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Channel Quantization Design in Multiuser MIMO Systems:

Asymptotic versus Practical Conclusions

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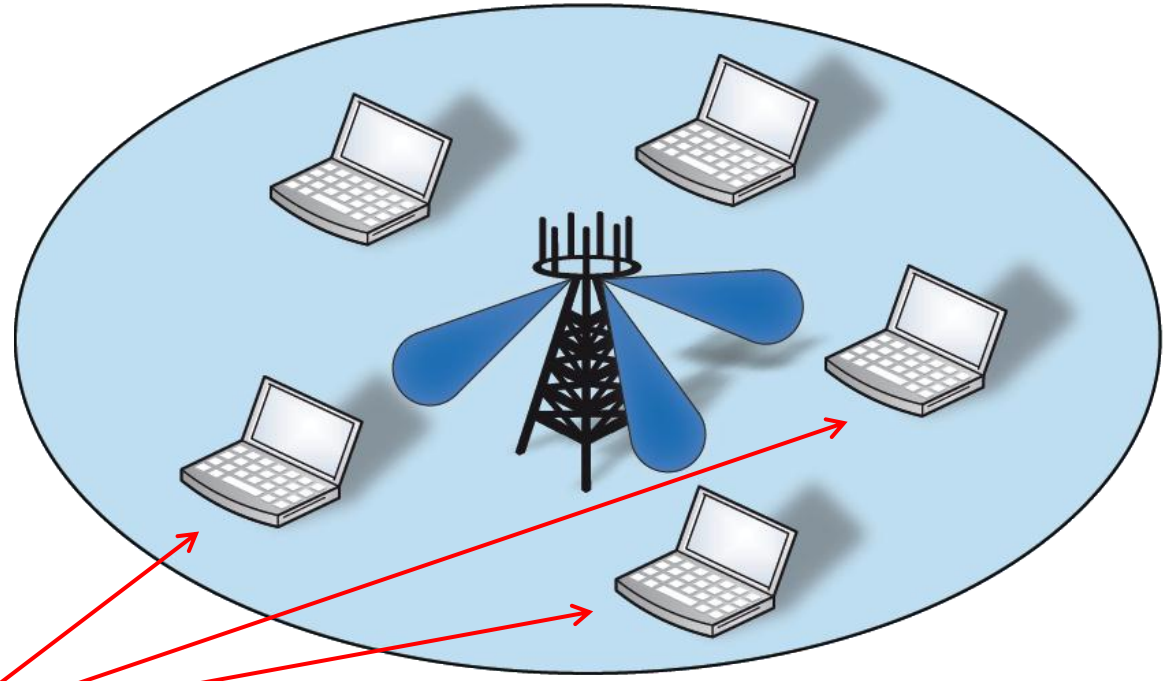
Outline

- Introduction
  - Multiuser MIMO and multiplexing gain
  - Impact of channel uncertainty
- Channel Information
  - Channel Directional Information (CDI)
  - Channel Quality Information (CQI)
- Tradeoff between CDI and CQI
  - How to divide feedback bits between CDI and CQI?
  - Impact of spatial correlation and number of users?
  - Asymptotic analysis
  - Simulations under practical conditions

Multiuser MIMO

- Downlink Transmission
  - One N_t-antenna transmitter
  - K_r single-antenna users ($K_r \geq N_t$)
  - Constraint on total power



Serve subset of users

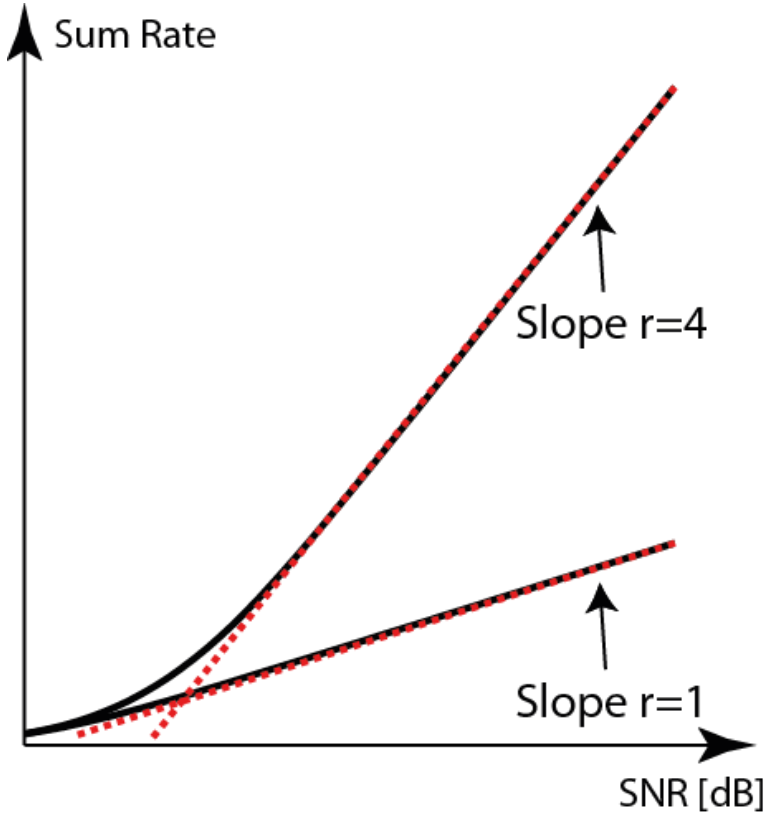
Space-Division Multiple Access (SDMA)

Why SDMA?

- Asymptotic Performance: Multiplexing Gain
  - Sum rate at high SNR: $\mathrm{r} \cdot \log_2(\mathrm{SNR}) + \mathrm{constant}$

Multiplexing Gain

  - Slope in SNR [dB] vs. sum rate:



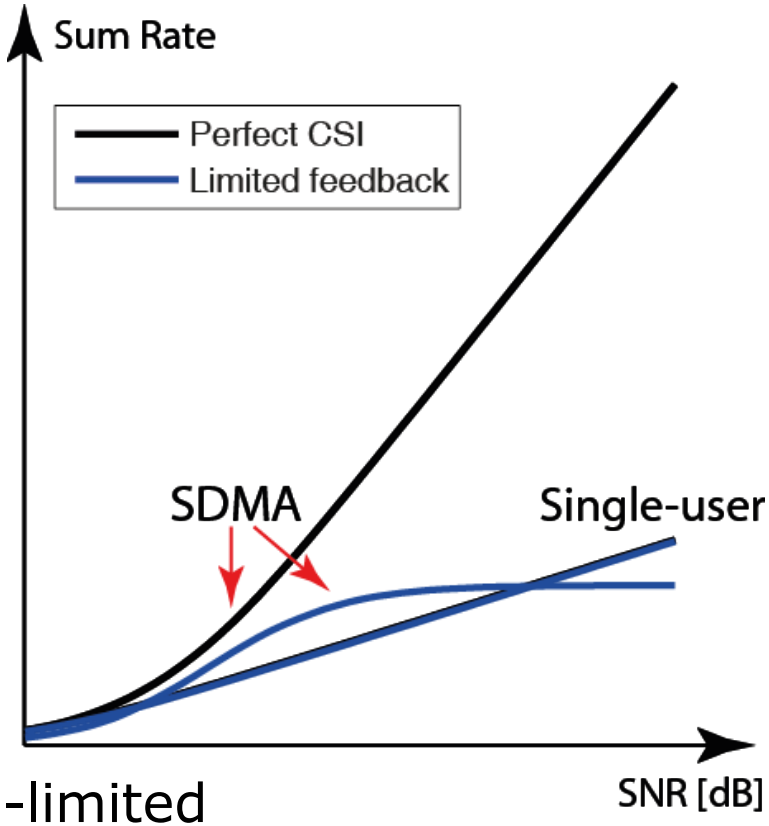
- Improves Multiplexing Gain!
  - r = #interference-free streams
  - SDMA: $\mathrm{r} = N_t$
  - Single user: $\mathrm{r} = 1$

Impact of Channel Uncertainty

- Channel State Information (CSI)
  - Estimation, quantization, and limited feedback
  - Practical systems operate under CSI uncertainty

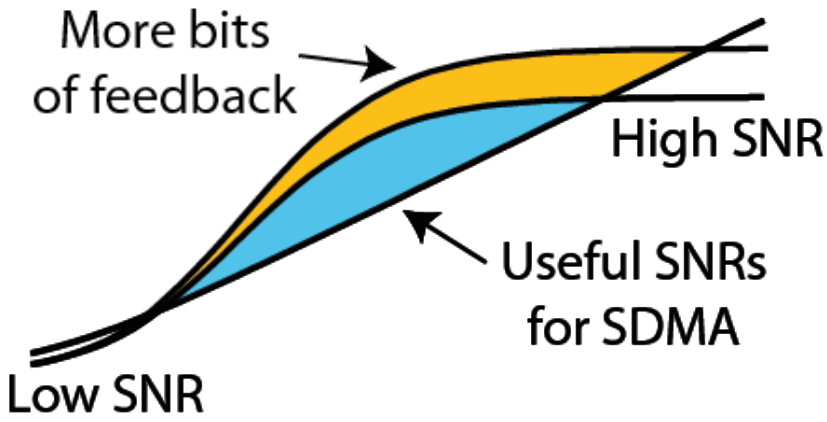
- SDMA Requires Accurate CSI
  - Control co-user interference
  - Multiplexing gain $r \leq 1$ under quantized CSI [Jindal'06]

- Sensitivity to Uncertainty
  - Single user:
    No interference - robust
  - SDMA:
    Very sensitive - Interference-limited



Multiuser MIMO: Quantized feedback

- Each channel described by b bits
  - Low SNR: SDMA has negligible impact
  - High SNR: SDMA is interference-limited

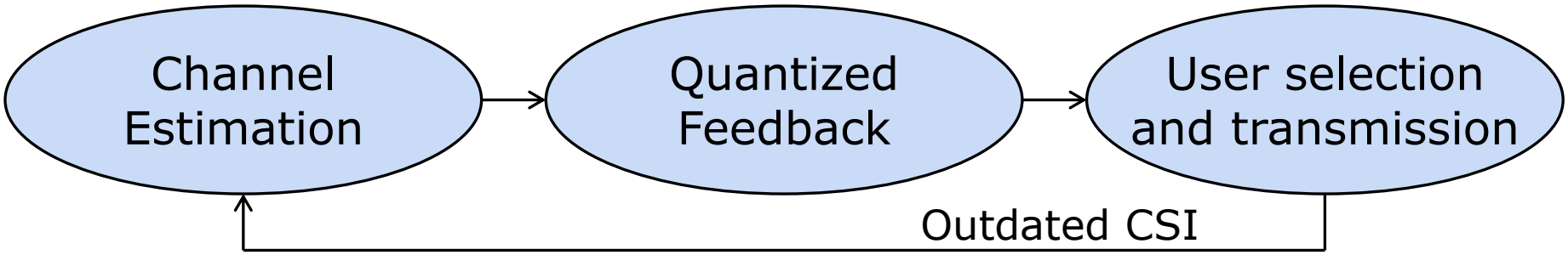


- SDMA only useful at medium SNRs

- Increasing b = Increasing useful SNR range

Performance with Quantized CSI

- How to evaluate performance?
  - Actual sum rate: Unknown under quantized CSI
  - Ergodic sum rate: Impossible with short-term scheduling
  - Both appear in literature! – Infeasible with block model:



- Exploit available quality information:
  - Select rate supported with high probability
  - ϵ-outage rate $R_{k,out}$: $\Pr\{\log_2(1+\mathrm{SINR}_k) \le R_{k,out}\} \le \epsilon$

- Proposed Performance Measure:
  ϵ-outage sum rate: $R_{sum,out} = \sum_k R_{k,out}$

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Channel Quantization Assumptions

- b feedback bits/user – use efficiently
  - Maximize ϵ-outage sum rate
- Rayleigh fading channels
  - To user k: $\mathbf{h}_k \sim CN(\mathbf{0}, \mathbf{R}_k)$ (known statistics)
- Two categories of CSI
  - Direction $\mathbf{h}_k/\|\mathbf{h}_k\|$ (CDI): User selection, beamforming
  - Quality $\|\mathbf{h}_k\|^2$ (CQI): User selection, rate adaptation
  - Tradeoff in quantization – Often disregarded

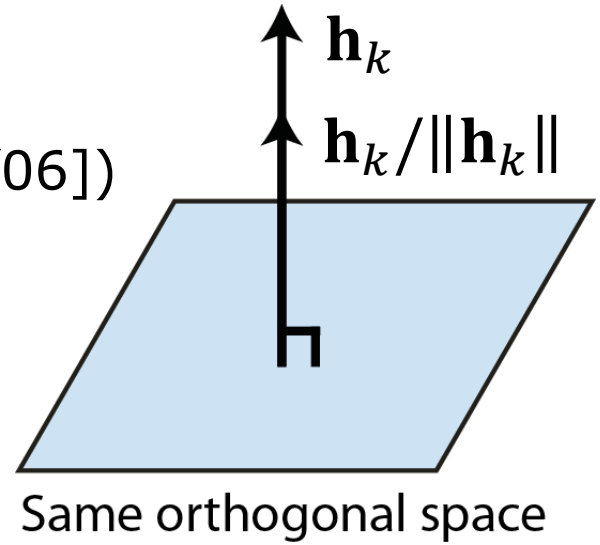
How to divide b bits between direction and quality information?

Asymptotic Observation 1: Only CDI

ϵ-Outage Sum Rate behaves as $N_t \cdot \log_2(\mathrm{SNR}) + \mathrm{const}$

- As $\mathrm{SNR} \to \infty$ and for any $\epsilon > 0$
- If perfect CDI is available ($\mathbf{h}_k/\|\mathbf{h}_k\|$ for all users)

- Proof idea
  - Zero-forcing beamforming (as in [Jindal'06])
  - Select ϵ-outage rates using statistics



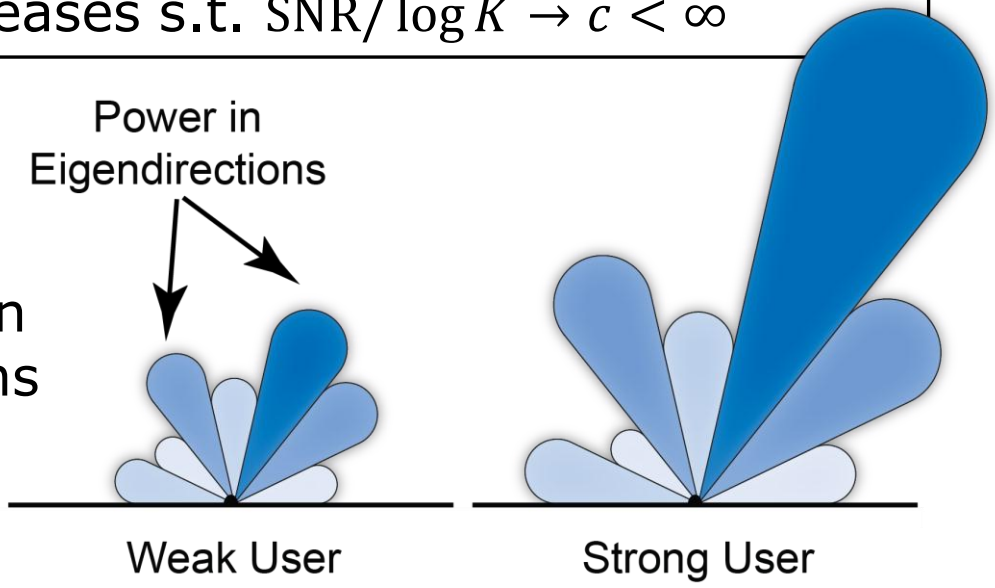
- Indication
  - Only directional feedback is essential?
  - Does it say anything for practical SNRs?

Asymptotic Observation 2: Only CQI

ϵ-Outage Sum Rate behaves as $N_t \cdot \log_2(\mathrm{SNR}) + \mathrm{const}$

- As $\mathrm{SNR} \to \infty$ and for any $\epsilon > 0$
- If perfect CQI is available (indicator γ_k for all users)
- If number of users K increases s.t. $\mathrm{SNR}/\log K \to c < \infty$

- Proof idea
  - Select strong users
  - Asymptotically channels in dominating eigendirections



- Indication
  - Only quality feedback is essential?
  - How many users are required in practice?
  - Do we exploit unreasonable tails of the channel distribution?

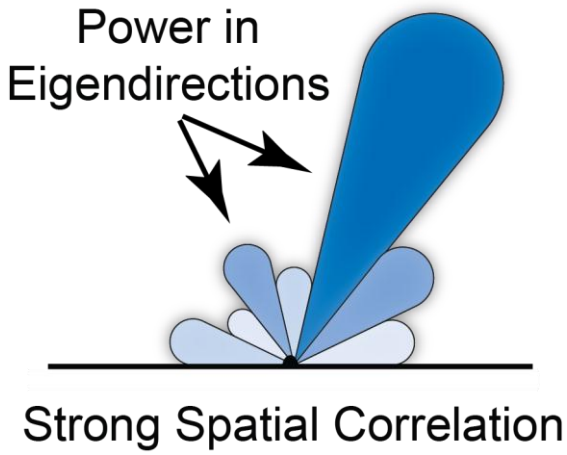
Asymptotic Observation 3: No feedback

ϵ-Outage Sum Rate behaves as $N_t \cdot \log_2(\mathrm{SNR}) + \mathrm{const}$

- As $\mathrm{SNR} \to \infty$ and for any $\epsilon > 0$
- If spatial correlation increases s.t. $\dfrac{\mathrm{SNR}}{\lambda_{k,1} / \lambda_{k,2}} \to c_k < \infty$

Two largest eigenvalues of $\mathbf{R}_k$

- Proof idea
  - High spatial correlation ⇔ Channel directions known



- Indication
  - No feedback is actually needed?
  - How much spatial correlation is required?

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Conclusions from Asymptotic Analysis

- Diverse Observations
  - Only CDI feedback is needed
  - Only CQI feedback is needed (many users)
  - No feedback is needed (much spatial correlation)

- What Applies to Practical Scenarios?
  - Illustrated by simulations

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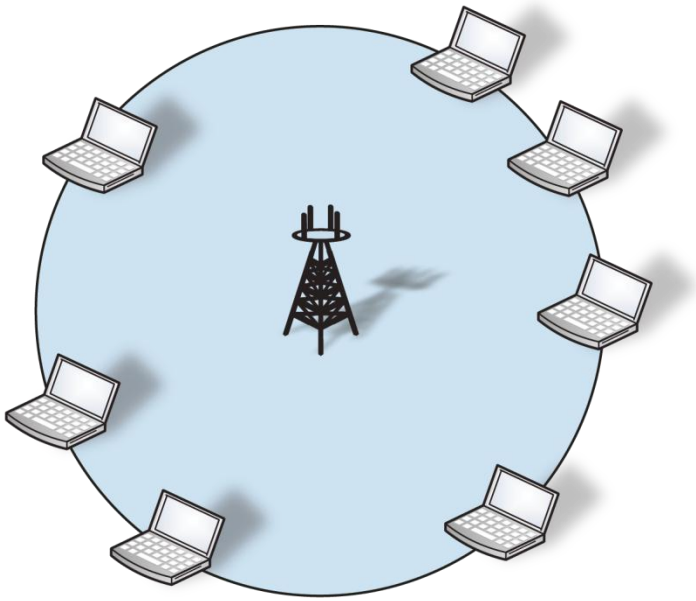
Simulations

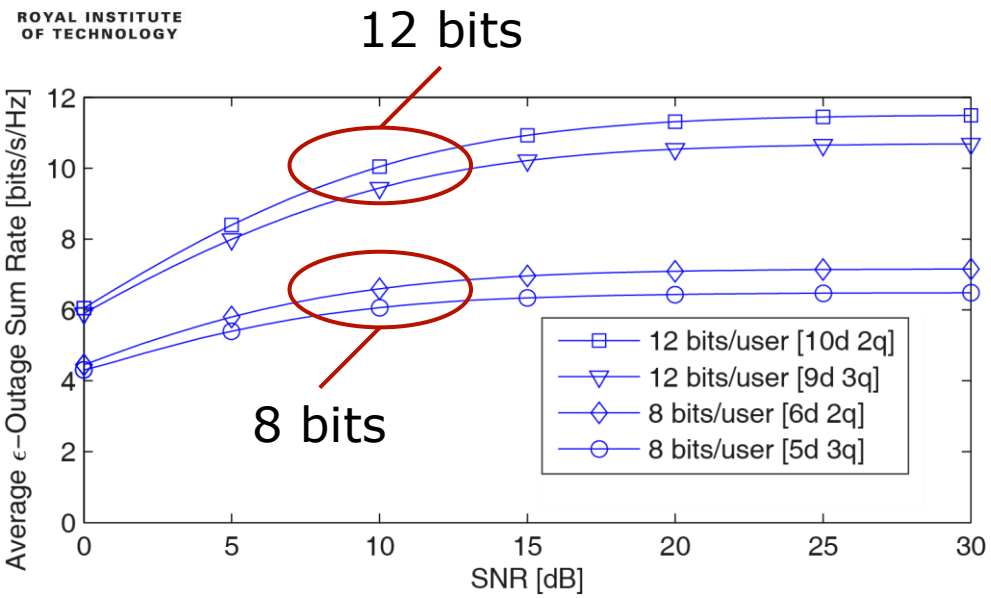
- Simple SDMA with Quantized Feedback
  - d bits of CDI: Correlated Grassmannian codebook
  - q bits of CQI: Entropy maximizing codebook

  Separate
  - Fixed total bits: $b = d + q$
  - Perfect CSI at receivers

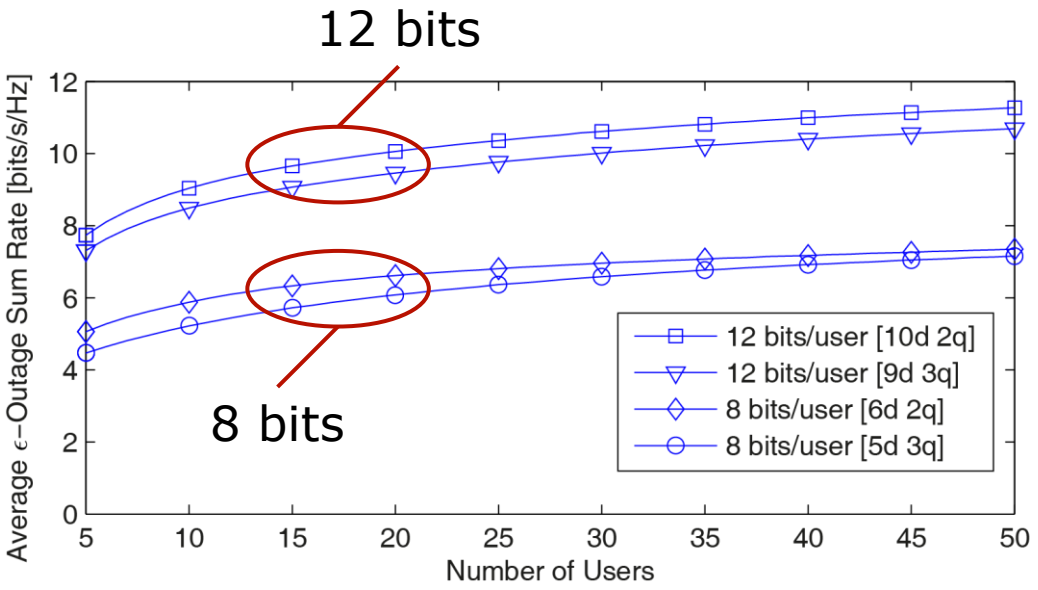


- Resource Allocation
  - $N_t = 4$ transmit antennas
  - Random users on a circle:
  - Scheduling algorithm from [Trivellato'07]
  - Approximate lower bound on SINR: $\widehat{\mathrm{SINR}}_k$
  - Fade-margin α: $\Pr\left\{ \log_2(1 + \mathrm{SINR}_k) \leq \log_2\left(1 + \alpha\widehat{\mathrm{SINR}}_k\right)\right\} \leq 0.05$

Simulations: Uncorrelated channels



Varying SNR, 20 users

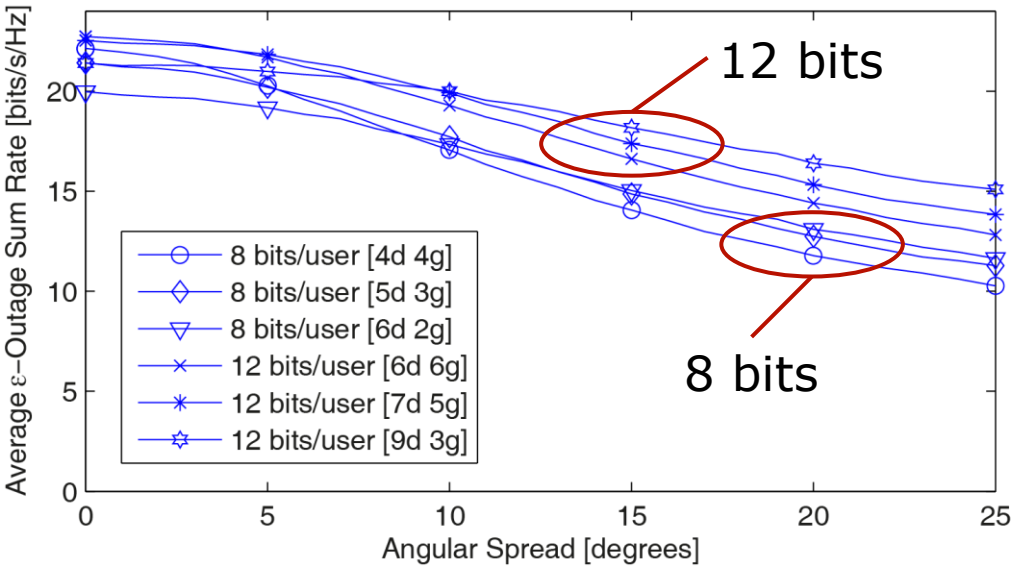


SNR 10 dB, Varying #users

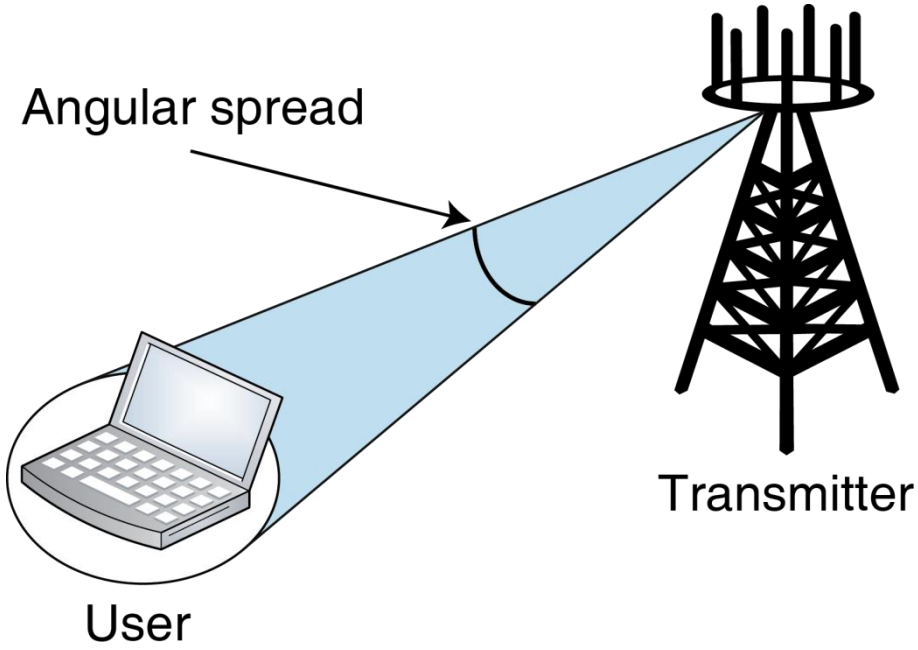
- Observations
  - 2 bits/user for CQI, remaining for CDI
  - More users → CQI slightly more important

- Agrees with asymptotic observation 1: CDI most important

Simulations: High spatial correlation



SNR 10 dB, 20 users



- Observations
  - High correlation: More than 2 bits/user on CQI feedback
  - Small difference – Small range of angular spreads

- Also agrees well with asymptotic observation 1:
  2-3 bits for CQI feedback, remaining for CDI feedback

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Summary

- Multiuser MIMO system
  - Excellent performance with perfect channel knowledge
  - Limited in practice by feedback quantization
- How to Quantization the Channel?
  - Tradeoff between quality and directional information
  - What is their relative importance?
- Asymptotic Observations
  - Anything can be shown – Handle with care!
- Simulation Observations
  - 2-3 bits/user for quality, remaining for directional feedback
  - Impact of spatial correlation and number of users is small
  - Agrees with one asymptotic observation

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Thank You for Listening!

Questions?

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