15: Fairness index versus UE distribution

- FFR and SFR performance depends on UE distribution
- Autonomous ICIC shows the highest fairness index

Fairness Index

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$$\boxed{\frac{1}{K} \leq J(R_1, ..., R_K) \leq 1}$$

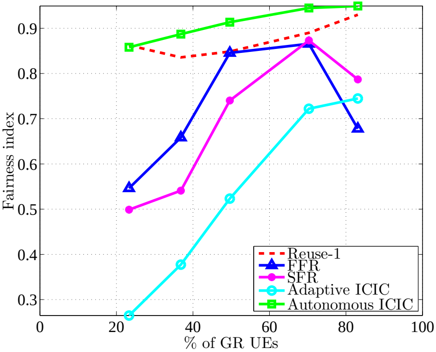

Figure 15: Fairness index versus UE distribution

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Overview

Cooperative Resource and Power Allocation

- X2 interface interconnects adjacent cells
- Signaling messages concerning resource usage
- Compromise between centralized and decentralized approaches

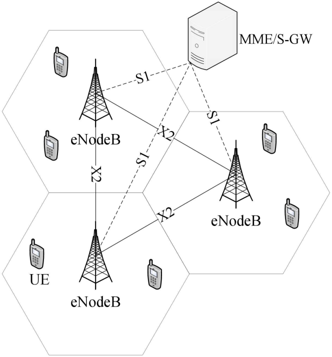
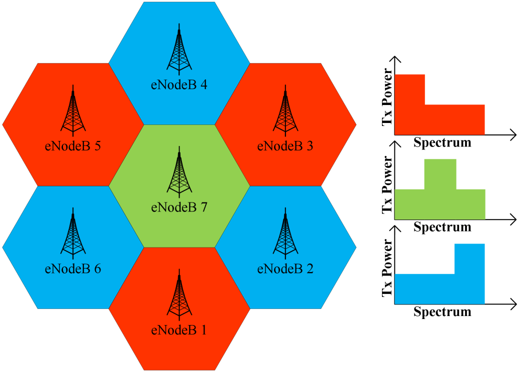


Figure 16: LTE/LTE-A system architecture

Cooperative ICIC

- First phase (collaborative)
  - Request information about neighbors satisfaction
  - Send *Stop* messages to the neighbors
  - Adjust power allocation if needed
  - Send *Release* messages to the neighbors
- Second phase (autonomous)
  - Locally adjust resource allocation between cell zones



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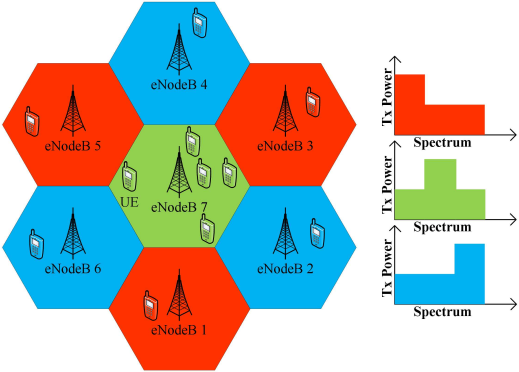

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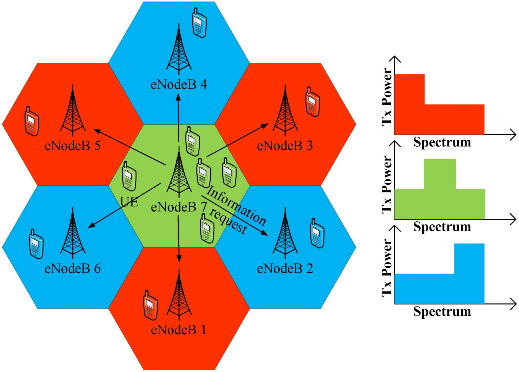

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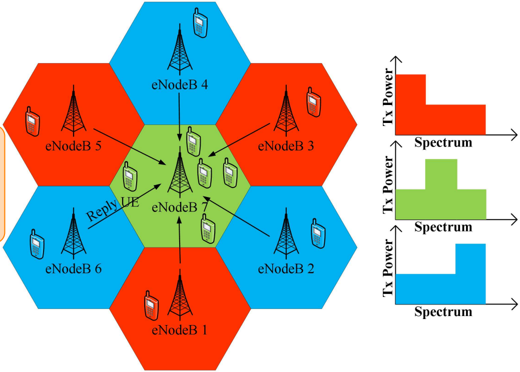
Reply message:
Power allocation
UE throughput



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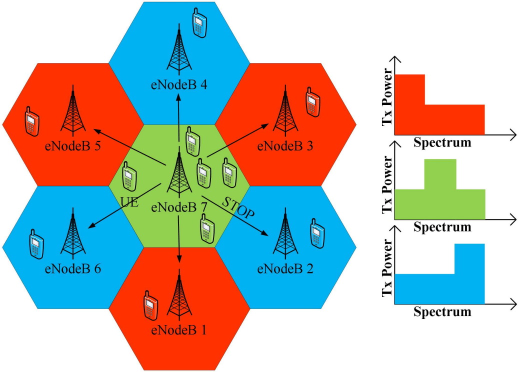

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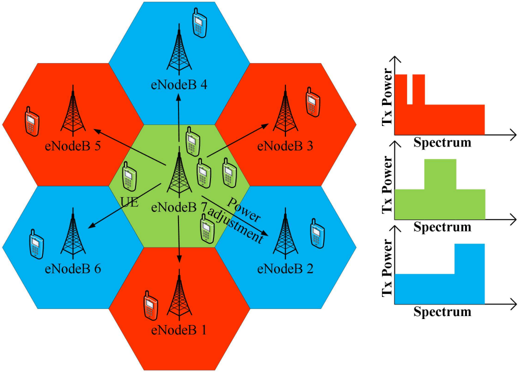

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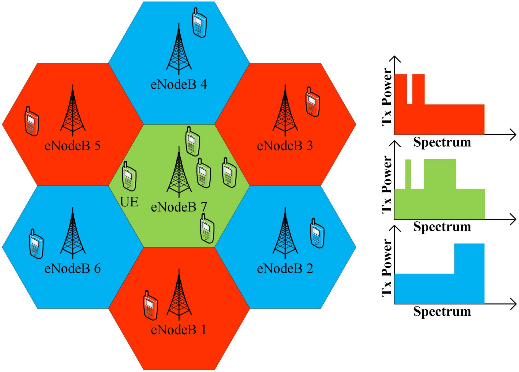

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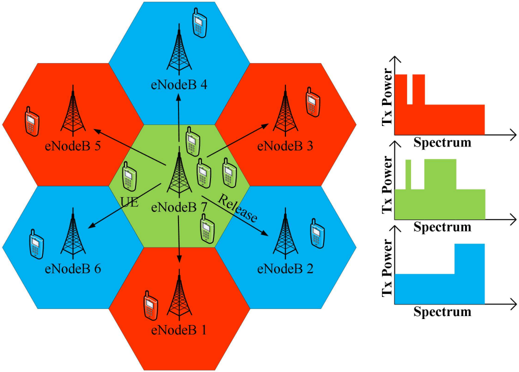

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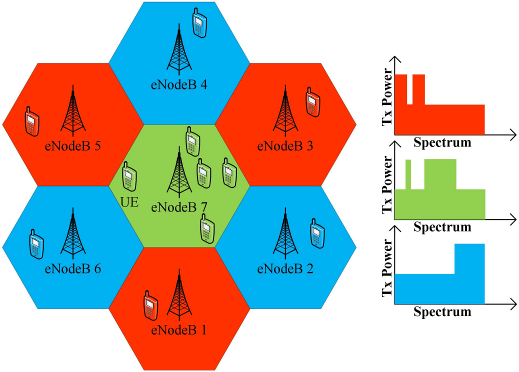

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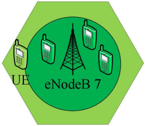

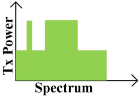

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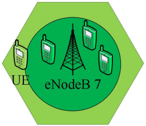

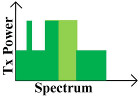

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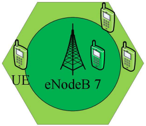

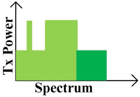

UE Satisfaction

- Satisfaction function: $S_k(t) = 1 - \exp(-\frac{R_k(t)}{R_S})$

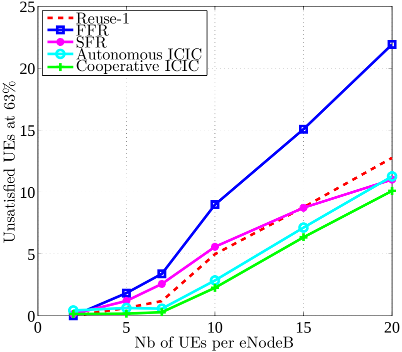

Figure 17: UE satisfaction versus network load

- Percentage of unsatisfied UEs increases with network load
- Cooperative ICIC: lowest percentage of unsatisfied UEs

Energy Efficiency

- Crucial need for green networks

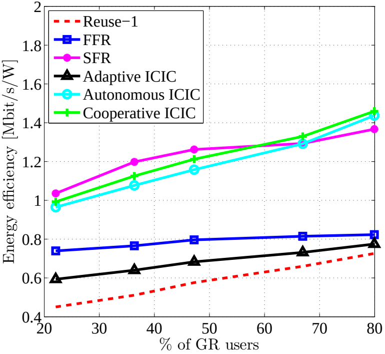

Figure 18: Energy efficiency versus UE distribution

- Performance comparable to SFR and autonomous ICIC

Overview

Summary

- Resource and power allocation in wireless networks
- Dense cellular networks with aggressive frequency reuse ⇒ ICI
- Overview and classification of ICIC techniques
  - Cooperation, objectives, tools, technology
  - Quantitative comparisons
- Centralized multi-cell joint resource and power allocation
- Decentralized power allocation based on game theory
- Autonomous and cooperative ICIC techniques
- System level simulations and comparisons

Summary

- Centralized versus decentralized ICIC
  - Centralized: optimal solution, high processing load, high complexity
  - Decentralized: near-optimal solution and lower complexity
- Autonomous ICIC techniques
  - Efficient for self-organizing networks
  - Do not generate additional signaling messages
  - Improve static ICIC techniques performance
- Cooperative ICIC techniques
  - Compromise between centralized and decentralized approaches
  - Make use of the signaling messages between adjacent cells

Short-Term Perspectives

- Interference-aware heterogeneous wireless networks
  - Co-tier interference
  - Cross-tier interference
- Enhanced ICIC for downlink/uplink imbalance problems
  - Downlink/uplink decoupling
  - Handover more UEs to the small cells

Long-Term Perspectives

- Compromise between spectral efficiency and energy efficiency
  - Cannot be maximized simultaneously
  - Crucial need for future green networks
- Practical implementation of ICIC algorithms
  - Limitations: latency, processing time, reliability
  - Functionality split between access and core networks