On the Principles of Multicell Precoding with Centralized and Distributed Cooperation

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Content

- Multicell Precoding
  - Users served by multiple base stations
  - Goal: Control interference with full frequency reuse
  - Also known as:

    Network MIMO,

    Coordinated Multipoint transmission (CoMP)
- Different Types of Cooperation
  - Fully and partially centralized schemes
  - Fully distributed schemes
- Conclude on General Design Principles

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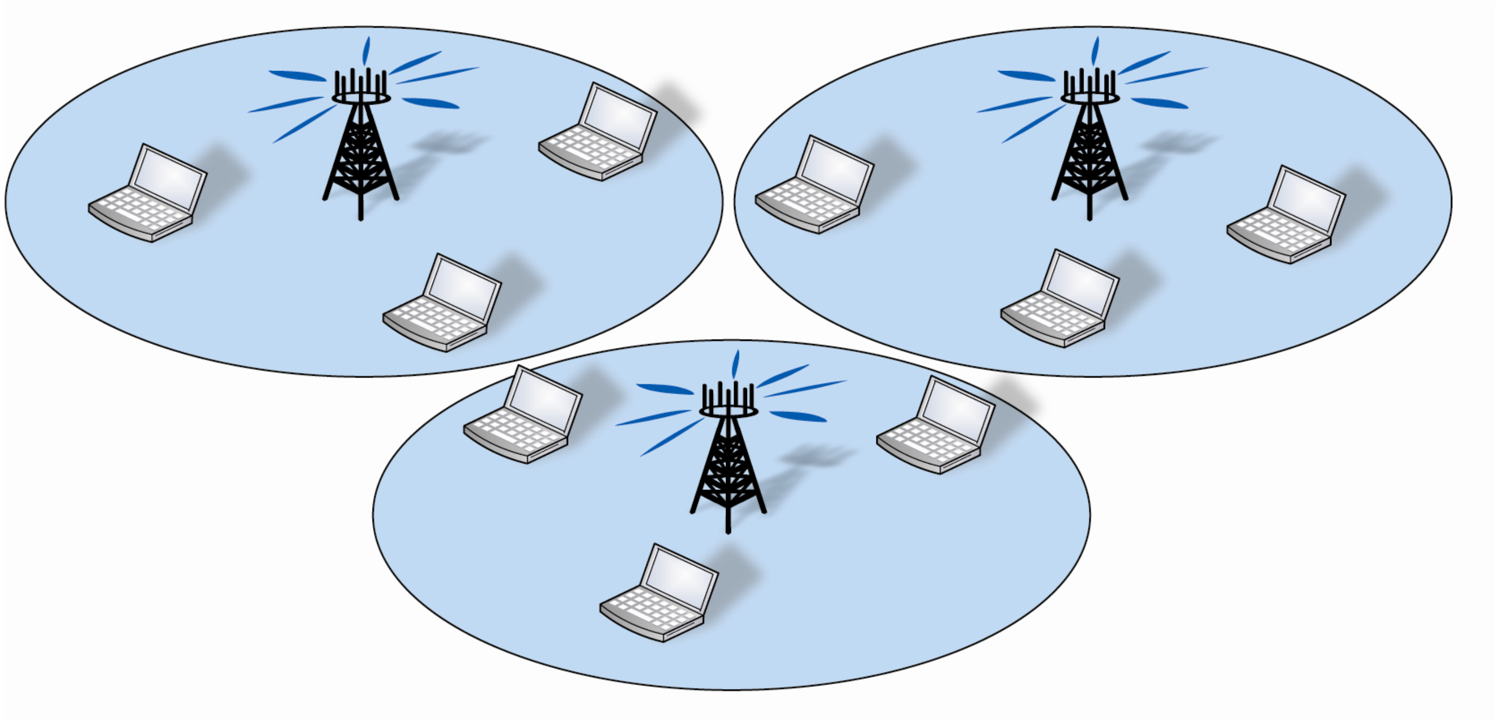
Intro: Multicell Downlink



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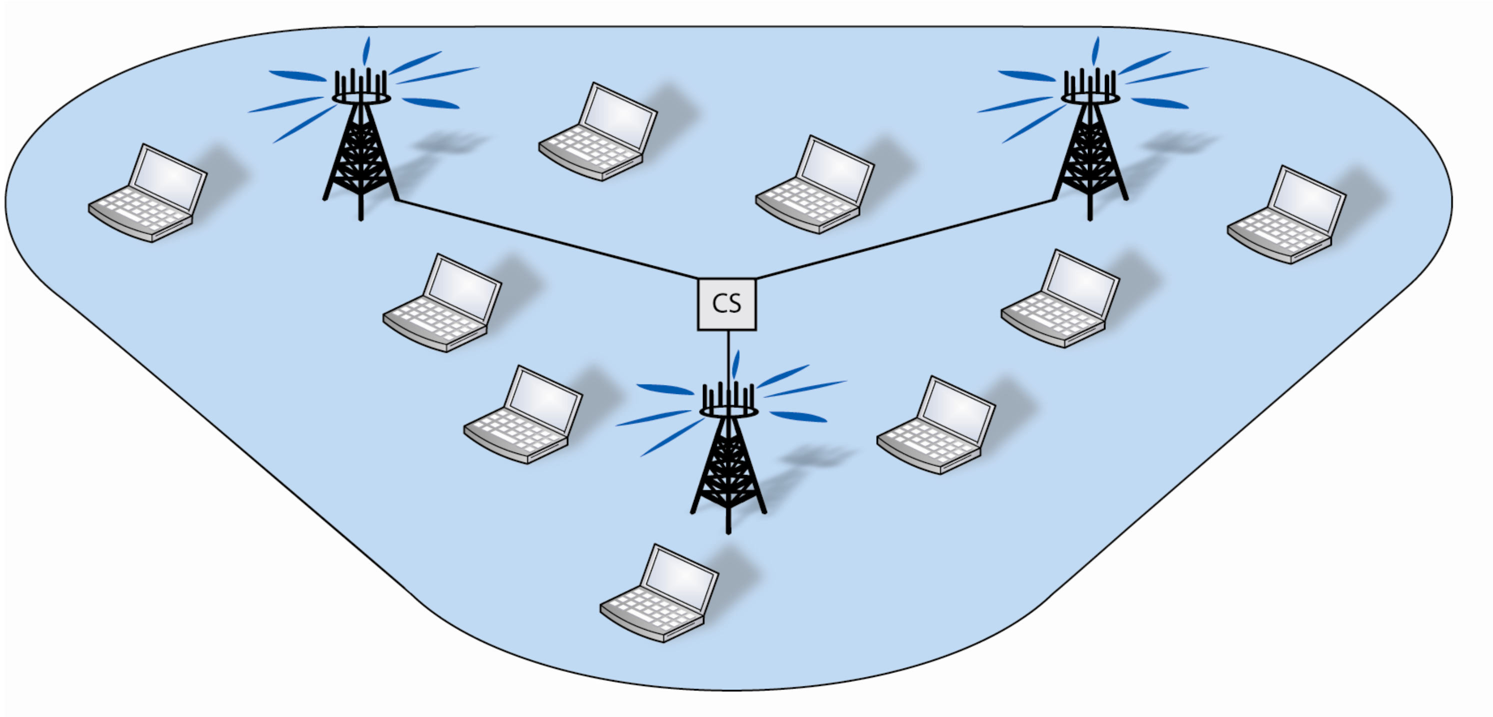
- Non-Cooperative Solution
  - Conventional single cell processing
  - Interference at cell edge users uncontrollable
  - Can be improved by coordinating interference (improves sum rate and fairness)

Intro: Multicell Downlink



- Fully Cooperative Solution
  - Backhaul network and central station (CS)
  - Centralized processing as "one cell"
  - Capacity in [Yu06], [Weingarten06]
    (MIMO broadcast, special power constraints)

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System Model

- K_t multi-antenna base stations
- K_r single-antenna user terminals
- $\mathbf{h}_{jk}$ channel vector from BS_j to MS_k
- Backhaul network
  - Data sharing
  - CSI sharing
  - Synchronization
- Central station (CS)
  - Centralized computations and decisions

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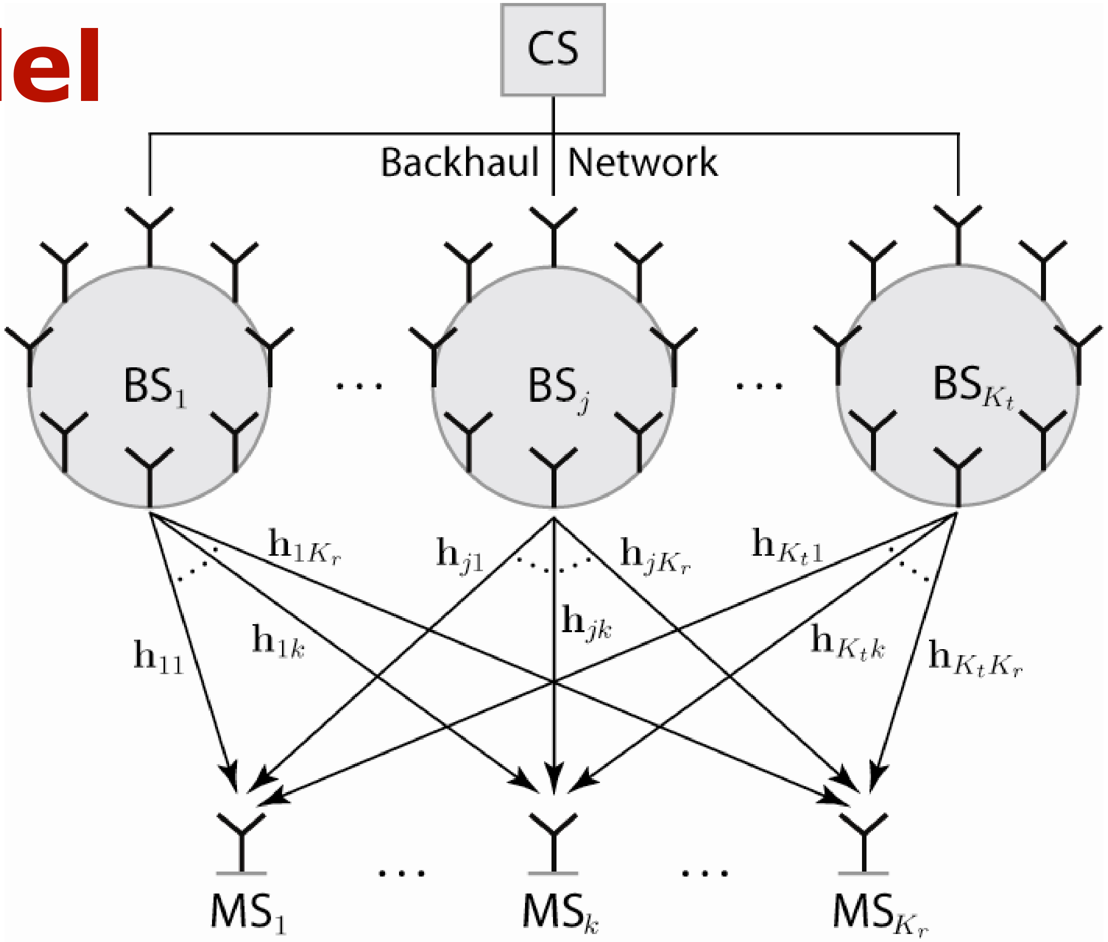

Receive-side CSI	Transmit-side CSI
Exact value of $\mathbf{h}_{jk}$ for all j (all BSs)	$\mathbf{h}_{jk} \in \mathcal{CN}(\bar{\mathbf{h}}_{jk}, \mathbf{Q}_{jk})$ for all k (all MSs)
Noise power σ^2	Noise power σ^2

Why Rician CSI?

- With Rician transmit-side CSI

$$\mathbf{h}_{jk} \in \mathcal{CN}(\bar{\mathbf{h}}_{jk}, \mathbf{Q}_{jk})$$

we can jointly analyze:

1. **Perfect Instantaneous CSI**

   $\mathbf{h}_{jk} = \bar{\mathbf{h}}_{jk}$ and $\mathbf{Q}_{jk} = \mathbf{0}$

2. **Estimated CSI (e.g., in TDD)**

   Estimate: $\bar{\mathbf{h}}_{jk}$

   Error covariance: $\mathbf{Q}_{jk}$

3. **Statistical CSI**

   Rician fading $(\bar{\mathbf{h}}_{jk} \neq \mathbf{0})$

   Rayleigh fading $(\bar{\mathbf{h}}_{jk} = \mathbf{0})$

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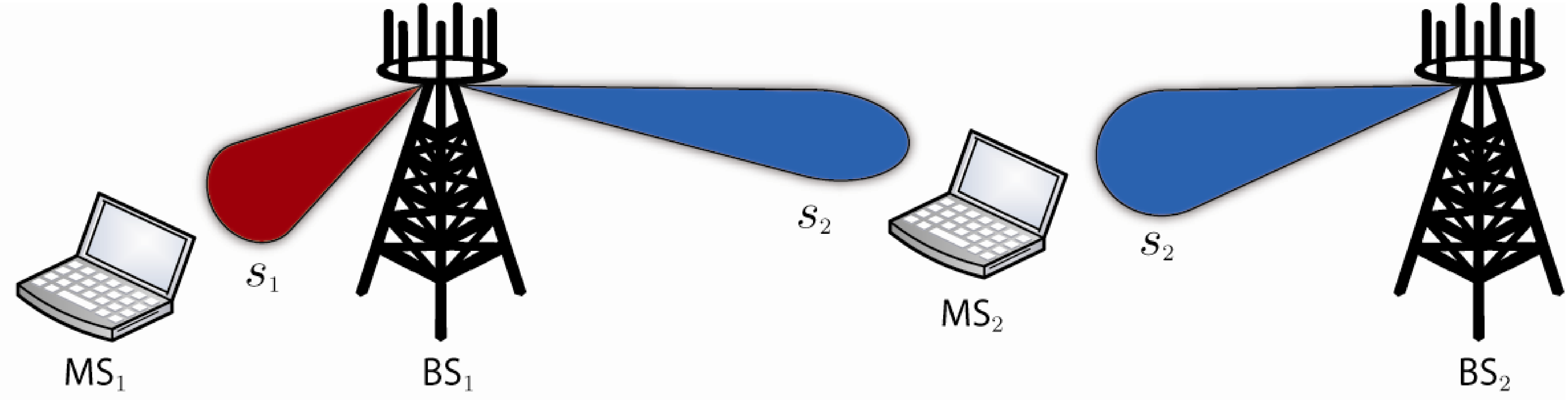
Multicell Precoding

- Symbol $s_k \in \mathcal{CN}(0,1)$ intended for MS_k
  - Available at all transmitters
  - Enables cooperative multicell precoding
- Signal from BS_j: $\mathbf{x}_j = \sum_{k=1}^{K_r} \boxed{\sqrt{p_{jk}}}\,\boxed{\mathbf{w}_{jk}}\, s_k$

Power allocation
$\sum_{k=1}^{K_r} p_{jk} \leq P_j$

Beamformer
(unit norm)



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Multicell Precoding

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Beamformer (unit norm)

- SINR at MS$_k$:

$$\mathrm{SINR}_k = \frac{\left|\sum_{j=1}^{K_t} \sqrt{p_{jk}}\mathbf{h}_{jk}^H \mathbf{w}_{jk}\right|^2}{\sum_{\substack{\bar{k}=1\\ \bar{k}\neq k}}^{K_r} \left|\sum_{j=1}^{K_t} \sqrt{p_{j\bar{k}}}\mathbf{h}_{jk}^H \mathbf{w}_{j\bar{k}}\right|^2 + \sigma^2}$$

(perfect synchronization)

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Centralized Precoding

- Performance Measure

$$\max_{\substack{\{\mathbf{w}_{jk}\in\mathbb{C}^{N_t}\ \forall j,k;\ \|\mathbf{w}_{jk}\|=1\} \\ \{p_{jk}\geq 0\ \forall j,k;\ \sum_{k=1}^{K_r} p_{jk}\leq P_j\}}} \underbrace{\sum_{k=1}^{K_r} \mathbb{E}\{\log_2(1+\mathsf{SINR}_k)\}}_{\text{Expected Sum Rate}}$$

  - Requires all transmitter's CSI
  - Gathered at CS through backhaul
  - Precoding optimization at CS

- How to Evaluate Expected Sum Rate?

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Centralized Precoding (2)

- **Theorem 1:** Expected sum rate is

$$\sum_{k=1}^{K_r} \mathbb{E}\{\log_2(1+\mathsf{SINR}_k)\} = \sum_{k=1}^{K_r} g(\bar{\mathbf{v}}_k, \mathbf{\Lambda}_k, \sigma^2) - g(\tilde{\bar{\mathbf{v}}}_k, \tilde{\mathbf{\Lambda}}_k, \sigma^2)$$

where

$$g(\bar{\mathbf{v}}, \mathbf{\Lambda}, \sigma^2) = \frac{e^{-\bar{\mathbf{v}}^H \mathbf{\Lambda}^{-1} \bar{\mathbf{v}}}}{\log(2)} \sum_{i=1}^{N} \frac{e^{\sigma^2/\lambda_i}}{\prod_{j \neq i} \left(1 - \frac{\lambda_j}{\lambda_i}\right)} \sum_{m=0}^{\infty} d_i[m]$$

$$\times \sum_{k=0}^{\infty} \frac{\left(\frac{|v_i|^2}{\lambda_i}\right)^k}{(m+k)!} \sum_{j=0}^{k} \frac{\left(-\frac{\sigma^2}{\lambda_i}\right)^j}{j!} \sum_{l=0}^{k-j} \frac{\Gamma(l, \frac{\sigma^2}{\lambda_i})}{\Gamma(l+1)}.$$

for certain vectors/matrices depending on channel statistics and precoding.

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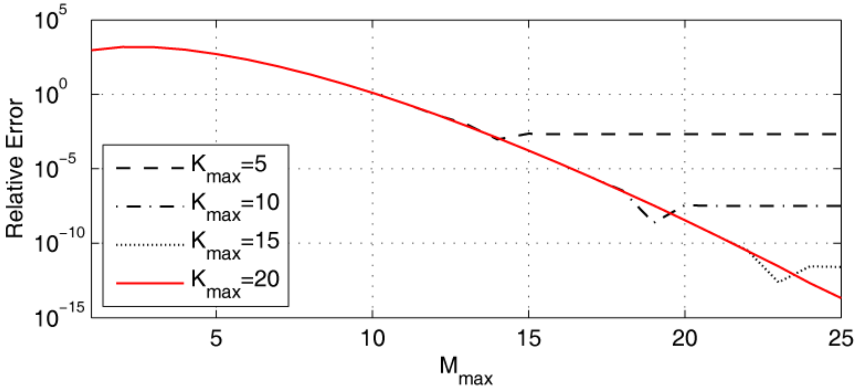
Centralized Precoding (3)

- Difficulties with the Expression:
  - Infinite summations: Easily truncated!



  - Non-convex: Finding optimum not guaranteed
  - Computational demanding

- Special CSI Cases:
  - Perfect instantaneous: SINR is non-stochastic
  - Rayleigh fading: Simpler expression in [Björnson10]

Still non-convex in both cases!

Centralized Precoding (4)

- Pros:
  - We might achieve the best performance
- Cons:
  - Computational demanding optimization
  - Centralized: Delays and much backhaul signalling
  - Difficult scalability in K_t, K_r

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Partially Centralized Precoding

- Most Demanding Optimization Part?
  - Power allocation rather simple and insensitive
  - Beamforming is multidimensional and sensitive
- Reduce Complexity by Heuristic Beamforming
  - Zero-forcing in [Karakayali06], [Kobayashi09]
  - We generalize it to Rician conditions
- Power Allocation Optimization
  - Numerical search for sum rate maximization
  - Iterative outage minimization in [Kobayashi09]

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Partially Centralized (2)

- Pros:
  - Zero-forcing vectors can be evaluated locally
  - Centralized power allocation can be combined with scheduling decisions
- Cons:
  - Sub-optimal performance
  - Zero-forcing requires high SNR, small uncertainty
  - Still delay limitations and backhaul demands

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Fully Distributed Precoding

- Local Precoding with Only Local CSI
  - Only heuristic solutions possible

- Proposal: Maximize virtual SINR

Average Signal Power

$$\mathbf{w}_{jk} = \underset{\|\mathbf{w}\|=1}{\arg\max} \frac{\boxed{\mathbb{E}\{|\mathbf{h}_{jk}^H \mathbf{w}|^2\}}}{\frac{\sigma^2}{p_{jk}} + \boxed{\sum_{\bar{k}\neq k} \mathbb{E}\{|\mathbf{h}_{j\bar{k}}^H \mathbf{w}|^2\}}}$$

Average Interference at other users

  - Solved as Rayleigh quotient, using
    $$\mathbb{E}\{|\mathbf{h}_{j\bar{k}}^H \mathbf{w}|^2\} = \mathbf{w}^H(\mathbf{Q}_{j\bar{k}} + \bar{\mathbf{h}}_{j\bar{k}}\bar{\mathbf{h}}_{j\bar{k}}^H)\mathbf{w}$$
  - Used for interference channels in [Zakhour09]
  - Used in non-Rician case in [Zakhour10], [Björnson10]

Fully Distributed Precoding (2)

- Heuristic Power Allocation
  - More power allocated to strong users

- Proposal: Based on percentage of total gain

$$p_{jk} = \frac{\mathrm{tr}\{\mathbf{Q}_{jk} + \bar{\mathbf{h}}_{jk}\bar{\mathbf{h}}_{jk}^H\}}{\sum_{\bar{k}=1}^{K_r} \mathrm{tr}\{\mathbf{Q}_{j\bar{k}} + \bar{\mathbf{h}}_{j\bar{k}}\bar{\mathbf{h}}_{j\bar{k}}^H\}} P_j$$

  - More advanced power allocation in [Björnson10]
  - Small performance difference

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Fully Distributed Precoding (3)

- Pros:
  - Limited computational demands
  - Limited use of backhaul
  - Scalable to large networks (with some scheduling)
- Cons:
  - Sub-optimal performance

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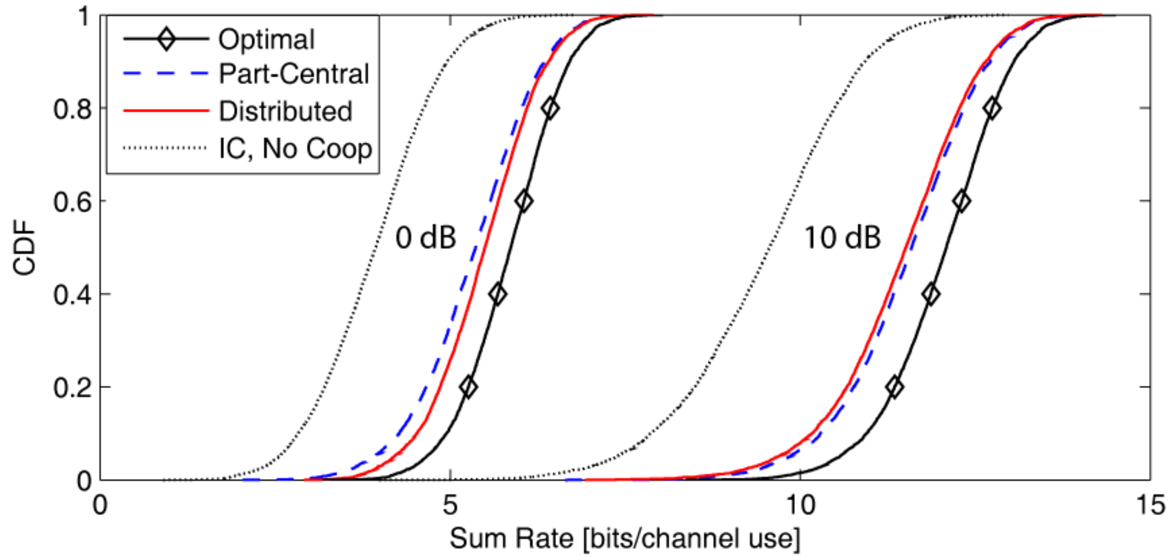
Conclusion: Design Principles

Simulation
Cell Edge Performance

2 BS, 2 MS
3 antennas/BS

zero-mean
i.i.d. channels



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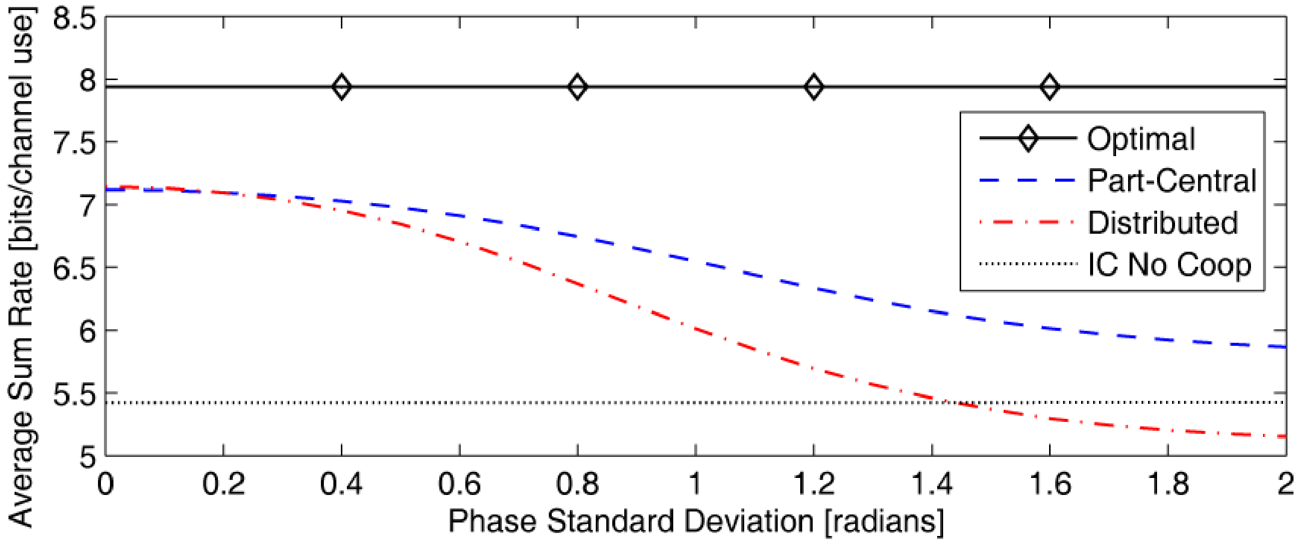
- Principle 1: Small gain with full centralization
  - 5-9%: Is it really worth it? Achievable in practice?
- Principle 2: Marginal difference between partially centralized and fully distributed
  - Limited need for centralized power allocation

Conclusion: Design Principles (2)

Simulation, cont.
Synchronization error:

$$\mathbf{h}_{jk}^{\text{actual}} = \mathbf{h}_{jk} e^{i\phi_{jk}}$$
$$\phi_{jk} \in \mathcal{N}(0, \theta)$$

SNR: 5 dB



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- Principle 3: Robust to small sync-errors
  - E.g., channel uncertainty, hardware delays, etc.
- Principle 4: Large sync-errors handled centrally
  - Avoid multicell precoding when large errors
  - Serve each MS by BS with strongest link

Summary

- Multicell Systems Typically Interference Limited
- Managed by Base Station Cooperation
- Optimal Multicell Precoding Impractical
  - Non-scalable computational/backhaul demands
- Distributed Schemes: Good Performance
  - Only 5-9% loss with proposed scheme
- Necessary with Tight Synchronization
  - Robustness to small deviations
  - Centralization power allocation can treat large errors

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Thank You for Listening!

Questions?

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