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Optimality Properties and Low-Complexity Solutions to

Coordinated Multicell Transmission

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Outline

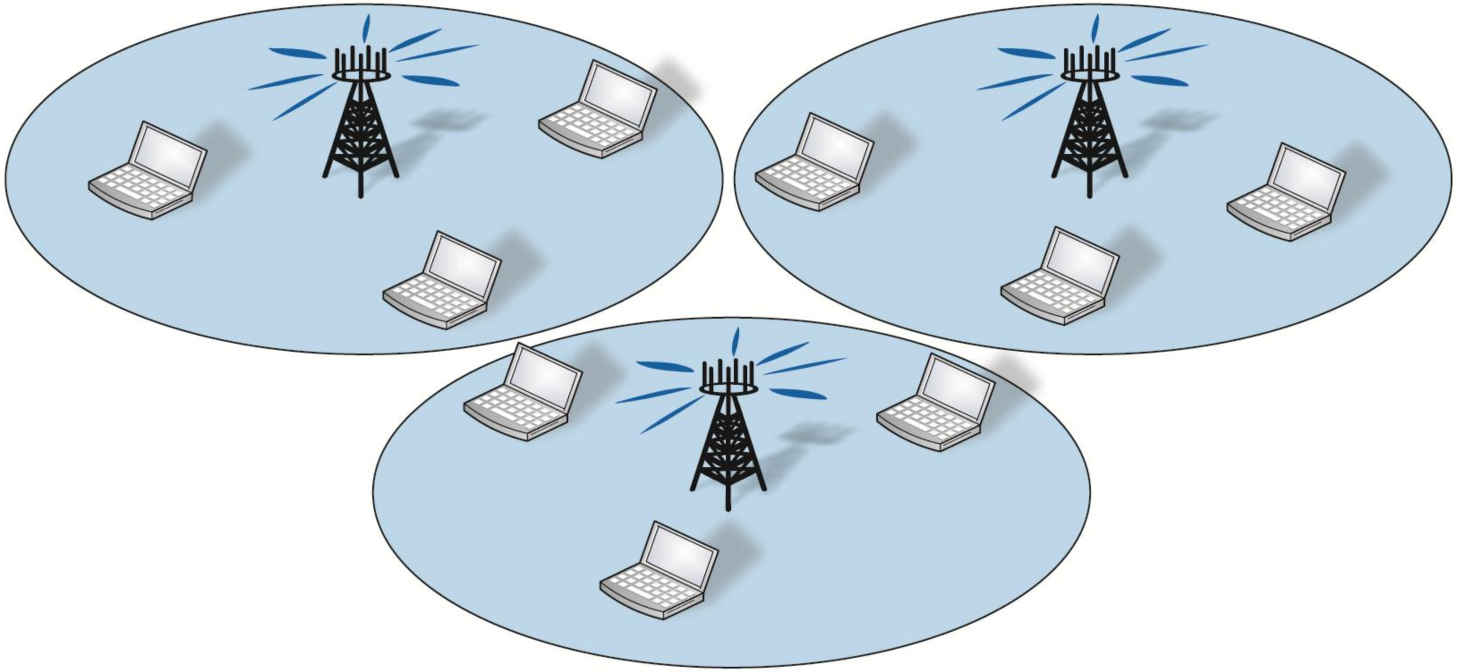
- Introduction: Multicell Transmission

- How to measure performance?
  - Weighted sum performance
  - Simplified convex problem

- Common Optimality Properties
  - Power allocation and beamforming structure

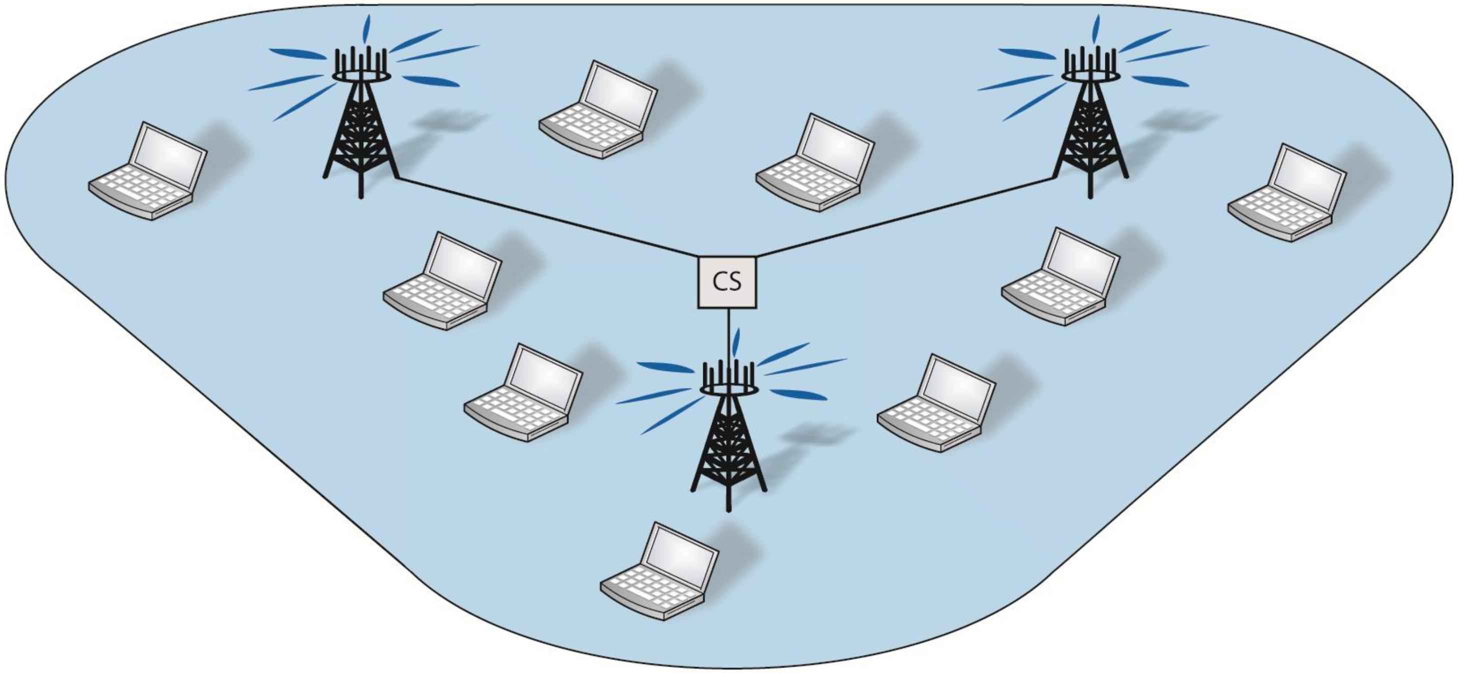
- Low-Complexity Solution
  - Approximation suitable for distributed precoding
  - Evaluated on measured multicell channels

Intro: No Coordination



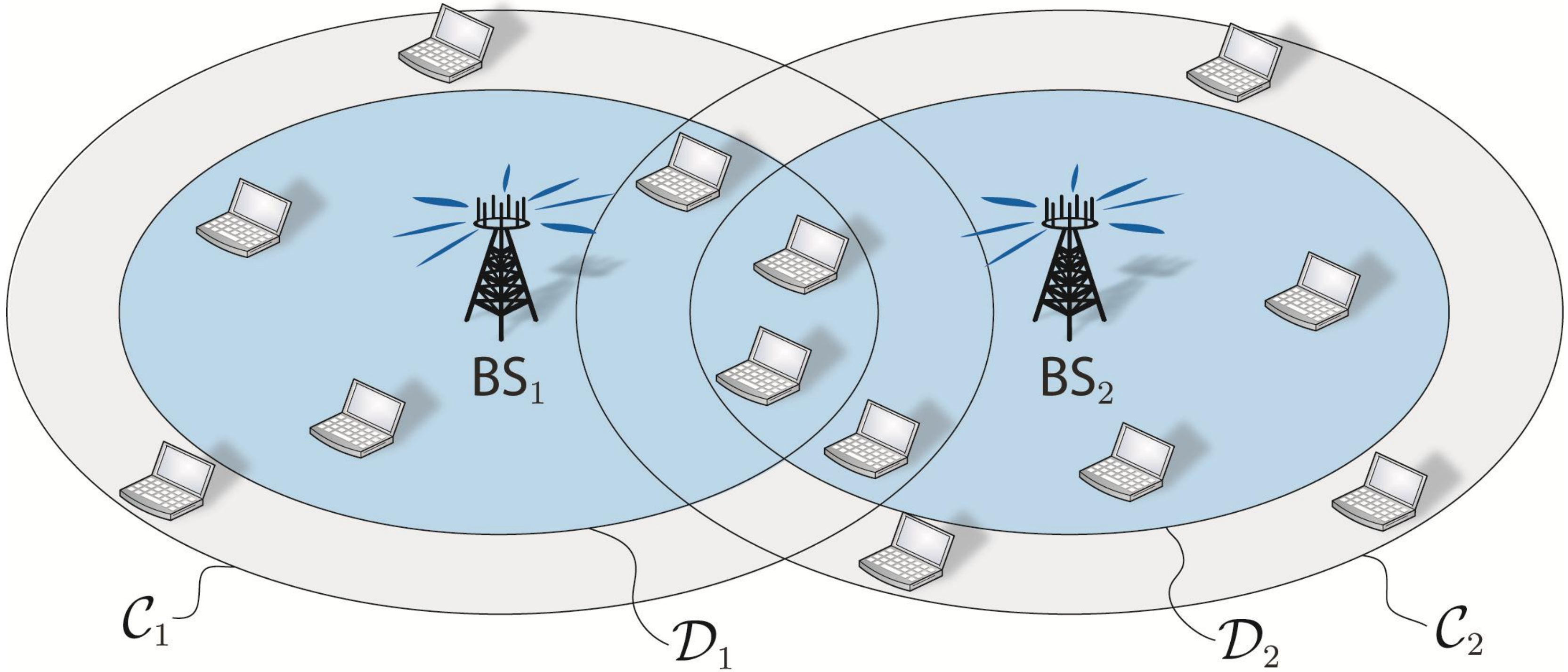
- Non-Cooperative Multicell Downlink
  - Conventional single cell processing
  - Interference at cell edge users uncontrollable
  - Can be improved by coordinating interference

Intro: Full Coordination



- Centralized Cooperative Multicell Downlink
  - Backhaul network and central station (CS)
  - Centralized processing as “one cell”
  - Impractical?

Intro: Dynamic Clusters



- Practical Coordination Structure
  - $\mathcal{C}_k$ = Coordinate interference to terminals
  - $\mathcal{D}_k$ = Data transmission to terminals
  - Limits sharing of data and channel knowledge (full/no coordination are special cases)

System Model

- Assumptions
  - K_t base stations with N_t antennas
  - K_r single-antenna user terminal
  - Channel from all BSs to MS$_k$:
  - BS$_j$ knows $\mathbf{h}_{jk}$ for $k \in \mathcal{C}_j$

$$\mathbf{h}_k = \begin{bmatrix} \mathbf{h}_{1k} \\ \vdots \\ \mathbf{h}_{K_t k} \end{bmatrix}$$

- Data Transmission
  - Signal vector to MS$_k$: $\mathbf{s}_k$
  - Received signal:

$$y_k = \mathbf{h}_k^H \underbrace{\mathbf{C}_k}_{\text{Sorts out signals from coordinating BSs}} \sum_{\bar{k}=1}^{K_r} \underbrace{\mathbf{D}_{\bar{k}}}_{\text{Sorts out transmit antennas}} \mathbf{s}_{\bar{k}} + \underbrace{n_k}_{\text{Noise and distant interference}}$$

System Model (2)

- Transmission Strategies
  - Signal correlation matrix: $\mathbf{S}_k = \mathbb{E}\{\mathbf{s}_k \mathbf{s}_k^H\}$
  - Arbitrary rank

- Power Constraints
  - Per base station: $$\sum_{k \in \mathcal{D}_j} \mathrm{tr}\{\mathbf{D}_{jk} \mathbf{S}_k \mathbf{D}_{jk}^H\} \leq P_j$$

Sorts out antennas of BS$_j$

  - Models hardware, regulations, economy, etc.
  - Extension to arbitrary constraints: [Björnson2011]

How to Measure Performance?

- User Performance Measure: R_k
  - Increasing function of SINRs (depend on $\mathbf{S}_k = \mathbb{E}\{\mathbf{s}_k\mathbf{s}_k^H\}$)
  - E.g., data rate, bit error rate, MSE, etc.

- System Performance: Weighted Sum

$$\underset{\mathbf{S}_1,\mathbf{S}_2,\ldots}{\text{maximize}} \quad \mu_1 R_1 + \mu_2 R_2 + \ldots$$

  - Finds Pareto optimal points
  - Fairness depends on $\mu_1, \mu_2, \ldots$

(P1): Weighted Sum Maximization

- Optimization Problem

$$\text{(P1):}\quad \begin{aligned} \underset{\mathbf{S}_1,\ldots,\mathbf{S}_{K_r}}{\text{maximize}} \quad & \sum_{k=1}^{K_r} \mu_k R_k(\mathbf{S}_1,\ldots,\mathbf{S}_{K_r},\sigma_k^2) \\ \text{subject to} \quad & \sum_{\bar{k}\in\mathcal{D}_j} \mathrm{tr}\{\mathbf{D}_{j\bar{k}}\mathbf{S}_{\bar{k}}\mathbf{D}_{j\bar{k}}^H\} \leq P_j \;\; \forall j \\ & \mathbf{S}_k \succeq \mathbf{0} \;\; \forall k. \end{aligned}$$

- Difficult Problem
  - Non-convex and NP-hard
  - Find structure of the optimal solution?

(P2): Quality of Service Constraints

- Given Performance/QoS Point $(\gamma_1, \dots, \gamma_{K_r})$
  - Find strategy: $R_k \geq \gamma_k \; \forall k$
- What to Optimize?
  - Minimize power? ⇨ Solution may use too much power!
  - Instead: Best possible under power constraints
- Solution: Optimize worst noise $\alpha^2 \sigma_k^2$ that can be handled
  - α-parameter: Constraints $R_k \geq \gamma_k$ satisfied if $\alpha \geq 1$

Second order cone = Convex problem

(P2):
$$\begin{aligned} \underset{\mathbf{S}_1,\dots,\mathbf{S}_{K_r},\alpha}{\text{maximize}} \quad & \alpha \\ \text{subject to} \quad & R_k(\mathbf{S}_1, \dots, \mathbf{S}_{K_r}, \alpha^2 \sigma_k^2) \geq \gamma_k \;\; \forall k, \\ & \mathbf{S}_k \succeq \mathbf{0}, \;\; \sum_{\bar{k} \in \mathcal{D}_j} \mathrm{tr}\{\mathbf{D}_{j\bar{k}} \mathbf{S}_{\bar{k}} \mathbf{D}_{j\bar{k}}^H\} \leq P_j \;\; \forall j, k. \end{aligned}$$

Connection: (P1) and (P2)

Optimize performance = Find optimal QoS per user + Find strategy fulfilling them

- (P2) solves "half" the original problem!

- Price for convexity
  - Need to know optimal user QoS!

- (P1) and (P2): Common Properties
  - Equal if optimal performance of (P1) are constraints in (P2)
  - Properties of (P2) that holds for any $(\gamma_1, \ldots, \gamma_{K_r})$
  - These also holds for (P1)!

Optimality Property 1

Exists optimal solutions with

1. Full power usage (if $|\mathcal{C}_k| \leq N_t$)
2. Single-stream beamforming (i.e., $\mathbf{S}_k = \mathbf{w}_k \mathbf{w}_k^H$)

- Intuitive Results – Non-trivial Proofs
  - Insufficient antennas: Power should be limited
  - Multi-stream solutions exists in special cases

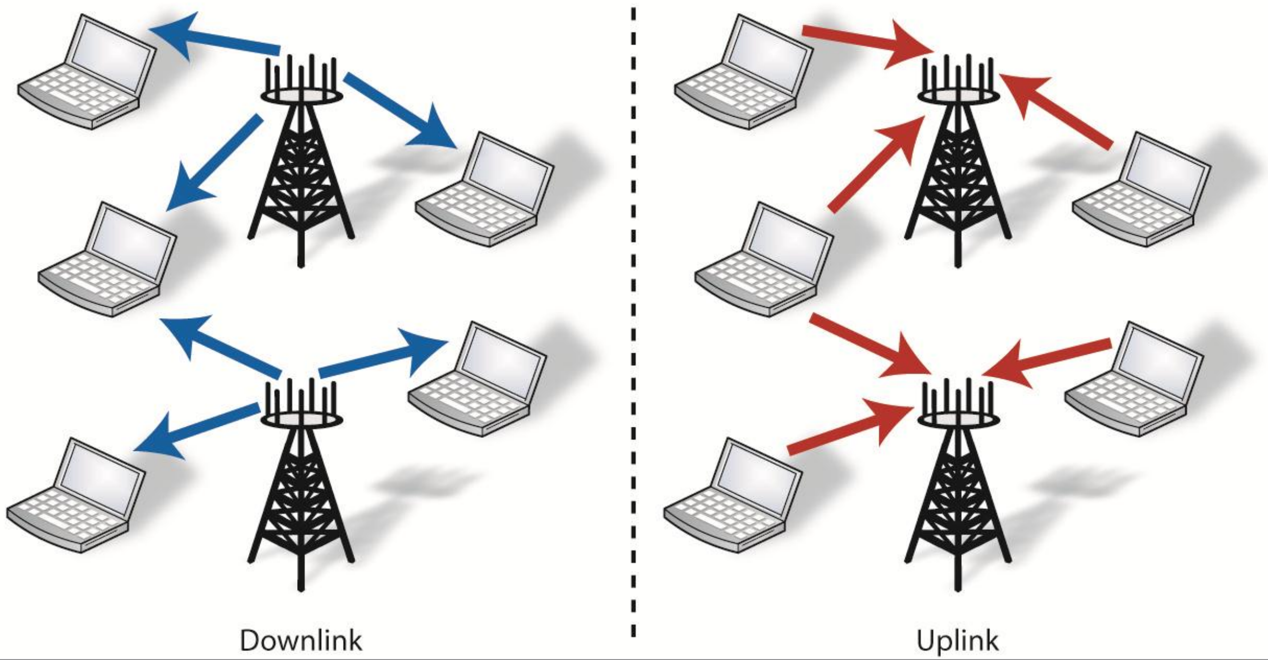
- Allows Simplifications
  - Use total power at all transmitters
  - No SIC-receivers or vector coding required

Optimality Property 2

Uplink-downlink duality for (P2)

- Based on Lagrange duality theory
- Transmit beamformers ⇔ Receive filters

- Motivation
  - Easier to solve uplink problems



Optimality Property 3

Beamforming Parametrization

- Optimal strategies $\mathbf{S}_k = \mathbf{w}_k \mathbf{w}_k^H$ satisfy

$$\mathbf{w}_k = c_k \left(\sum_j \boxed{a_j} \mathbf{D}_{jk} + \sum_{\bar{k} \neq k} \boxed{b_{\bar{k}}} \mathbf{D}_k^H \mathbf{C}_{\bar{k}}^H \mathbf{h}_{\bar{k}} \mathbf{h}_{\bar{k}}^H \mathbf{C}_{\bar{k}} \mathbf{D}_k \right)^{-1} \mathbf{D}_k^H \mathbf{h}_k$$

for some parameters $a_j,\ b_{\bar{k}} \in [0,1]$.

- Optimal Strategies
  - Depends on $K_t + K_r$ parameters
  - Power allocation c_k also function of these
- New Approach: Find Good Parameters
  - Iterative search
  - Heuristic selection – Easy to find good ones!

Simple Distributed Strategy

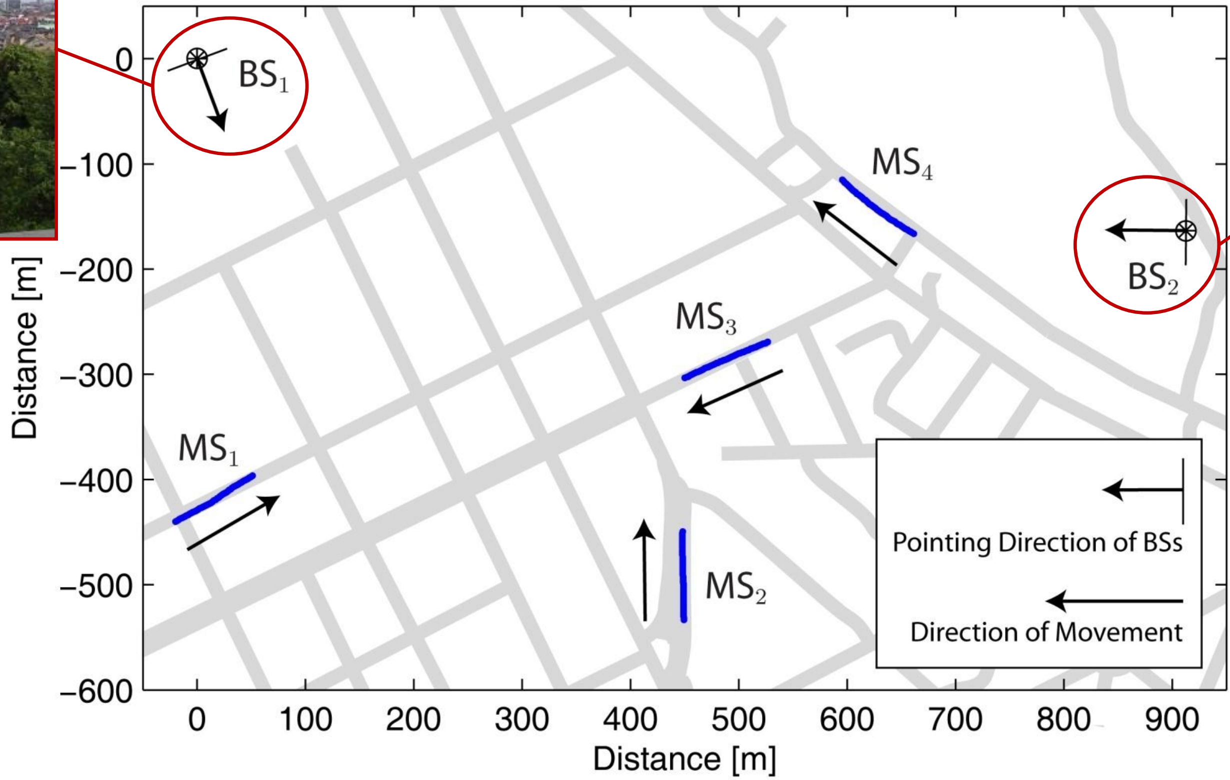
- Motivation: Centralized Solutions Require
  - Much backhaul signaling (CSI, data, sync)
  - High Computational Resources

- Distributed Low-Complexity Solution:
  - Select parameters a_j, $b_{\bar{k}}$ in Property 3 heuristically
  - Calculate independently on each BS

- Result
  - Distributed Virtual SINR (DVSINR) Beamforming
  - Tailored for weighted sum performance

Measurement-Based Evaluation

- Multicell Channel Measurements
  - Realistic urban scenario in Stockholm
  - Correlation between BSs (usually ignored)
  - Two sectorized 4-antenna BSs



BS: Rooftops

MS: Street level (4 users)

Measurement-Based Evaluation (2)

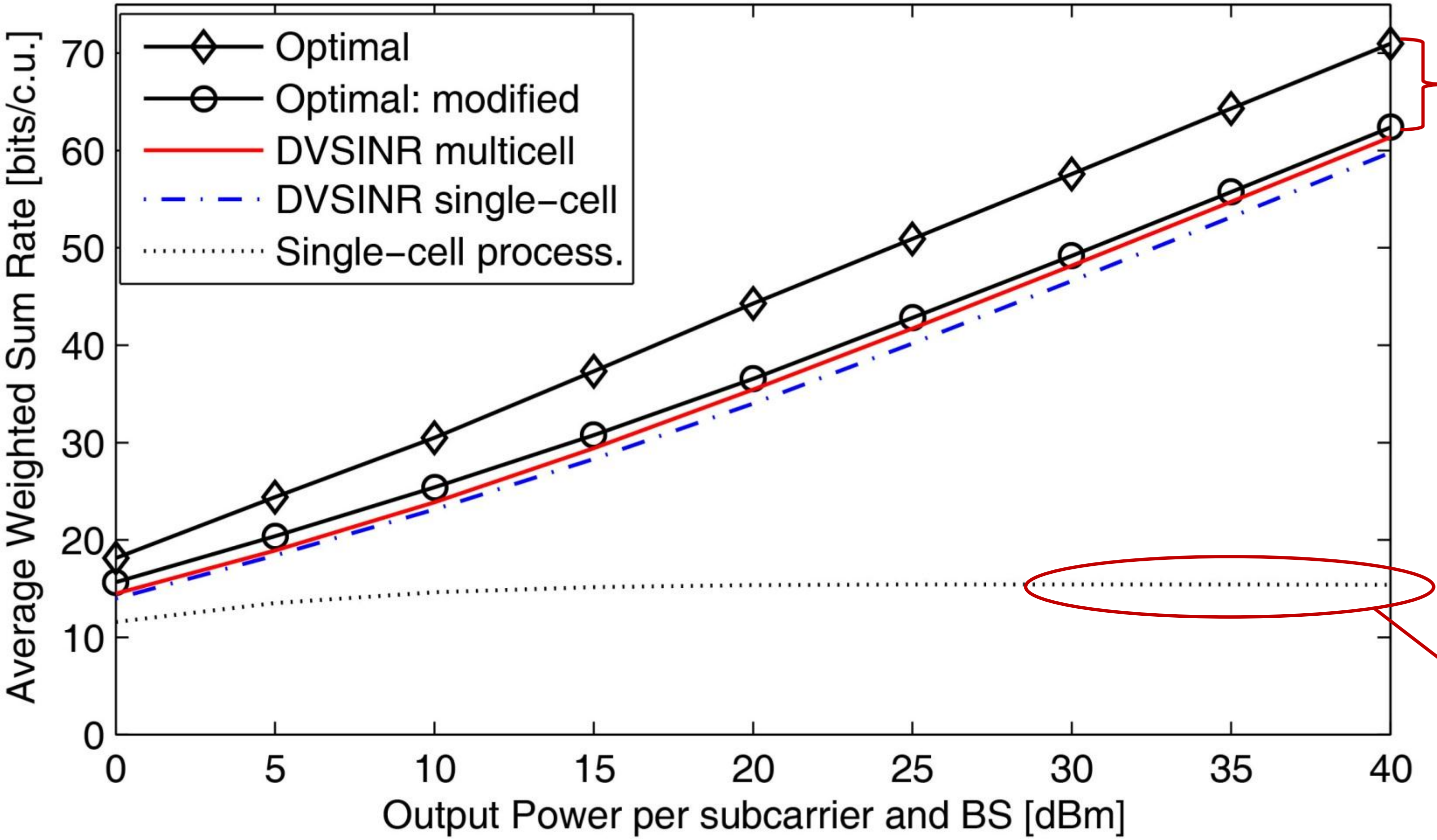
- Weighted Sum Rate
  - Data rate: $R_k(\cdot) = \log_2(1 + \mathrm{SINR}_k)$
  - Proportional fairness

- Precoding Schemes
  1. Optimal Precoding
  2. Modified Optimal Precoding: $|\sum_j \mathrm{inter.}_j|^2 \rightarrow \sum_j |\mathrm{inter.}_j|^2$

     (No interference cancellation between BSs)
  3. DVSINR – Multicell (data from both BSs)
  4. DVSINR – Single-cell (date from one BS)
  5. Single-cell processing

Measurement-Based Evaluation (3)

- Average Weighted Sum Rate
  - Large gain with interference coordination
  - Small gain with joint data: Both DVSINR approaches good



Gap:

Interference Cancellation between BS

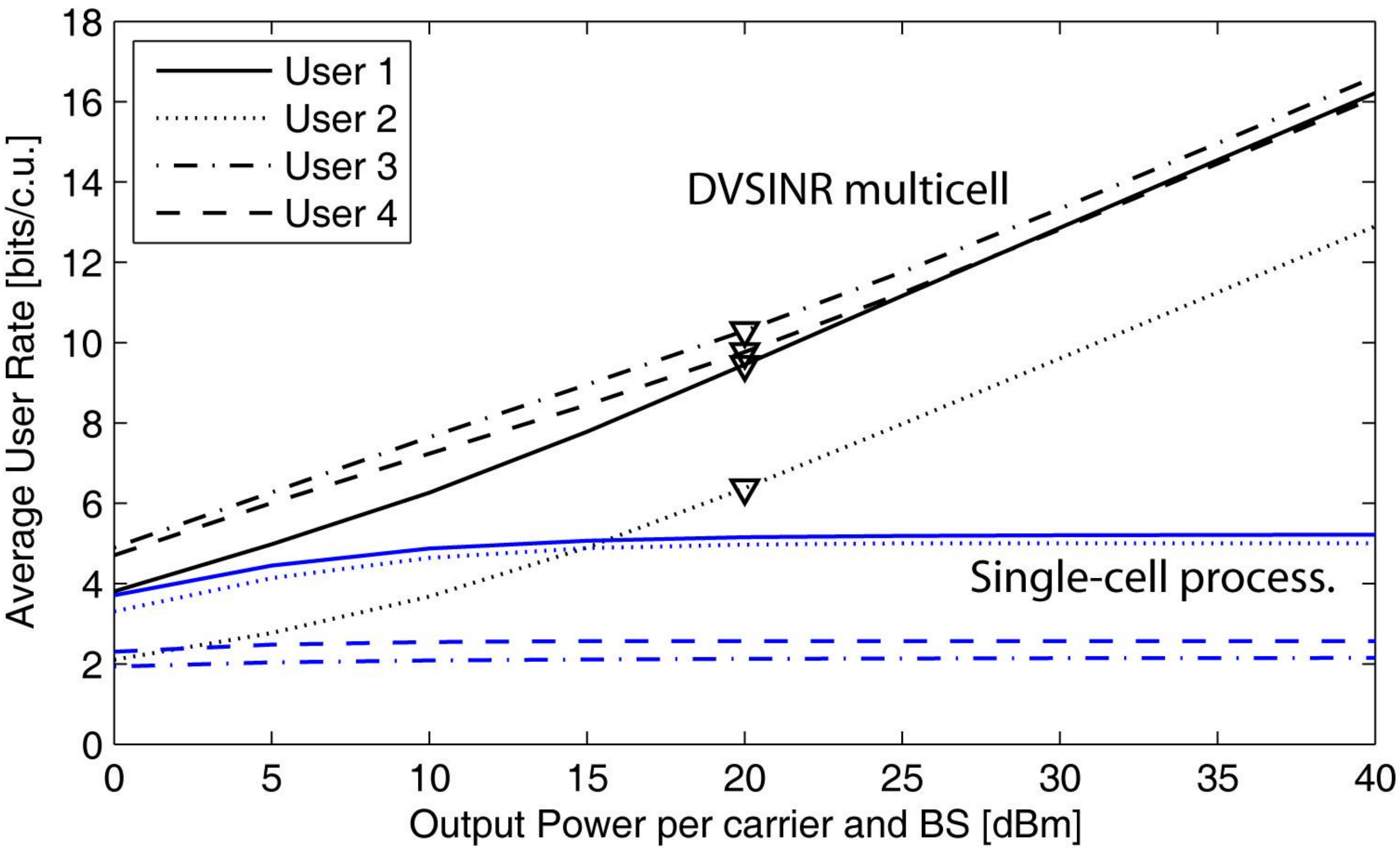
Unreasonable In Practice!

Single-cell processing:

Bounded performance

Measurement-Based Evaluation (4)

- Average User Rates
  - Large improvements for cell edge terminals
  - Not all terminals benefit from multicell coordination



Summary

- Interference Limits Multicell Performance
  - Managed by multicell coordination
- Optimization: Weighted Sum Performance
  - Full power usage and single-stream beamforming
  - Simple parametrization of optimal beamforming
- Distributed Approximation: DVSINR
  - Heuristic use of parameterization
- Measurement-based Multicell Evaluation
  - Interference coordination greatly improves performance
  - Important measurement observations:
    - Not all terminals benefit from multicell coordination
    - Small practical benefit with joint data transmission

References

- Journal version
  - Includes multicarrier and arbitrary power constraints

  E. Björnson, N. Jaldén, M. Bengtsson, B. Ottersten,
  "Optimality Properties, Distributed Strategies, and Measurement-Based Evaluation of Coordinated Multicell OFDMA Transmission,"
  Submitted to IEEE Trans. on Signal Processing.

- Previous work

  E. Björnson, R. Zakhour, D. Gesbert, and B. Ottersten, "Cooperative multicell precoding: Rate region characterization and distributed strategies with instantaneous and statistical strategies with instantaneous and statistical CSI," IEEE Trans. on Signal Processing, aug 2010.

  E. Björnson and B. Ottersten, "*On the Principles of Multicell Precoding with Centralized and Distributed Cooperation*," in Proc. WCSP'09, 2009. **Best Paper Award**.

Thank You for Listening!

Questions?

Papers and Presentations Available:
http://www.ee.kth.se/~emilbjo